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I N D C INTERNATIONAL NUCLEAR DATA COMMITTEE

WORKSHOP

ON NUCLEAR STRUCTURE AND DECAY DATA: THEORY AND EVALUATION,

2008

ICTP Trieste, Italy

28 April – 9 May 2008

Editors: A.L.Nichols and P.K.McLaughlin
IAEA Nuclear Data Section
Vienna, Austria

June 2008

IAEA NUCLEAR DATA SECTION, WAGRAMER STRASSE 5, A-1400 VIENNA

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WORKSHOP ON NUCLEAR STRUCTURE AND DECAY DATA: THEORY AND EVALUATION, 2008

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28 April – 9 May 2008

Editors

A.L. Nichols and P.K. McLaughlin

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Abstract

A two-week Workshop on Nuclear Structure and Decay Data under the auspices of the IAEA Nuclear Data Section was organised and held at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy from 28 April to 9 May 2008. This workshop constituted a further development of previous Nuclear Structure and Decay Data Workshops held in 2002, 2003, 2005 and 2006. The aims and contents of the 2008 workshop are summarized, along with the agenda, list of participants, comments and recommendations. All recent workshop material has been assembled in this INDC report, and is also freely available on CD-ROM (all relevant PowerPoint presentations and manuals along with appropriate computer codes):

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June 2008

TABLE OF CONTENTS

WORKSHOP
ON NUCLEAR STRUCTURE AND DECAY DATA: THEORY AND EVALUATION, 2008
Summary

ICTP Trieste, Italy

28 April – 9 May 2008

Prepared by

A.L. Nichols

IAEA Nuclear Data Section

Vienna, Austria

Abstract

Basic aspects of a two-week Workshop on Nuclear Structure and Decay Data: Theory and Evaluation are outlined in this short note for the record. The aims and contents of this 2008 workshop are summarized, along with the agenda, list of participants, comments and recommendations. Further consideration will be given to holding this specific workshop at various time intervals for training purposes on the advice of the International Nuclear Data Committee (INDC) and the International Network of Nuclear Structure and Decay Data Evaluators.

June 2008

1.1 OBJECTIVES

The International Atomic Energy Agency sponsored a two-week Workshop on "Nuclear Structure and Decay Data: Theory and Evaluation" at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste from 28 April to 9 May 2008. This workshop was organised and co-directed by A.L. Nichols (IAEA Nuclear Data Section), J.K. Tuli (NNDC, Brookhaven National Laboratory, USA) and A. Ventura (ENEA, Bologna, Italy).

As with earlier workshops [1-4], the primary objective was to familiarize nuclear physicists and engineers from both developed and developing countries with

(i) modern nuclear models;
(ii) relevant experimental techniques;
(iii) statistical analysis procedures to derive recommended data sets;
(iv) evaluation methodologies for nuclear structure and decay data;
(v) international efforts to produce and maintain the Evaluated Nuclear Structure Data File (ENSDF).

Reliable nuclear structure and decay data are important in a wide range of nuclear applications and basic research. Participants were introduced to both the theory and measurement of nuclear structure data, and the use of computer codes to evaluate decay data.

Detailed presentations were given by invited lecturers, along with computer exercises and workshop tasks. Participants were also invited to contribute their own thoughts and papers of direct relevance to the workshop.

1.2 PROGRAMME

The workshop programme is briefly summarised below.

1.2.1 Agenda

<u>Monday, 28 April 2008</u>

08:30 – 10:30	Registration
11:00 – 10:30	Opening Session Welcome (Alan Nichols (IAEA) and Jag Tuli (BNL) Aims (Jag Tuli) NSDD – general features (Jag Tuli) IAEA–NDS: NSDD network and recent CRPs (Alan Nichols)
12.30 – 14.00	Lunch break
14:00 – 15:30	Introduction to ICTP computer facilities (Johannes Grassberger/Kevin McLaughlin)
15.30 – 16.00	Coffee break
16:00 – 17:00	Web capabilities (Alan Nichols)
17:00 – 18:00	NuDat (Alejandro Sonzogni)

Tuesday, 29 April 2008

09:00 – 10:30	Nuclear theory (Piet Van Isacker)
10:30 – 11:00	Coffee break
11:00 – 12:30	ENSDF format + model exercises (Jag Tuli)
12:30 – 14:00	Lunch break
14:00 – 15:30	Bibliographic databases and ENSDF programs (Alejandro Sonzogni)
15:30 – 16:00	Coffee break
16:00 – 17:30	Students' presentations

Wednesday, 30 April 2008

09:00 – 10:30	Nuclear theory (Piet Van Isacker)
10:30 – 11:00	Coffee break
11:00 – 12:30	ENSDF – programs + model exercises (Jag Tuli)
12:30 – 14:00	Lunch break
14:00 – 15:30	ENSDF data access: Editor (Alejandro Sonzogni)
15:30 – 16:00	Coffee break
16:00 – 17:30	Workshop activities (Daniel Abriola; Jag Tuli; Alejandro Sonzogni; Coral Baglin; Eddie Browne; Kevin McLaughlin)

Thursday, 1 May 2008

09:00 – 10:30	Theory (Slobodan Brant)
10:30 – 11:00	Coffee break
11:00 – 12:30	ENSDF evaluation policies (Jag Tuli)
12:30 – 14:00	Lunch break
14:00 – 15:30	ENSDF- decay (Eddie Browne)
15:30 – 16:00	Coffee break
16:00 – 17:30	Workshop activities (Daniel Abriola; Jag Tuli; Alejandro Sonzogni; Coral Baglin; Eddie Browne; Kevin McLaughlin)

Friday, 2 May 2008

09:00 – 10:30	Theory (Slobodan Brant)
10:30 – 11:00	Coffee break
11:00 – 12:30	Model exercise – decay (lead by Eddie Browne)
12:30 – 14:00	Lunch break
14:00 – 15.30	Students' Presentations
15:30 onwards	Free time

Monday, 5 May 2008

09:00 – 10:30	ENSDF – reactions (Coral Baglin)
10:30 – 11:00	Coffee break
11:00 – 12:30	Data analyses (Desmond MacMahon)
12:30 – 14:00	Lunch break
14:00 – 15:30	Model exercise – reactions (lead by Coral Baglin)
15:30 – 16:00	Coffee break
16:00 – 17:30	Workshop activities (Jag Tuli; Daniel Abriola; Coral Baglin; Eddie Browne; Filip Kondev; Tibor Kibedi; Kevin McLaughlin)

Tuesday, 6 May 2008

09:00 – 10:30	Data analyses (Desmond MacMahon)
10:30 – 11:00	Coffee break
11:00 – 12:30	ENSDF- adopted levels (Coral Baglin)
12:30 – 14:00	Lunch break
14:00 – 15:30	Model exercises- adopted levels (Coral Baglin)
15:30 – 16:00	Coffee break
16:00 – 17:30	Workshop activities (Jag Tuli; Daniel Abriola; Coral Baglin; Eddie Browne; Filip Kondev; Tibor Kibedi; Kevin McLaughlin)

Wednesday, 7 May 2008

09:00 – 10:30	ENSDF – Experimental techniques (Filip Kondev)
10:30 – 11:00	Coffee break
11:00 – 12:30	ENSDF – Experimental techniques (Tibor Kibedi)
12:30 – 14:00	Lunch break
14:00 – 15:30	Workshop activities (Jag Tuli; Daniel Abriola; Coral Baglin; Eddie Browne; Filip Kondev; Tibor Kibedi; Kevin McLaughlin)
15:30 – 16:00	Coffee break
16:00 – 17:30	Workshop activities (Jag Tuli; Daniel Abriola; Coral Baglin; Eddie Browne; Filip Kondev; Tibor Kibedi; Kevin McLaughlin)

Thursday, 8 May 2008

09:00 – 10:30	ENSDF – Experimental techniques (Filip Kondev)
10:30 – 11:00	Coffee break
09:00 – 10:30	ENSDF – Other data considerations (Tibor Kibedi)
12:30 – 14:00	Lunch break
14:00 – 15:30	Workshop activities (Jag Tuli; Daniel Abriola; Coral Baglin; Eddie Browne; Filip Kondev; Tibor Kibedi; Kevin McLaughlin)
15:30 – 16:00	Coffee break
15:55 – 16:10	Round table meeting for CEI participants
16:00 – 17:30	Workshop activities (Jag Tuli; Daniel Abriola; Coral Baglin; Eddie Browne; Filip Kondev; Tibor Kibedi; Kevin McLaughlin)

Friday, 9 May 2008

09:00 – 10:30	Workshop activities (Jag Tuli; Daniel Abriola; Coral Baglin; Eddie Browne; Filip Kondev, Tibor Kibedi; Kevin McLaughlin)
10:30 – 11:00	Coffee break
11:00 – 12:30	Review of workshop (Jag Tuli; Daniel Abriola; Eddie Browne; Filip Kondev)
12:30 – 14:00	Lunch break
14:00 – 15:30	Workshop activities (Jag Tuli; Daniel Abriola; Coral Baglin; Eddie Browne; Kevin McLaughlin)
15:30	Close of workshop

1.2.2 Participants

Twenty-seven participants (predominantly from developing countries) many with full or partial support from the IAEA were selected to attend the workshop in April 2008. Selection was undertaken by Nuclear Data Section staff in association with the workshop directors and ICTP staff. Twenty-five of those selected were able to attend the course, and this number were augmented by seven ICTP affiliates and associates. Four students from Bulgaria and Ukraine were sponsored by the Central European Initiative (CEI), and discussed their thoughts and opinions of the workshop at a separate meeting with some of the lecturers and a co-director.

First row, seated from left to right:

Daniela Elena ALVAREZ (Argentina), Mogahed Ebrahim Ali AL-ABYAD (Egypt), Edgardo BROWNE-MORENO (USA), Mohammad ESKEF (Syria) , Yusuf Aminu AHMED (Nigeria), Coral M. BAGLIN (USA), Daniel ABRIOLA (IAEA), Desmond MacMAHON (UK), Jagdish K. TULI (USA)

Second row, standing from left to right:

Mahmoud Mohamed TAHA (Egypt), Khallefeh Suleiman ABU SALEEM (Jordan), Tibor KIBEDI (Australia), Ali Abdul Lateef Kareem ALZUBADI (IRAQ), Badamsambuu JIGMEDDORJ (Mongolia), Dmytro SYMOCHKO (Ukraine), Caroline Delini NESARAJA (Malaysia), Elaine KWAN (USA), Alpana GOEL (India), Marina de COMELLI (Sec, Italy), Ichinkhorloo DAGVADORJ (Mongolia), Moinul Haque A. K. M MEAZE (Bangladesh), Thuy Nham NGUYEN THI (Vietnam), Yazmyn Lizette PARAGUAY VILLA (Peru), Jamila Keranovna BAYIMBETOVA (Uzbekistan)

Third row, standing from left to right:

Dong YANG (China), Paresh Krishnakumar JOSHI (India), Ryan Patrick FITZGERALD (USA), Christian Van OUELLET (Canada), Rajarshi RAUT (India), Kevin McLAUGHLIN (IAEA), Muhammad Ikram SAFI (Pakistan), Zashmir NAIK (India)

Fourth row, standing from left to right:

Kalin Angelov GLADNISHKI (Bulgaria), Atanas Emilov DINKOV (Bulgaria), Mihail Yordanov TODOROV (Bulgaria), Christopher CHIARA (USA)

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1.3 PRESENTATIONS AVAILABLE IN ELECTRONIC FORM ON CD-ROM

Presentations by Lecturers

Aims of the Workshop - General features of NSDD, J. K. Tuli

Nuclear Theory:
Nuclear Structure: Single-Particle Models, P. Van Isacker
Nuclear Structure: Collective Models, P. Van Isacker
Structure of the Odd-Even Nuclei in the Interacting Boson Model, S. Brant
High Spin States in the Interacting Boson and Boson-Fermion Model, S. Brant
Structure of Odd-Odd Nuclei in the Interacting Boson-Fermion-Fermion Model, S. Brant
β Decay in the Interacting Boson-Fermion Model, S. Brant

Experimental Nuclear Spectroscopy:
Lecture I – Experimental Nuclear Structure Physics, F. Kondev (April 2005)
Lecture II – Experimental Nuclear Structure Physics at the Extreme, F. Kondev (April 2005)
Lecture I – Experimental Techniques to Deduce J^{π}, T. Kibedi (February 2006)
Lecture II – New Developments in Characterizing Nuclei Using Separators, T. Kibedi (February 2006)

Statistical Analyses:
Evaluation of Discrepant Data I, D. MacMahon
Evaluation of Discrepant Data II, D. MacMahon
Evaluation of Discrepant Data III, D. MacMahon
Evaluation of ^{56}Co Decay Data, D. MacMahon, Coral Baglin
Convergence of Techniques for the Evaluation of Discrepant Data, Desmond MacMahon, Andy Pearce, Peter Harris

ENSDF:
Evaluated Nuclear Structure Data Base, J. K. Tuli
Evaluations – A Very Informal History, J. K. Tuli
Evaluated Nuclear Structure Data File – A Manual for Preparation of Data Sets, J. K. Tuli
Guidelines for Evaluators, M. J. Martin, J. K. Tuli
Bibliographic Databases, T. W. Burrows
An Introduction to Nuclear Science References (NSR), A. Sonzogni
An Introduction to NuDat, A. Sonzogni

ENSDF Analysis and Utility Codes, T. W. Burrows:
- Their Descriptions and Uses, T. W. Burrows
- FMTCHK (Format and Syntax Checking), T. W. Burrows
- PowerPoint presentations, T. W. Burrows
- LOGFT (Calculates log *ft* for beta decay), T. W. Burrows
- GTOL (Gamma to Level), T. W. Burrows
- HSICC (Hager-Seltzer Internal Conversion Coefficients), T. W. Burrows

ENSDF – Data Access: Editor-evp, A. Sonzogni
ENSDF – Decay, E. Browne
ENSDF – Model Exercises – Decay, E. Browne
ENSDF – Reaction Datasets, C. Baglin
ENSDF – Model Exercises – Reaction Datasets, C. Baglin
ENSDF – Adopted Levels and Gammas, C. Baglin
ENSDF – Model Exercises – Adopted Levels and Gammas Datasets, C. Baglin

Additional Material:
IAEA: NSDD Network, Recent Relevant CRPs and Other Activities (PowerPoint presentation), A. L. Nichols
IAEA: NSDD Network, Recent Relevant CRPs and Other Activities (draft paper), A. L. Nichols
Nuclear Structure and Decay Data: Introduction to Relevant Web Pages (draft paper), T. W. Burrows, P. K. McLaughlin, A. L. Nichols

Presentations by Lecturers which are not included in this manual from previous NSDD workshops

Nuclear Theory:
Geometrical Symmetries in Nuclei – An Introduction, A. Jain
Geometrical Symmetries in Nuclei, A. Jain
Lectures on Geometrical Symmetries in Nuclei, A. Jain
Hartree-Foch-Bogoliubov Method, D. Vretenar
Self-consistent Mean-field Models – Structure of Heavy Nuclei, D. Vretenar
Quasiparticle OR BCS Method, Y. Gambhir (February 2006)
Hartree-Fock (HF) Mean Field Theory. Y. Gambhir (February 2006)

Experimental Nuclear Spectroscopy:
Introduction, P. von Brentano
Lecture I – Nuclear Shapes, P. von Brentano
Lecture II – Measurement of Lifetimes, P. von Brentano

Presentations by Participants

2003 Workshop:
ETFFS Calculations of the Low-Lying Strength in Ca Isotopes, E. Litvinova
A = 193 Mass Chain Evaluation: a summary, Guillermo V. Marti
Fission of ^{210}Po and ^{198}Hg Nuclei at Intermediate Excitation Energies, Houshyar Noshad
Neutron Cross Sections of Er Isotopes, A. K. M. Harun-Ar-Rashid
Comparison of Rotating Finite Range Model and Thomas-Fermi Fission barriers, K. Mahata
Target/Projectile Structure Dependence in Transfer Reactions, P. K. Sahu
^{152}Gd collective states, V. Pronskikh

2005 Workshop:
Compton Add-Back Protocols for Use with the EXOGAM Array, A. Garnswothy
Experimental Determination of Photon Emission Probabilities, A. Luca
Nuclear Data Activities for Astrophysics at Oak Ridge National Laboratory, C. Nesaraja
Tandar Laboratory, CNEA, Argentina, D. Abriola
Experimental Approach to the Dynamics of Fission, G. Ishak Boushaki
Laboratoire National Henri Becquerel, M. M. Bé
Nuclear structure by gamma-ray spectroscopy, a Completeness Perspective, N. Nica
Radioactive Beam Spectroscopy of ^{212}Po and ^{213}At with the EXOGAM array, N. Thompson
Developing ^{152}Eu into a Standard for Detector Efficiency Calibration, R. M. Castro

2006 Workshop:
Photo-Nuclear Reaction Cross Sections for Some Isotopes of Ti and Mo, E. Sansarbayar
Evolution of Massive Stars, Jameel Un Nabi
Pulsed Beam Method for Half-life Time Measurements M.R. Band Head in ^{197}Pb, S. Kumar
g-factor Measurement at RISING: The case of ^{127}Sn, Liliya Atanasova
BANDRRI, National Database at CIEMAT (SPAIN), M. Galan
An Appropriate Treatment of the Centre-of-Mass Motion in Finite Nuclei, P. Grygorov
Giant Dipole Resonances: Present & Future Perspectives at VECC, India, S. Bhattacharya

2008 Workshop:
Evaluation and Validation of Excitation Functions of Some (n,p) Reactions Leading to Therapeutic Radionuclides, Mogahed Ebrahim Al-Abyad
Hyperfine Interaction Studies in Solids Using the Perturbed Angular Correlation/Distribution Techniques, Ashok Kumar Bhati
Experimental Nuclear Astrophysics and Data Activities at Oak Ridge National Laboratory, Caroline D. Nesaraja
^{40}Ca (α,γ) ^{44}Ti Reaction Using DRAGON at TRIUMF, Chris Ouellet
Nuclear Structure Studies in the Vicinity of N = 82 Shell Closure, Rajarshi Raut
Nuclear Structure and Decay Data of Selected Actinide Nuclei, Khaliefeh Abu Saleem
Partial Cross Section Measurements for Neutron Induced Transitions in Cu, Ge and Pb for 0$\nu\beta\beta$ Decay Background, E. Kwan

Nuclear Structure Physics: Experimental Program at TIFR, P. K. Joshi
Radioactivity Metrology, Ryan Fitzgerald
Neutron Total Cross-sections of Ta, Nb and Pd, A. K. M. Moinul Haque Meaze
Excitation of Isomeric States of Rubidium Isotopes in (γ,n) Reactions, D. M. Symochko
The Investigation of the High Spin States of Nuclei, Yang Dong
Microscopic Explanation for Observed Band Structures of ^{131}Cs, Zashmir Naik

1.4 OTHER WORKSHOP MATERIALS ON CD-ROM

Atomic Masses
Access to NSDD Resources

NNDC Online Data Service Manual and Data Citation Guidelines

Introduction to International Nuclear Structure and Decay Data Network
Contact names and addresses

Access to ENSDF Format Summary and Examples

Nuclear Structure Manuals

All materials on the CD-ROM may also be accessed through the IAEA-NDS web site at:
http://www-nds.iaea.org/workshops/smr1939/

1.5 MANUAL

Significant quantities of written material were prepared for the Nuclear Structure and Decay Data workshop. Their accumulation in various forms has acted as an aid to the participants in their understanding of nuclear theory, measurement techniques, data analysis and ENSDF mass-chain evaluations, representing important technical information for future reference and other NSDD workshops. The most recent set of these presentations, background papers and other documents have been assembled for further use in the form of this particular report.

Our intention is to use and develop this material in the years to come, particularly for other workshops of this type. Another aim is to ensure that such presentations are not lost, and can be readily at hand for new mass-chain and decay-data evaluators to assist them in their preparation of recommended data for the ENSDF files.

1.6 RECOMMENDATIONS AND CONCLUSIONS

A number of important points can be made concerning the workshop:

1. Twenty-five selected participants attended a two-week workshop that covered nuclear theory and modelling, relevant experimental techniques, statistical analyses, and the philosophy and methodology for comprehensive mass chain evaluations. Support materials and information were also provided that described the International Network of Nuclear Structure and Decay Data Evaluators and the most relevant CRPs organized by the IAEA Nuclear Data Section. Furthermore, a number of ICTP affiliates and associates registered for and attended this course.

2. Workshop participants were introduced to mass chain evaluations through group and individual PC/computing activities (over 50% of the agenda of the second week). CD-ROM and hardcopy materials were also provided by IAEA staff for all students/lecturers.

3. Administrative functions leading up to and during the course of the workshop worked smoothly, including visa arrangements, travel and subsistence payments to students and lecturers, additional banking transactions, and hotel/guest-house accommodation. Unfortunately two students experienced difficulties in obtaining visas at their countries of origin and were unable to attend.

4. Specific participants were identified for future involvement in NSDD and mass chain evaluations.

5. Various important lessons were learnt by the IAEA staff and lecturers involved in this ICTP workshop. Students were given the opportunity to review the workshop through a written questionnaire and direct discussions (on 9 May). Their main comments and recommendations are as follows:

(a) provision of all lecture materials prior to the workshops – all lecture materials were available on the ICTP website prior to the workshop; and also made available on CD-ROMs provided to all participants at the end of the second week;

(b) most common/regular workshop exercises should be demonstrated at the first session of workshop activities (e.g. FMTCHK and GTOL);

(c) begin PC activities earlier in the course (although this would pose difficulties with respect to students' awareness of the nature of the work through their need to experience the series of eight highly relevant ENSDF lectures);

(d) contradictive requests for more lectures and more practical exercises (within "Workshop activities"), while being comfortable with the two-week duration of the workshop;

(e) divide workshop into a basic and a higher levels (difficult to see the merit in this proposal, unless students were allowed to "pick and choose" their attendance which could pose problems);

(f) requested the organization of outside activities during the middle weekend (ICTP to note).

As before, this combination of Wednesday/Thursday written questionnaire and Friday face-to-face review produced substantial feedback. The overall opinion of the vast majority of the students was that they had thoroughly enjoyed the 2-week workshop, made useful new contacts, and learnt much about nuclear structure and decay data.

ACKNOWLEDGEMENTS

The authors wish to thank their fellow co-directors for their support leading up to the start of the workshop, and particularly the lecturers (all experts in their fields) for their enthusiasm and provision of the various technical inputs to this document.

Administrative aspects of the workshop were considerable leading up to and during the course – as an ICTP-supported activity, all such features and problems were smoothly handled by Ms Marina de Corelli (ICTP), and her efforts were much appreciated. Finally, none of the lectures and associated materials would have been delivered in such a professional manner without the enthusiastic involvement of all participants at this workshop.

REFERENCES

1. PRONYAEV, V.G., NICHOLS, A.L., Summary Report on Workshop on Nuclear Structure and Decay Data Evaluation, 18-22 November 2002, INDC(NDS)-439, January 2003; http://www-nds.iaea.org/reports-new/indc-reports/indc-nds/indc-nds-0439.pdf

2. NICHOLS, A.L., McLAUGHLIN, P.K., Workshop on Nuclear Structure and Decay Data: Theory and Evaluation, Manual, Parts 1 and 2, INDC(NDS)-452, November 2004; http://www-nds.iaea.org/reports-new/indc-reports/indc-nds/indc-nds-0452-Part1.pdf http://www-nds.iaea.org/reports-new/indc-reports/indc-nds/indc-nds-0452-Part2.pdf

3. NICHOLS, A.L., McLAUGHLIN, P.K., Workshop on Nuclear Structure and Decay Data: Theory and Evaluation, Addendum - 2005, INDC(NDS)-0473, July 2005; http://www-nds.iaea.org/reports-new/indc-reports/indc-nds/indc-nds-0473.pdf

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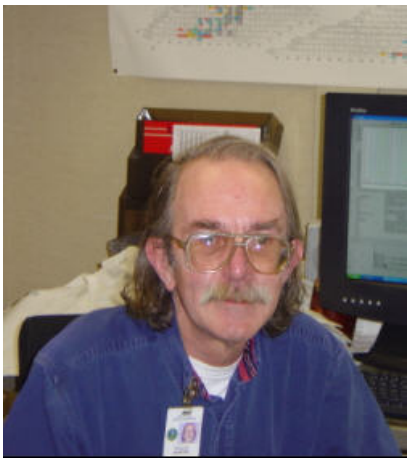
Tom Burrows (1943-2008)



We were deeply saddened to learn of the death of Tom Burrows (US National Nuclear Data Center, Brookhaven National Laboratory) from cancer on 1st July 2008. Tom was a major contributor to the evolution and development of ENSDF, and played a significant role in the IAEA-ICTP Workshops on Nuclear Structure and Decay Data as both a lecturer and demonstrator. His illness prevented him from attending and participating directly in this most recent April/May 2008 workshop, although reference was regularly made to his work during the course of the two weeks and his original lecture notes were used with his blessing.

Apart from his post-doc studies at the University of Kentucky, Tom spent his entire professional career at the National Nuclear Data Center, Brookhaven National Laboratory, USA. He was an extremely competent nuclear data evaluator for ENDF and ENSDF, and rapidly established a worldwide reputation for being an exceptionally thorough, highly dedicated and hard working nuclear scientist with an added ability to produce and develop extremely useful software that assisted greatly in our nuclear structure evaluations. All members of the International Network of Nuclear Structure and Decay Data Evaluators were greatly appreciative of the meticulous care with which he improved and maintained vital data analysis codes. Furthermore, throughout his time at NNDC, he played a very important role as mentor to a generation of new nuclear structure evaluators discovering and working on the ENSDF project.

Tom was both a gentleman and a gentle man, and will be greatly missed by all of us in the nuclear data community.

(ENSDF = Evaluated Nuclear Structure Data File; ENDF = Evaluated Nuclear Data Files (for more direct nuclear applications))

Workshop on
Nuclear Structure and Decay Data: Theory and Evaluation

28 April - 9 May 2008

ICTP, Miramare - Trieste, Italy

INTRODUCTION

The International Atomic Energy Agency (IAEA, Vienna, Austria) in co-operation with the Abdus Salam International Centre for Theoretical Physics (ICTP, Trieste, Italy) and the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente (ENEA, Bologna, Italy) organized a *"Workshop on Nuclear Structure and Decay Data: Theory and Evaluation"* at the ICTP in Trieste from 28 April to 9 May 2008. This workshop was co-directed by Drs. A. Ventura (ENEA, Bologna), A.L. Nichols (IAEA, Vienna) and J.K. Tuli (Brookhaven National Laboratory, USA).

The workshop constituted a unique opportunity for scientists to gain extensive and up-to-date training on the evaluation of nuclear structure and decay data, as developed for the Evaluated Nuclear Structure Data File (ENSDF) and *Nuclear Data Sheets* for the nuclear physics community. Reliable evaluated nuclear structure and decay data are of vital importance in a large number of nuclear applications such as power generation, material analysis, dosimetry and medical diagnostics, as well as basic nuclear physics and astrophysics. Important features of these needs are satisfied by the work undertaken by the international Nuclear Structure and Decay Data Evaluators' Network (NSDD). The main products of this worldwide network are the recommended data files and evaluated decay data.

ENSDF is an enormous source of nuclear data and information for basic research and applications. Both the maintenance and further developments of these files are vitally important, and require continuing scientific effort. While the input to ENSDF from developing countries has been limited in the past, the time has come for scientists from these countries to make a significant contribution to these on-going efforts. The workshop represented the initiation of a suitable mechanism to achieve this aim by focusing on advances in nuclear structure physics and evaluation methodologies through practical training.

Aims

The primary objective of the workshop was to familiarize nuclear physicists from both developing and developed countries with:
(i) new data that characterize the decay properties of nuclei and their nuclear structure;
(ii) nuclear models;
(iii) evaluation methodologies for the derivation of recommended nuclear structure and decay data.

Participants were introduced to the rigorous criteria adopted to evaluate nuclear structure data, and how these data are entered into ENSDF. Important aspects of the workshop included the use of computer codes to evaluate the nuclear structure and decay data, and the construction of data files for ENSDF. Presentations were given by invited lecturers, along with well-defined exercises involving the use of the relevant computer codes. Participants were also be invited to contribute their own thoughts of direct technical relevance to the workshop.

The workshop programme included coverage of the following topics:
review of modern nuclear models and new data obtained at experimental installations;
ENSDF and related bibliographic databases;
computer codes used for NSDD evaluations;
computer exercises with real NSDD evaluations and preparation of the data sets for inclusion in ENSDF;
network of NSDD evaluators, their products and communication links; and
participants' presentations of their own work in NSDD.

Scientists attended from countries that are members of the United Nations, UNESCO or IAEA. Although the main purpose of the ICTP is to help scientists from developing nations through a programme of training activities within a framework of international cooperation, applicants from developed countries were also encouraged to attend.

Workshop manual

Significant quantities of written material were prepared for the workshop. Their accumulation in various forms acted as aid to the participants in their understanding of nuclear theory, measurement techniques, data analysis and ENSDF mass-chain evaluations, representing an important combination of technical information for future reference and other NSDD workshops. Therefore, these presentations, background papers and supportive documents have been assembled in the form of this document for further use.

Our intention is to use and develop this material in the years to come, particularly for other workshops of this type. Another aim is to ensure that such presentations are not lost, and can be readily at hand for new mass-chain and decay-data evaluators to assist them in their preparation of recommended data for the ENSDF files.

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10 June 2008

3.

Evaluations:
A Very Informal History

J. Tuli

NNDC, BNL

E-mail: tuli@bnl.gov

Trieste08

Jagdish K. Tuli
National Nuclear Data Center
Brookhaven National Laboratory
Upton, NY 11973 USA

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Trieste08

- Workshop Aims
- Introduction to Evaluation
- History of Evaluation
- NSDD network

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Workshop Aims

International Evaluation Activity in Nuclear Structure Physics

Nuclear Structure and Decay Data Network

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Workshop Aims

Get new evaluators into the system

Technical Assistance

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Workshop - General

Databases currently in use:

NSR

ENSDF

XUNDL

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Workshop - General

Evaluation Methods and Policies

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Workshop - General

Hands-on exercises

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Introduction

The first American Nobel Laureate, Albert A. Michelson, in an 1894 speech at the University of Chicago lamented that

"The most important fundamental laws and facts of physical science have all been discovered."

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Introduction-cont

"These are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. Our future discoveries must be looked for in the sixth place of decimals."

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Introduction-cont

Within three years of this speech,

x-rays,

electron,

radioactivity

were discovered!!

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Introduction-cont

Over the last couple of decades we have seen the advent of:

Fax

Internet

cellular phone

(liquid crystals, GPS technology)

nanotechnology

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Evaluation History

Compilation:

Webster's Dictionary defines "to compile" as

"to put together, in a new form, out of materials already existing"

Scientifically involves: to compact and serve as a convenient source of detailed information

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Evaluation History

Evaluation:

To evaluate means “to appraise; to determine value”

A good “compilation” always involves “evaluation”

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Evaluation History-cont

The Radioactive Constants as of 1930,

Reviews of Modern Physics, **3**, 427 (1931)

By M. Curie, A. Debierne, A.S. Eve, H. Geiger, O. Hahn, S.c. Lind, St. Meyer, E. Rutherford and E. Schweidler

Decay half-lives, lifetimes, decay constants

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Evaluation History-cont

First compilation of known nuclides was published by Giorgio Fea in 1935:

Tabelle Riassunitive E Bibliografia delle Transmutazioni Artificiali,

Nuovo Cimento **6**, 1 (1935)

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Evaluation History-cont

Nuclear Dynamics, Experimental

Review of Modern Physics, **9**, 359 (1937)

M. Stanley Livingston and H.A. Bethe

Nuclide decay modes, half-life, decay energy, production

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Evaluation History-cont

First evaluation as Table of Isotopes published by J.J. Livingwood and G. T. Seaborg –
Rev Mod Phys **12**, 30 (1940)
Evaluation limited to
artificially produced nuclear species –
Immediate use was in identification of radionuclides and radiotracers

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Evaluation History - cont

The subsequent editions of Table of Isotopes included all nuclear species:

- G.T. Seaborg, Rev Mod Physics **16**, 1 (1944)
- G.T. Seaborg, I. Perlman, *ibid.* **20**, 585 (1948)
- J. M. Hollander, I. Perlman and G. T. Seaborg, ibid., **25**, 469 (1953)
- D. Strominger, J.M. Hollander, G.T. Seaborg, ibid., **30**, 585 (1958)

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Evaluation History - cont

Subsequent editions of Table of Isotopes published by John Wiley:

6th Edition: C. M. Lederer, J. M. Hollander and I. Perlman

7th Edition: Editors: C. M. Lederer, V. S. Shirley;
Principal Authors: E. Browne, J. M. Dairiki and R. E. Doebler;
Authors: A. A. Shihab-Eldin, L. J. Jardine, J. K. Tuli and A. B. Buyrn

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Evaluation History - cont

8th and the last edition of Table of Isotopes was also published by John Wiley in two volumes, ~3000 pages + CD ROM:

Editors: R. B. Firestone, V. S. Shirley

Assistant Editors: C. M. Baglin, S. Y. Chu, J. Zipkin

Unlike previous editions, the contents were derived, and not an independent evaluation

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Evaluation History - cont

An Editor of Table of Isotopes in 1941observed

"The rate at which radioactivities are discovered may be reduced very considerably and the table would itself become stable."

That clearly did not happen!

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Evaluation History - cont

There were other parallel evaluation efforts: Some of these were:

T. Lauritsen (and later F. Ajzenberg-Selove), 1948-on

B. S. Dzhelepov (and later with L. Peker and others) in USSR, 1950-on

P. M. Endt (and later with C. van der Leun), 1954 – on

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Evaluation History - cont

Wall Chart

Emilio Segre, as part of Enrico Fermi's group, introduced the first chart, with Z along the x-axis and N along the Y axis

Segre's chart was published in 5/1945 as Los Alamos report with classified data omitted!

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Evaluation History - cont

GE Wall Chart

1948: G. Friedlander and M. Perlman, at GE Research Lab, created the first GE chart with Z and N reversed. Sixteen editions have since been published by Knolls Atomic Power Laboratory

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Evaluation History - cont

Nuclear Data Sheets

Katherine Way began collecting nuclear data as part of Manhattan Project while working at Clinton Lab (later renamed ORNL)

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Evaluation History - cont

Nuclear Data Sheets

1948: Katherine Way headed the Nuclear Data Project at US National Bureau of Standards

(later renamed US National Institute of Standards and Technology (NIST))

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Evaluation History - cont

A “Nuclear Data” report was published in 1950

Data included measured values, with references, for:

Isotopic abundances, methods of production, neutron cross sections, half-lives, decay modes, energies and intensities of radiations, conversion coefficients and some reaction data and decay schemes.

There were no recommended values or uncertainties given

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Evaluation History - cont

1953: the Nuclear Data Project moved to the US National Academy of Sciences-National Research Council in Washington, DC

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Evaluation History - cont

Published data, as AEC reports, now also included coincidences, mass assignments, n-, p- separation energies, total disintegration energies, spins, magnetic and electric moments. Uncertainties were given. Also a single decay scheme for all isobars for given A

Data were in form of loose-leaf pages called "NUCLEAR DATA SHEETS"

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Evaluation History - cont

1964: the Nuclear Data Project under the leadership of Katherine Way moved back to Oak Ridge National Laboratory, where her effort had originally started in 1948

Nuclear Data Sheets were once again to be published in book form by Academic Press, rather than as single sheets of data.

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Evaluation History - cont

Nuclear Data Sheets - Journal

A journal Nuclear Data - Section A was started in December 1965 as Atomic Data Tables.

February 1966: Nuclear Data Sheets started as Section B of the journal Nuclear Data, and later as simply Nuclear Data Sheets, published by Academic Press

August 1973: two journals Atomic Data and Atomic Data A merged to become Atomic and Nuclear Data Tables, with K. Way as Editor

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Evaluation History - cont

Evaluations limited to NDP - ORNL effort

Time lag in evaluations (1970-71)

Employment situation was not good for PhDs

NSF/NAS joined to make evaluations more current, and created a three-year NIRA program. Recruited two sets of 12 young PhDs for two-year terms. Some stayed in the evaluation business at the end of the program (1971-74)

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Evaluation History - cont

Hand-written data sheets.
Draftsman prepared drawings.

Bruce Ewbank at ORNL was instrumental in computerization of recent references (NSR)

Computerization of drawings

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Evaluation History - cont

ENSDF

Common input format for tables and drawing

Evaluated Nuclear Structure Data File

Manual by B. Ewbank and M. Schmorak

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Evaluation History - cont

Subsequent to the completion of the NIRA program, proposed in 1975 that the evaluation activity be decentralized with international involvement under the auspice of IAEA, Nuclear Data Section

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Evaluation History - cont

The evaluation responsibility was divided amongst various data centers within and outside the USA. NNDC at BNL coordinated the national and international efforts for the US/DOE

But the lead role in editing and processing the evaluations continued at NDP/ORNL

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Evaluation History - cont

Change of production responsibility to NNDC occurred in 1980, when ORNL management support for the activity dropped considerably

NNDC took over production of Nuclear Data Sheets in 1981 and completely computerized the process

Photo-ready copy of the journal has since been supplied to the publisher

BROOKHAVEN NATIONAL LABORATORY

Evaluation History - cont

ORNL and NNDC jointly edited the journal until June 1998, when Murray Martin, who started evaluation work with Katherine Way and served as the Editor-in-Chief of the journal while working at the Nuclear Data Project, ORNL, retired.

With Murray's retirement the editing responsibility completely shifted to the National Nuclear Data Center.

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Evaluation History - cont

Nuclear Data Sheets:

1966-1968	Editor: K. Way
	Asstt: A. Artna, N. B. Gove, W. B. Ewbank
1969-1976	Editor: D. Horen
	Asstt. Editor: W. B. Ewbank
1976-1980	Editor: W. B. Ewbank
1981-1998	Editor-in-Chief: M. J. Martin
	Editor: J. K. Tuli
1999→	Editor: J. K. Tuli

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International Network of Nuclear Structure and Decay Data Evaluators

Created in 1975 under auspice of the IAEA, Nuclear Data Section.

1. IAEA coordinates international groups
2. Meets every two years
3. Discuss responsibilities
4. Cooperate in evaluation and program development

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International Network of Nuclear Structure and Decay Data Evaluators –Cont.

US Network (~ 6 FTE)

BNL
ANL
LBNL
McMaster, Canada
ORNL
TUNL
(Texas A&M)

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International Network of Nuclear Structure and Decay Data Evaluators –Cont.

Non-US Contributors

(Argentina)
Australia
(Belgium)
(Bulgaria)
Canada
China
(Germany, Sweden, UK)
France
India
Japan
Kuwait
Russia

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International Network of Nuclear Structure and Decay Data Evaluators –Cont.

WHAT DO WE DO?

Primary mission:

Evaluate (or compile) structure and decay data, A = 1-294, for inclusion in ENSDF (or XUNDL) database

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International Network of Nuclear Structure and Decay Data Evaluators –Cont.

WHAT DO WE DO?

Other responsibilities:

- Maintenance of checking and evaluation software
- Peer review of evaluations
- Dissemination of data

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International Network of Nuclear Structure and Decay Data Evaluators –Cont.

OUR PRINCIPAL DATABASES

Web accessible from NNDC or mirror sites;
http://www.nndc.bnl.gov links you to them

- **NSR** - Nuclear Science References
- **ENSDF** - Evaluated Nuclear Structure Data File
- **NUDAT** - Nuclear Data Retrieval
- **XUNDL** - Unevaluated data compiled from recently published literature

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International Network of Nuclear Structure and Decay Data Evaluators –Cont.

Analysis Programs

Services to community and evaluators

Web access, from NNDC or mirror sites
http://www.nndc.bnl.gov links to all

Publications: Nuclear Data Sheets (NDS)
Table of Isotopes (TOI)
Wallet Cards (WC)

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Evaluation of Decay Data

A. L. Nichols

IAEA Nuclear Data Section

E-mail: a.nichols@iaea.org

International Atomic Energy Agency

Evaluation of Decay Data: Relevant IAEA Coordinated Research Projects

Alan Nichols
Nuclear Data Section
Vienna, Austria

18 March 2008

IAEA Nuclear Data Section

- Provision of *atomic and nuclear data services* to scientists worldwide (data libraries, bibliographies and related materials) through the internet, CD and other media
- Coordination of three international atomic and nuclear data networks
- Production of new databases through *Coordinated Research Projects* (CRPs) and *Data Development* projects
- Assist developing countries through *technology transfer* activities

Applications of Nuclear Data

- Energy applications
  - fission power
  - fusion technology
- Non-energy applications
  - safeguards
  - radiation safety
  - waste management
  - environmental research
  - nuclear medicine
  - materials analysis
  - process control
  - basic research (e.g. nuclear astrophysics) and education

Nuclear Data Files

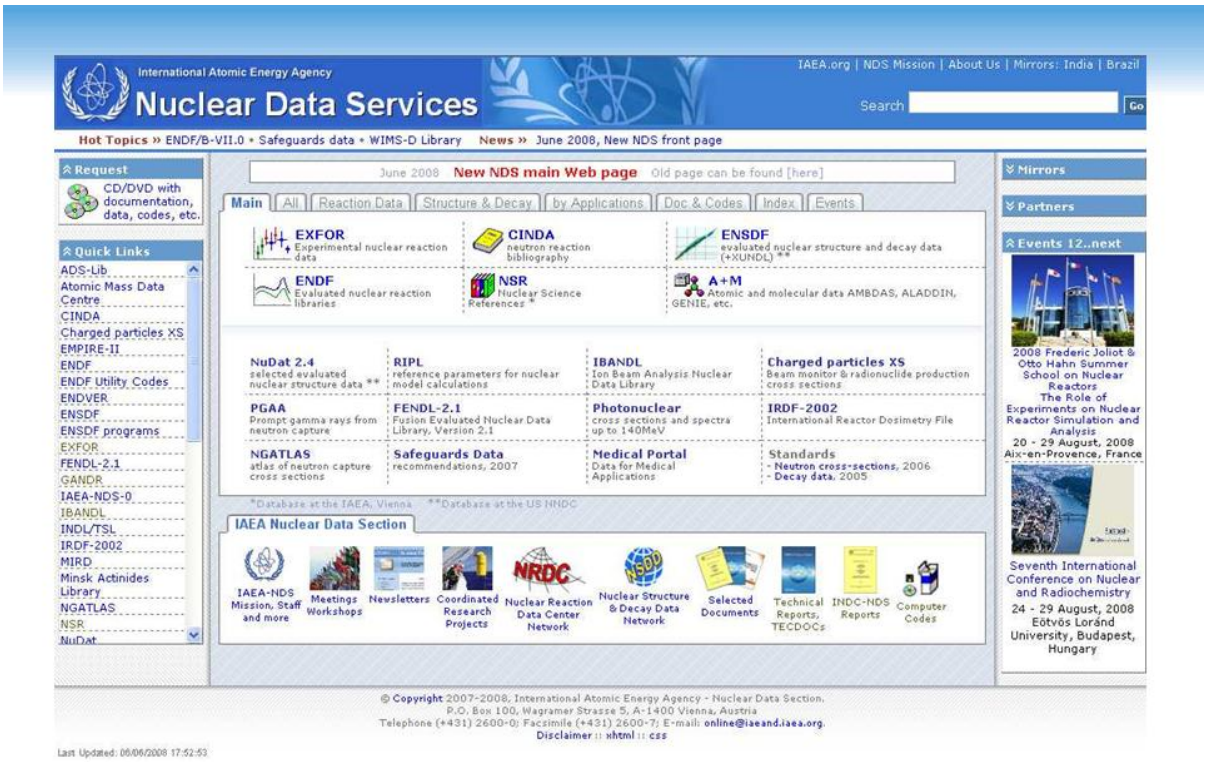
- Compiled bibliographic data **(e.g. CINDA, NSR)**
- Compiled experimental data **(e.g. EXFOR)**
- Evaluated data **(e.g. ENDF, ENSDF)**
- Calculated data **(e.g. EMPIRE, TALYS)**
- Nuclear reaction data **(e.g. EXFOR, ENDF)**
- Nuclear structure and decay data **(e.g. ENSDF)**

Data Centre Activities

- Compilation
  - new cross-section data in EXFOR
  - master files in cooperation with other centres
  - collect evaluated and specialized libraries
- On-line and off-line data services with particular emphasis on the needs of developing countries
- Co-ordination of Data Centre Network

IAEA Nuclear Data Section

http://www-nds.iaea.org/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EXFOR
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NuDat
June 2008 New NDS main Web page Old page can be found [here]
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Reaction Data
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Experimental nuclear reaction data
CINDA
neutron reaction bibliography
ENSDF
evaluated nuclear structure and decay data (+XUNDL) **
ENDF
Evaluated nuclear reaction libraries
NSR
Nuclear Science References *
A+M
Atomic and molecular data AMBDAS, ALADDIN, GENIE, etc.
NuDat 2.4
selected evaluated nuclear structure data **
RIPL
reference parameters for nuclear model calculations
IBANDL
Ion Beam Analysis Nuclear Data Library
Charged particles XS
Beam monitor & radionuclide production cross sections
PGAA
Prompt gamma rays from neutron capture
FENDL-2.1
Fusion Evaluated Nuclear Data Library, Version 2.1
Photonuclear
cross sections and spectra up to 140MeV
IRDF-2002
International Reactor Dosimetry File
NGATLAS
atlas of neutron capture cross sections
Safeguards Data
recommendations, 2007
Medical Portal
Data for Medical Applications
Standards
- Neutron cross-sections, 2006
- Decay data, 2005
*Database at the IAEA, Vienna **Database at the US NNDC
IAEA Nuclear Data Section
IAEA-NDS Mission, Staff and more
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Newsletters
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Computer Codes
Mirrors
Partners
Events 12..next
2008 Frederic Joliot & Otto Hahn Summer School on Nuclear Reactors
The Role of Experiments on Nuclear Reactor Simulation and Analysis
20 - 29 August, 2008
Aix-en-Provence, France
Seventh International Conference on Nuclear and Radiochemistry
24 - 29 August, 2008
Eötvös Loránd University, Budapest, Hungary
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P.O. Box 100, Wagramer Strasse 5, A-1400 Vienna, Austria
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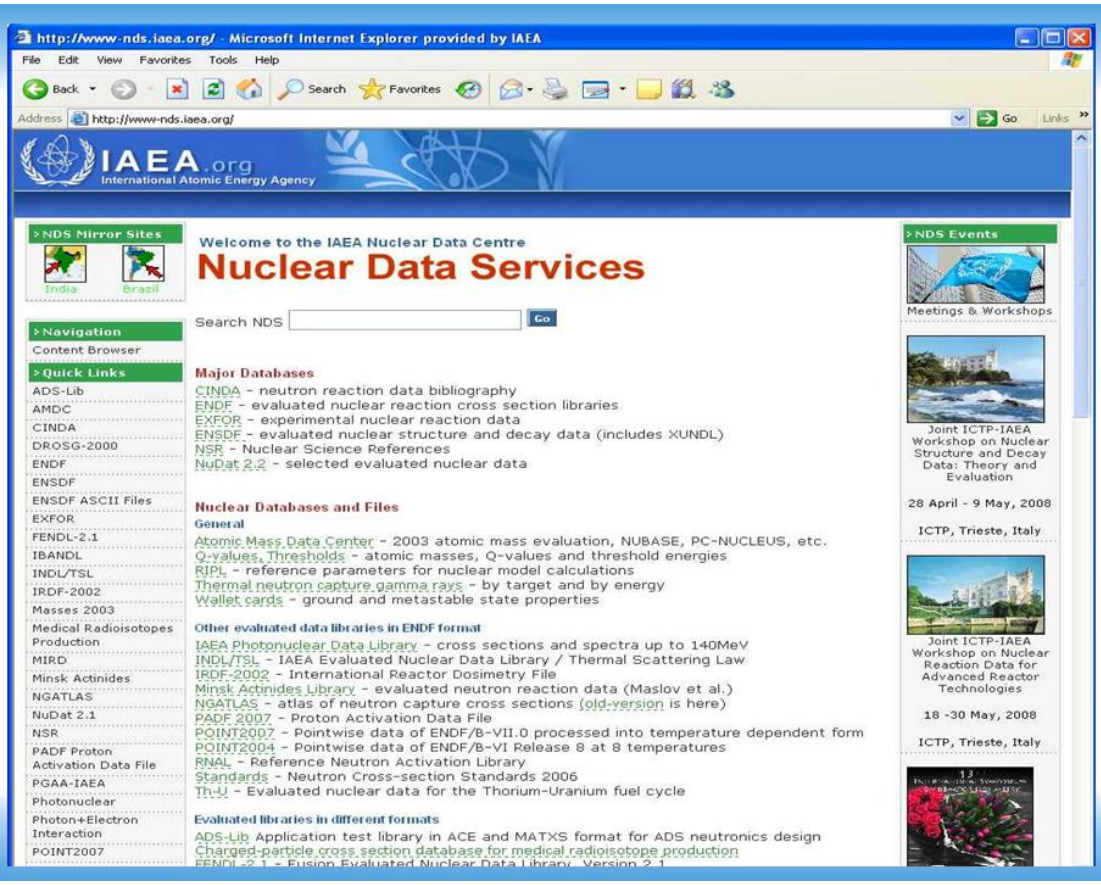
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ENDF
ENSDF
ENSDF ASCII Files
EXFOR
FENDL-2.1
IBANDL
INDL/TSL
IRDF-2002
Masses 2003
Medical Radioisotopes Production
MIRD
Minsk Actinides
NGATLAS
NuDat 2.1
NSR
PADF Proton Activation Data File
PGAA-IAEA
Photonuclear
Photon+Electron Interaction
POINT2007
Welcome to the IAEA Nuclear Data Centre
Nuclear Data Services
Search NDS
Go
Major Databases
CINDA - neutron reaction data bibliography
ENDF - evaluated nuclear reaction cross section libraries
EXFOR - experimental nuclear reaction data
ENSDF - evaluated nuclear structure and decay data (includes XUNDL)
NSR - Nuclear Science References
NuDat 2.2 - selected evaluated nuclear data
Nuclear Databases and Files
General
Atomic Mass Data Center - 2003 atomic mass evaluation, NUBASE, PC-NUCLEUS, etc.
Q-values, Thresholds - atomic masses, Q-values and threshold energies
RIPL - reference parameters for nuclear model calculations
Thermal neutron capture gamma rays - by target and by energy
Wallet cards - ground and metastable state properties
Other evaluated data libraries in ENDF format
IAEA Photonuclear Data Library - cross sections and spectra up to 140MeV
INDL/TSL - IAEA Evaluated Nuclear Data Library / Thermal Scattering Law
IRDF-2002 - International Reactor Dosimetry File
Minsk Actinides Library - evaluated neutron reaction data (Maslov et al.)
NGATLAS - atlas of neutron capture cross sections (old-version is here)
PADF 2007 - Proton Activation Data File
POINT2007 - Pointwise data of ENDF/B-VII.0 processed into temperature dependent form
POINT2004 - Pointwise data of ENDF/B-VI Release 8 at 8 temperatures
RNAL - Reference Neutron Activation Library
Standards - Neutron Cross-section Standards 2006
Th-U - Evaluated nuclear data for the Thorium-Uranium fuel cycle
Evaluated libraries in different formats
ADS-Lib Application test library in ACE and MATXS format for ADS neutronics design
Charged-particle cross section database for medical radioisotope production
FENDL-2.1 - Fusion Evaluated Nuclear Data Library, Version 2.1
NDS Events
Meetings & Workshops
Joint ICTP-IAEA Workshop on Nuclear Structure and Decay Data: Theory and Evaluation
28 April - 9 May, 2008
ICTP, Trieste, Italy
Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies
18 -30 May, 2008
ICTP, Trieste, Italy

Nuclear Data Networks

- Network of *Nuclear Reaction Data Centres*
  - four core centres:
    - IAEA Nuclear Data Section, **Vienna**
    - OECD NEA Data Bank, **Paris, France**
    - US National Nuclear Data Center, **Brookhaven, USA**
    - Russia Nuclear Data Centre, **Obninsk, Russian Federation**
  - Expanded network includes additional co-operating specialized centres in **Russian Federation (3), China, Japan (2), Hungary, Korea and Ukraine**
- *Network of Nuclear Structure and Decay Data Evaluators*
  - IAEA Nuclear Data Section, **Vienna (Co-ordination)**
  - US National Nuclear Data Center, **Brookhaven, USA (Master database)**
  - 18 data evaluation centres in **Australia, Bulgaria, Canada, China (2), France, IAEA, India (2), Japan, Kuwait, Russian Federation, USA (6),**
  - Data dissemination centres **IAEA, NNDC/USA**

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Major consequences of nuclear databases for nuclear physics

- **archive of all nuclear data for future generations**
- **beneficial to many applied areas such as nuclear medicine, reactor engineering, activation analysis, environmental monitoring and impact assessments, etc.**
- **encourages interplay between decay data and reaction data**
- **beneficial consequences for developments in nuclear theory**
- **resolves differences between overlapping and contradictory results**
- **identifies needs for and stimulates new measurements**

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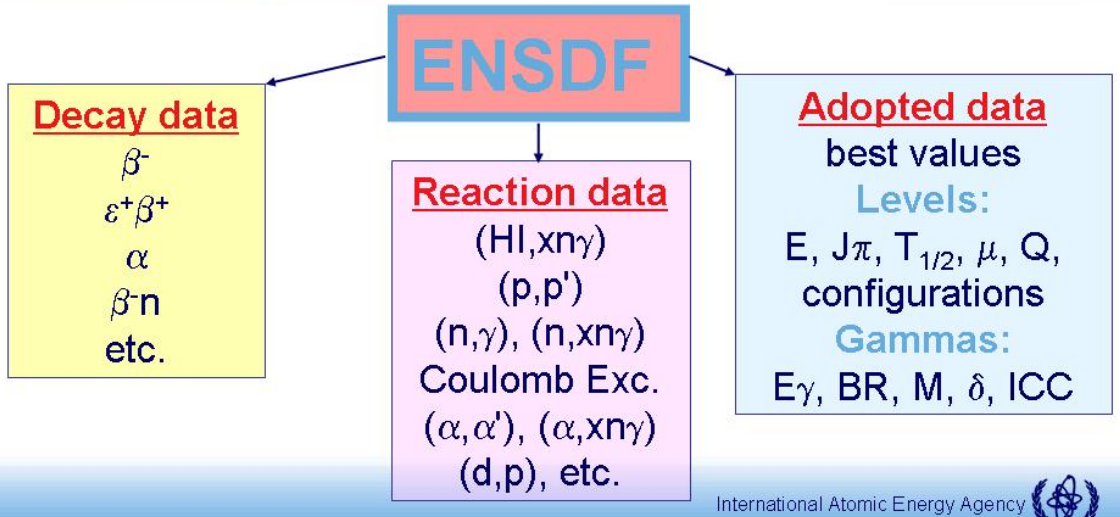
International Network of Nuclear Structure and Decay Data Evaluators

- Collaborating multinational team of nuclear structure and decay data evaluators
- Maintain and update ENSDF (Evaluated Nuclear Structure Data File)
- Master database held at NNDC, BNL, USA
- Individual regular communications
- Biennial meetings held since 1974 under the auspices of the IAEA

Major NSDD products

ENSDF - www.nndc.bnl.gov/ensdf - J.K. Tuli, *NNDC*

Contents: Evaluated nuclear structure and decay data for all known nuclei, organized into over 290 mass chains



ENSDF: Major Data Sources and Derivatives

Contributing Databases:

Atomic Masses (Wapstra & Audi)

Nuclear Science References (NSR)

MC Codes
- MCNPX
- GEANT

ORTEC & CANBERRA

ENSDF

ref.

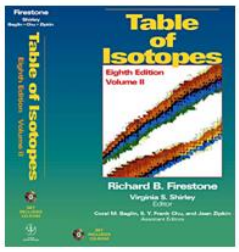
IE

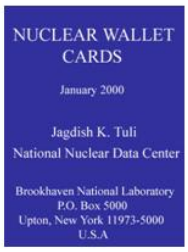
NuDat

Derivative Databases:

NUBASE | MIRD | RIPL | JANIS | RADWARE | ...

Derivative Publications:





International Network Connections

International Nuclear Structure and Decay Data Evaluators' Network

Long-Term Contributors:	Emerging New Contributors:
BELGIUM	[ARGENTINA]
CANADA	AUSTRALIA
CHINA	BULGARIA
FRANCE	INDIA
JAPAN	
KUWAIT	
RUSSIA	8.4 FTE (US & Canada)
USA	2.0 FTE

Total: 10.4 FTE

International Network Connections

International Nuclear Structure and Decay Data Evaluators' Network: responsible centres – June 2008

Centre	*FTE*	*Centre*	*FTE*
CNDC, Beijing, China	0.25	NNDC, USA	3.40
Jilin, China	0.25	ORNL, USA	0.25
B-le-Châtel, France	0.20	LBNL, USA	1.95
JAEA, Japan	0.45	TUNL, USA	0.60
Kuwait	0.20	ANL, USA	1.20
PNPI, Russia	0.25	McMaster, Canada	1.00
ANU, Australia	0.20		8.40
IIT, India	0.20		
	2.00	TOTAL	10.4

International Network Connections

International Network of Nuclear Structure and Decay Data Evaluators responsible centres

Total of ~ 10.4 FTE per annum

"12 FTE per annum required to keep ENSDF in reasonably good shape"

- quoted by Jagdish Tuli (coordinator of ENSDF, NNDC), Summary Report of an IAEA Technical Meeting, Coordination of the International Network of Nuclear Structure and Decay Data Evaluators, 6-10 June 2005, McMaster University, Hamilton, Canada

Multinational mass chain evaluations for ENSDF: numbers of responsible laboratories/institutes

	Year			
	1981	1986	1996	2008
North America	6	6	6	6
Europe	6	5	4	1 → 0
Russia	2	2	2	1
Japan	1	1	1	1
China	-	-	1	2
Rest of the World	1	1	1	3
	16	15	15	14 → 13

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Multinational mass chain evaluations for ENSDF: numbers of responsible laboratories/institutes

1981: Europe
BELGIUM
FRANCE
FRG
NETHERLANDS
SWEDEN
UK

2008: Europe
[[BELGIUM]] *
[FRANCE] *

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Multinational mass chain evaluations for ENSDF: numbers of responsible laboratories/institutes

Long-Term Contributors:

BELGIUM *
CANADA *
CHINA
FRANCE *
JAPAN *
KUWAIT
RUSSIA
USA *

~ 60% of the evaluators are close to retirement age (or beyond!)

IAEA/ICTP NSDD training workshops have achieved some success

IAEA-ICTP NSDD Workshops

Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy

IAEA-ICTP NSDD Workshops

Nuclear Structure and Decay Data: Theory and Evaluation

One-week pilot workshop
IAEA Headquarters, Vienna, Austria
18 – 22 November 2002: 8 students only

Two-week workshops
Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy
17 – 28 November 2003: 24 students
4 – 15 April 2005: 27 students
20 February – 3 March 2006: 23 students
28 April – 9 May 2008: 30 students

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Challenges

Long-Term Contributors:

BELGIUM *
CANADA *
CHINA
FRANCE *
JAPAN *
KUWAIT
RUSSIA
USA *

~60% of the evaluators are close to retirement age (or beyond!)

IAEA/ICTP NSDD training workshops have achieved some success

Compilation and evaluation work is a useful service to the research community. We would like to ask you for your help and support.
If we don't act today, it may be too late tomorrow! *NEW MASS CHAIN EVALUATORS REQUIRED NOW !!!*
YOUR COUNTRY (AND ENSDF) NEEDS YOU !!!
- contact JK Tuli (NNDC, BNL)

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Want to be kept informed?

Available as hardcopy and from WWW in pdf format

IAEA Nuclear Data Newsletter

A newsletter of the Nuclear Data Section (NDS)
Issue No. 44, September 2007 ISSN 0257-4376

In This Issue

- On-line News, p.1
- Staff Items, p.1
- Coordinated Research Projects, p.1
- Database News, p.2
- Computer Codes and Data Libraries, p.2
- Selected Charts, Reports and Documents, p.3
- Meetings Reports, p.5

All services provided to users are free of charge. Please contact us on the following addresses:

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On-line News

Ongoing Service

The Nuclear Data Section is currently compiling an accessible electronic library of all documents produced by the IAEA pertaining to our Nuclear Data Services. These documents include IAEA-NDS, INDC and other NDS technical reports. Many only existed on microfiche or in paper form. All known documents will eventually be converted to PDF and placed on our web site.

This project continues to be ongoing and can be accessed on:

http://www-nds.iaea.org/reports-new/

Staff Items

Otto Schwerer retired from the Nuclear Data Section at the end of August 2007 after over 31 years of service with the Agency, covering his full working life. Over recent years, Otto has been extensively involved with improvements to and maintenance of the EXFOR nuclear reaction cross-section database and the associated CINDA bibliographic database. Much of this work has been undertaken through the cooperative studies of members of the IAEA-sponsored International Network of Nuclear Reaction Data Centres (NRDC), for which he was the IAEA representative, sometime chairman and most recently the coordinator of all database entries. His day-to-day input to this work will be sorely missed, although the Section is hoping to retain his expertise through a series of Special Service Agreements as appropriate, with Otto and his family planning to remain in Vienna.

Coordinated Research Projects

IAEA Coordinated Research Projects (CRPs) are a valuable mechanism for stimulating research in IAEA Member States of relevance to IAEA programmes. CRPs of the Nuclear Data Section, both active and recently completed, can be found at:

http://www-nds.iaea.org/programmes/crps/nd/crps.htm

Data Access and Services

- WWW
  - IAEA Nuclear Data Services homepage: http://www-nds.iaea.org/
  - BARC, India mirror server: http://www-nds.indcentre.org.in/
  - IPEN, Brazil mirror server: http://www-nds.ipen.br/

- Mail services (request hardcopies, CD-ROMs etc.): e-mail to *services@iaeand.iaea.org*

Recent IAEA-NDS Coordinated Research Projects

Short Title	Duration	Participants
Neutron Cross Section Standards	2002-06	14
RIPL-III: Parameters for Nuclear Reaction Calculations – Non-energy Applications	2003-07	12
Nuclear Data for Th-U Fuel Cycle	2002-07	11
Cross Sections for Production of Therapeutic Radionuclides	2003-07	8
Updated Decay Data Library for Actinides	2005-09	9
Reference Database for Ion Beam Analysis	2005-09	9
Reference Database for Neutron Activation Analysis	2005-09	8
Minor Actinide Neutron Reaction Data	2007-11	12

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Nuclear Structure and Decay Data: Relevant IAEA-NDS Coordinated Research Projects

Title	Duration	Participants
Decay Data of the Transactinium Nuclides (Technical Reports Series No. 261, IAEA Vienna, 1986)	1977-85	6
X-ray and Gamma-ray Standards for Detector Calibration (IAEA-TECDOC-619, IAEA Vienna, 1991)	1986-90	9
Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications (Vols. 1 and 2, STI/PUB/1287, IAEA Vienna, 2007)	1998-2003	13
Updated Decay Data Library for Actinides	2005-09	9

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X-ray and Gamma-ray Standards for Detector Calibration

IAEA-TECDOC-619, September 1991

Primary Objective

- produce a recommended set of decay parameters for selected radionuclides judged as the most important for the efficiency calibration of equipment used to detect and quantify x-ray and gamma-ray emissions

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X-ray and Gamma-ray Standards for Detector Calibration

Participants

- W. Bambynek, CEC-JRC, Central Bureau for Nuclear Measurements (CBNM), Geel, Belgium
- Y. Yoshizawa, Hiroshima University, Hiroshima-shi, Japan
- R.G. Helmer, Idaho National Engineering Laboratory (INEL), Idaho Falls, Idaho, USA
- N. Coursol, Laboratoire de Metrologie des Rayonnements Ionisants (LMRI), Gif-sur-Yvette, France
- F.J. Schima, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, USA
- T. Barta and R. Jedlovszky, National Office of Measures (OMH), Budapest, Hungary
- P. Christmas, National Physical Laboratory (NPL), Teddington, Middlesex, UK
- K. Debertin, Physikalisch Technische Bundesanstalt (PTB), Braunschweig, Germany
- A.L. Nichols, AEA Technology, Winfrith Technology Centre, Dorchester, Dorset, UK

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X-ray and Gamma-ray Standards for Detector Efficiency Calibration

Ancillary Objectives

- selection of appropriate efficiency calibration nuclides
- assessment of the status of existing data
- identification of data discrepancies and limitations
- stimulation of measurements to meet data needs
- evaluation and recommendation of improved efficiency calibration data

X-ray and Gamma-ray Standards for Detector Efficiency Calibration

- cover as wide a range of photon energy as possible (5 keV to approximately 10 MeV)
- x-ray and low-energy gamma-ray emitting radionuclides from 5 to 100 keV
- commonly used and readily available nuclides
- nuclides used and offered as standards by national laboratories, multi-line nuclides for rapid calibrations
- definition of a set of single-line nuclides to avoid the need for coincidence summing corrections
- choice of nuclides with accurately known emission probabilities

X-ray and Gamma-ray Standards for Detector Calibration

International Atomic Energy Agency,
IAEA-TECDOC-619, September 1991

- coordination of measurements within the project,
- stimulation of measurements outside the project,
- recommended decay data for 36 radionuclides up to a γ-ray energy of 3.6 MeV,
- recommended X-ray data from 5 to 90 keV,
- consideration of neutron and proton capture reactions for higher γ-ray energies (up to 14 MeV)

X-ray and Gamma-ray Standards for Detector Efficiency Calibration

Half-life inconsistencies: further measurements were recommended

Priority 1 – ^{55}Fe, ^{56}Co, ^{125}I and ^{155}Eu

Priority 2 – ^{54}Mn, ^{75}Se and ^{109}Cd

Priority 3 – ^{22}Na, ^{58}Co, ^{65}Zn and ^{133}Ba

X-ray and Gamma-ray Standards for Detector Efficiency Calibration

Higher-energy gamma rays?

^{66}Ga decay

Neutron and proton reactions:

^{14}N(n, γ)^{15}N*

^{35}Cl(n, γ)^{36}Cl*

^{48}Ti(n, γ)^{49}Ti*

^{52}Cr(n, γ)^{53}Cr*

^{53}Cr(n, γ)^{54}Cr*

^{11}B(p, γ)^{12}C*

^{14}N(p, γ)^{15}O*

^{23}Na(p, γ)^{24}Mg*

^{27}Al(p, γ)^{28}Si*

Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications (1998 – 2003)

M. Herman
IAEA Nuclear Data Section

International Atomic Energy Agency

Update of X-ray and Gamma-ray Decay Data Standards

International Nuclear Data Committee, 1997: strongly recommended IAEA to re-visit and place further emphasis on the development of improved decay data for "standards" applications

- detector efficiency calibration
- other applications (e.g. nuclear medicine, dosimetry, safeguards and environmental monitoring)

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Update of X-ray and Gamma-ray Decay Data Standards

Participants

- M.-M. Bé, BNM-CEA/LNHB, Centre d'Etudes Nucleaires de Saclay, Gif-sur-Yvette, France
- V.P. Chechev, VG Khlopin Radium Institute, St. Petersburg, Russia
- O. Helene and V.R. Vanin, Instituto de Física, Universidade de São Paulo, Brazil
- R.G. Helmer, Idaho National Engineering and Environmental Laboratory, Idaho Falls, USA
- S. Hlaváč, Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia
- A. Marcinkowski, The Andrzej Soltan Institute for Nuclear Studies, Warsaw, Poland
- G.L. Molnar, Institute of Isotope and Surface Chemistry, Budapest, Hungary
- A.L. Nichols, AEA Technology plc, Harwell, UK
- E. Schönfeld and R. Dersch, Physikalisch Technische Bundesanstalt, Braunschweig, Germany
- M.J. Woods, Centre for Ionising Radiation Metrology, National Physical Laboratory, Teddington, UK

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Update of X-ray and Gamma-ray Decay Data Standards

Main issues

1. Update of the current database
   IAEA-TECDOC-619 data for 36 radionuclides were revisited and revised - experimental data measured and published after 1990,
   - average x-ray energies and emission probabilities are given in IAEA-TECDOC-619 – require systematic analysis of the energies and emission probabilities of the individual $K_{\alpha 1}$, $K_{\alpha 2}$, $K_{\beta 1'}$ and $K_{\beta 2'}$ components
2. Additional radionuclides
   68 radionuclides formulated at Consultants' Meeting, and adopted as a suitable starting point; re-defined as 62 radionuclides and two heavy element decay chains
3. Extension of energy range
   - new nuclear techniques (for example radiotherapy) suffer from a lack of high-energy calibration standards,
   - data required for the calibration of γ-ray detectors up to 25 MeV,
   - appropriate radionuclides (^{56}Co, ^{66}Ga) and nuclear reactions identified, and γ-ray emission probabilities compiled and evaluated

Update of X-ray and Gamma-ray Decay Data Standards

Main issues (cont.)

4. γ - γ coincidence: absolute γ-ray detection efficiency without absolutely calibrated γ-ray source:
   - angular correlation coefficients of specific nuclei from 136 keV to 2.75 MeV,
   - ^{24}Na, ^{46}Sc, ^{60}Co, ^{66}Ga, ^{75}Se, ^{88}Y, ^{94}Nb, ^{111}In, ^{134}Cs, ^{152}Eu and ^{207}Bi

5. Covariances
   - lack of necessary data (and detail) in published measurements,
   - instructions proposed for communication to authors concerning data requirements for covariance analysis

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Update of X-ray and Gamma-ray Decay Data Standards

Evaluations undertaken in conjunction with Decay Data Evaluation Project (DDEP) – member laboratories of the International Committee for Radionuclide Metrology (ICRM)

- co-ordinator: E. Browne (Lawrence Berkeley National Laboratory),
- CRP evaluations carried out under agreed DDEP methodology/procedures for consistency,
- recommendations reviewed and approved by DDEP prior to acceptance for CRP,
- adopted by DDEP

http://www.nucleide.org/DDEP_WG/DDEPdata.htm

Update of X-ray and Gamma-ray Decay Data Standards

Selected radionuclides and applications.

Nuclide	X/γ-Ray Standard	Dosimetry Standard	Medical Applications	Environmental Monitoring	Waste Management	Safeguards
^{22}Na	P	-	x	-	-	-
^{24}Na	P	-	-	-	-	-
^{40}K	S	-	-	x	-	-
^{46}Sc	P	-	-	-	-	-
^{51}Cr	S	-	x	-	-	-
^{54}Mn	P	-	-	x	x	-
^{56}Mn	P	-	x	-	-	-
^{55}Fe	S	-	x	-	x	-
^{59}Fe	S	-	x	-	-	-
^{56}Co	S	-	-	-	-	-
^{57}Co	P (122 keV)	-	x	-	-	x
^{58}Co	P	-	-	x	-	-
^{60}Co	P	-	x	x	x	x
^{64}Cu	-	-	x	-	-	-
^{65}Zn	S	-	-	x	x	-
^{66}Ga	S	-	x	-	-	-
^{67}Ga	S	-	x	-	-	-

Update of X-ray and Gamma-ray Decay Data Standards

Selected radionuclides and applications (cont.).

Nuclide	X/γ-Ray Standard	Dosimetry Standard	Medical Applications	Environmental Monitoring	Waste Management	Safeguards
^{68}Ga	-	-	x	-	-	-
^{75}Se	S	-	x	-	-	-
^{85}Kr	-	-	-	x	-	-
^{85}Sr	P	-	x	x	-	-
^{88}Y	P (1836 keV) S (898 keV)	-	-	-	-	-
^{93m}Nb	-	x	-	-	-	-
^{94}Nb	P	-	-	-	-	-
^{95}Nb	P	-	-	x	-	x
^{99}Mo–^{99m}Tc	P (140.5 keV)	-	x	-	-	-
^{99m}Tc	P (140.5 keV)	-	x	-	-	-
^{103}Ru	-	-	x	x	-	x
^{106}Ru–^{106}Rh	S	-	x	x	-	x
^{110m}Ag (^{110}Ag)	S	-	-	x	x	-
^{109}Cd	S	-	-	x	-	-
^{111}In	P	-	x	-	-	-
^{113}Sn	P	-	-	-	-	-
^{125}Sb	-	-	-	x	-	x

Update of X-ray and Gamma-ray Decay Data Standards

Selected radionuclides and applications (cont.).

Nuclide	X/γ-Ray Standard	Dosimetry Standard	Medical Applications	Environmental Monitoring	Waste Management	Safeguards
^{123m}Te	-	-	x	-	x	-
^{123}I	P	-	x	-	-	-
^{125}I	S	x	x	-	-	-
^{129}I	S	-	-	x	x	-
^{131}I	S	x	x	x	-	x
^{134}Cs	S	-	-	x	-	x
^{137}Cs	P	x	-	x	x	x
^{133}Ba	S	-	x	-	-	-
^{139}Ce	P	-	-	x	-	-
^{141}Ce	S	-	-	x	-	x
^{144}Ce–^{144}Pr	S	-	x	x	-	x
^{153}Sm	-	-	x	-	-	x
^{152}Eu	S	-	-	x	x	x
^{154}Eu	S	-	-	x	x	x
^{155}Eu	S	-	-	x	x	x
^{166m}Ho–^{166}Ho	S	-	x	-	-	x

International Atomic Energy Agency

Update of X-ray and Gamma-ray Decay Data Standards

Selected radionuclides and applications (cont.).

Nuclide	X/γ-Ray Standard	Dosimetry Standard	Medical Applications	Environmental Monitoring	Waste Management	Safeguards
^{170}Tm	S	-	-	-	-	-
^{169}Yb	S	-	x	-	-	-
^{192}Ir	S	x	x	-	-	-
^{198}Au	P	-	-	-	-	-
^{203}Hg	P	-	-	-	-	-
^{201}Tl	-	-	x	-	-	-
^{207}Bi	P (569.7 keV)	-	x	-	-	-
^{226}Ra decay chain	S	x	-	x	x	x
^{228}Th decay chain	P	-	-	x	-	x
^{234m}Pa	-	-	-	x	x	-
^{241}Am	P	-	-	x	x	x
^{243}Am	-	-	-	-	x	x

P primary efficiency calibration standard.
S secondary efficiency calibration standard.

Update of X-ray and Gamma-ray Decay Data Standards

High-energy Gamma-ray Standards:

^{226}Ra up to 2.45 MeV

^{56}Co up to 3.55 MeV

^{66}Ga up to 4.8 MeV

^{14}N(n, γ)^{15}N* up to 10.8 MeV

^{35}Cl(n, γ)^{36}Cl* up to 8.6 MeV

^{48}Ti(n, γ)^{49}Ti* up to 6.8 MeV

^{50,52,53}Cr(n, γ)^{51,53,54}Cr* up to 9.7 MeV

^{11}B(p, γ)^{12}C* up to 13.9 MeV

^{14}N(p, γ)^{15}O* up to 8.3 MeV

^{23}Na(p, γ)^{24}Mg* up to 11.6 MeV

^{27}Al(p, γ)^{28}Si* up to 10.8 MeV

Update of X-ray and Gamma-ray Decay Data Standards

CRP

IAEA technical document:

Update of X Ray and Gamma Ray Decay Data Standards for Detector Calibration and Other Applications, Volumes 1 and 2

M.-M. Bé, V.P. Chechev, R. Dersch, O.A.M. Helene, R.G. Helmer, M. Herman, S. Hlaváč, A. Marcinkowski, G.L. Molnár, A.L. Nichols, E. Schönfeld, V.R. Vanin and M.J. Woods

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Update of X-ray and Gamma-ray Decay Data Standards

DDEP

Recommended complete decay schemes available through
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

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^{56}Mn – Comments on evaluation of decay data

Evaluated: November 1999
Re-evaluated: January 2004

Evaluation Procedures:

Limitation of Relative Statistical Weight Method (LWM) was applied to average numbers throughout the evaluation. The uncertainty assigned to the average value was always greater than or equal to the smallest uncertainty of the values used to calculate the average.

Decay Data Evaluation Project (DDEP)

Reference	Half-life (days)
1968Sh07	0.10771(4)
1971GoYM	0.10742(33)
1972Em01	0.10779(25)
1973La12	0.107438(8)
1980RuZY	0.107350(33)
1992An13	0.107454(4)[§]
1994Ya02	0.1040(20)[*]
Evaluated value	0.107449(19)

[§] Uncertainty increased to ± 0.000008 to ensure weighting factor not greater than 0.50.
[*] Method development study: removed from data set due to uncharacteristically large uncertainty.

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Gamma-ray Emission Probabilities: Relative to P_γ(846.7638 keV) of 100%

	P_γ^{rel}						
E_γ(keV)	1967Au01	1968Sh07	1973Ar15	1974Ho25	1974Ti01	2004MiXX	Recommended Value*
846.7638(19)†	100(3)	100(3)	100(3)	100(3)	100(3)	100.000(103)	100(3)
1037.8333(24)†	-	-	0.06(1)	0.03(1)	0.040(5)	-	0.040(4)§
1238.2736(22)†	-	-	0.14(3)	0.13(1)	0.10(1)	0.097(2)	0.098(2)§
1810.726(4)†	30(3)	29.4(16)	28.6(15)	26.9(13)	27.5(8)	26.610(72)	27.2(4)
2113.092(6)†	17.4(17)	16.0(9)	16.0(8)	14.3(7)	14.5(4)	13.956(53)	14.4(3)§
2523.06(5)‡	1.10(15)	1.6(5)	1.14(5)	1.01(5)	1.00(3)	1.025(9)	1.03(2)
2598.438(4)†	-	-	0.026(5)	0.02(1)	0.019(2)	-	0.020(2)
2657.56(1)‡	0.60(10)	0.66(6)	0.71(4)	0.66(7)	0.66(2)	0.648(8)	0.652(7)§
2959.92(1)‡	0.31(6)	0.26(3)	0.30(2)	0.32(3)	0.31(1)	0.314(6)	0.311(5)§
3119.3(5)#	-	0.08(4)	-	-	-	-	-
3369.84(4)‡	0.22(5)	0.20(4)	0.15(2)	0.16(2)	0.17(1)	-	0.17(1)

† Energy adopted from 2000He14.
‡ Energy calculated from the nuclear level energies specified by 1999Hu04.
# Energy from 1968Sh07, but transition not included in proposed decay scheme.
* Weighted mean values adopted using LWEIGHT, unless stated.
§ Recommended values adopted from a combination of the normalised residuals and Rajeval methods (see 2004MaYY).

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$^{56}_{25}\mathrm{Mn}_{31}$

1 Decay Scheme

Mn-56 decays by beta minus emission to excited levels of Fe-56.
Le manganèse 56 se désintègre par émission bêta moins vers les niveaux excités du fer 56.

2 Nuclear Data

$T_{1/2}(^{56}\mathrm{Mn})$: 2,57878 (46) h
$Q^-(^{56}\mathrm{Mn})$: 3695,5 (3) keV

2.1 β^- Transitions

	Energy keV	Probability × 100	Nature	lg *ft*
$\beta^-_{0,7}$	250,2 (3)	0,020 (2)	Allowed	6,57
$\beta^-_{0,6}$	325,7 (3)	1,20 (3)	Allowed	5,17
$\beta^-_{0,5}$	572,6 (3)	0,040 (4)	Allowed	7,5
$\beta^-_{0,4}$	735,6 (3)	14,5 (3)	Allowed	5,34
$\beta^-_{0,3}$	1037,9 (3)	27,5 (4)	Allowed	5,621
$\beta^-_{0,2}$	1610,4 (3)	0,057 (6)	Allowed	9,06
$\beta^-_{0,1}$	2848,7 (3)	56,6 (7)	Allowed	7,101

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2.2 Gamma Transitions and Internal Conversion Coefficients

	Energy keV	$P_{\gamma+ce}$ × 100	Multipolarity	α_K	α_L	α_M+	α_T
$\gamma_{1,0}$(Fe)	846,776 (5)	98,88 (3)	E2	0,000270 (8)	0,0000250 (8)	0,0000037 (1)	0,000300 (9)
$\gamma_{5,2}$(Fe)	1037,85 (2)	0,040 (4)	M1+0.04%E2	0,000130 (4)	0,0000120 (4)	0,0000060 (2)	0,0001500 (45)
$\gamma_{2,1}$(Fe)	1238,300 (12)	0,097 (2)	E2	0,000110 (3)	0,0000100 (3)	0,00000200 (6)	0,000120 (4)
$\gamma_{3,1}$(Fe)	1810,786 (15)	26,9 (4)	M1+3%E2	0,0000460 (14)	0,00000430 (13)	0,00000063 (2)	0,0000510 (15)
$\gamma_{4,1}$(Fe)	2113,15 (1)	14,2 (3)	M1+4%E2				

	Energy keV	$P_{\gamma+ce}$ × 100	Multipolarity	α_K	α_L	α_M+	α_T
$\gamma_{6,1}$(Fe)	2523,06 (5)	1,02 (2)	M1+E2				
$\gamma_{7,1}$(Fe)	2598,53 (2)	0,020 (2)	M1+E2				
$\gamma_{3,0}$(Fe)	2657,56 (1)	0,645 (7)	E2				
$\gamma_{4,0}$(Fe)	2959,92 (1)	0,307 (5)	E2				
$\gamma_{6,0}$(Fe)	3369,84 (4)	0,17 (1)	E2				

Decay Data Evaluation Project (DDEP)

3 Atomic Data

3.1 Fe

ω_K : 0,355 (4)
ω_L : 0,0060 (6)
n_{KL} : 1,447 (4)

3.1.1 X Radiations

		Energy keV		Relative probability
X_K				
	$K\alpha_2$	6,39091		51
	$K\alpha_1$	6,40391		100
	$K\beta_1$	7,05804	}	
	$K\beta_3'$	7,1083	}	20,6

3.1.2 Auger Electrons

		Energy keV	Relative probability
Auger K			
	KLL	5,370 – 5,645	100
	KLX	6,158 – 6,400	27,4
	KXY	6,926 – 7,105	1,87
Auger L		0,510 – 0,594	307

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4 Electron Emissions

		Energy keV	Electrons per 100 disint.
e_{AL}	(Fe)	0,510 - 0,594	0,0428 (3)
e_{AK}	(Fe)		0,0180 (1)
	KLL	5,370 - 5,645	}
	KLX	6,158 - 6,400	}
	KXY	6,926 - 7,105	}
$\beta^-_{0,7}$	max:	250,2 (3)	0,020 (2)
$\beta^-_{0,7}$	avg:	73,5 (1)	
$\beta^-_{0,6}$	max:	325,7 (3)	1,20 (3)
$\beta^-_{0,6}$	avg:	99,1 (1)	
$\beta^-_{0,5}$	max:	572,6 (3)	0,040 (4)
$\beta^-_{0,5}$	avg:	190,4 (2)	
$\beta^-_{0,4}$	max:	735,6 (3)	14,5 (3)
$\beta^-_{0,4}$	avg:	255,2 (2)	
$\beta^-_{0,3}$	max:	1037,9 (3)	27,5 (4)
$\beta^-_{0,3}$	avg:	381,9 (2)	
$\beta^-_{0,2}$	max:	1610,4 (3)	0,057 (6)
$\beta^-_{0,2}$	avg:	636,3 (2)	
$\beta^-_{0,1}$	max:	2848,7 (3)	56,6 (7)
$\beta^-_{0,1}$	avg:	1216,8 (2)	

Decay Data Evaluation Project (DDEP)

5 Photon Emissions

5.1 X-Ray Emissions

		Energy keV	Photons per 100 disint.	
$XK\alpha_2$	(Fe)	6,39091	0,00295 (4)	} Kα
$XK\alpha_1$	(Fe)	6,40391	0,00578 (7)	}
$XK\beta_1$	(Fe)	7,05804 }	0,00119 (2)	K$'\beta_1$
$XK\beta''_5$	(Fe)	7,1083 }		

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5.2 Gamma Emissions

	Energy keV	Photons per 100 disint.
$\gamma_{1,0}$(Fe)	846,7638 (19)	98,85 (3)
$\gamma_{5,2}$(Fe)	1037,8333 (24)	0,040 (4)
$\gamma_{2,1}$(Fe)	1238,2736 (22)	0,097 (2)
$\gamma_{3,1}$(Fe)	1810,726 (4)	26,9 (4)
$\gamma_{4,1}$(Fe)	2113,092 (6)	14,2 (3)
$\gamma_{6,1}$(Fe)	2523,06 (5)	1,02 (2)
$\gamma_{7,1}$(Fe)	2598,438 (4)	0,020 (2)
$\gamma_{3,0}$(Fe)	2657,56 (1)	0,645 (7)
$\gamma_{4,0}$(Fe)	2959,92 (1)	0,307 (5)
$\gamma_{6,0}$(Fe)	3369,84 (4)	0,17 (1)

Decay Data Evaluation Project (DDEP)

6 Main Production Modes

Cr – 56(β^-)Mn – 56
Mn – 55(n,γ)Mn – 56
Mn – 55(d,p)Mn – 56
Fe – 58(d,α)Mn – 56

7 References

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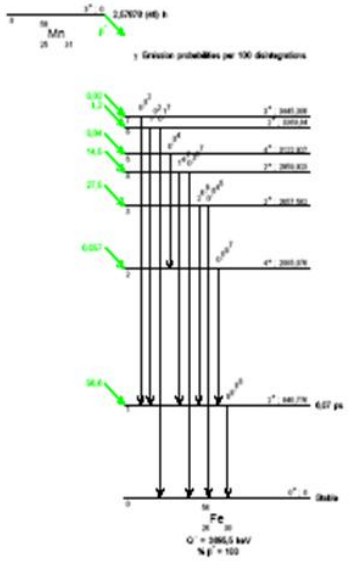

Decay Data Evaluation Project (DDEP)

8 Remarks

8.1 Nuclear Data

Half-life adopted from the evaluation of Woods for the IAEA-CRP: Update of X- and Gamma-ray Decay Data Standards for Detector Calibration. The measurements of 1968Sh07, 1971GoYM, 1972Em01, 1973La12, 1980RuZY, 1992An13 and 1994Ya02 were considered.

8.2 β^- Transitions

All beta-particle energies were calculated from the structural details of the proposed decay scheme. The nuclear level energies of 1999Hu04 and the Q-value were used to determine the energies and uncertainties of the beta-particle transitions to the various levels. The beta-particle emission probabilities were calculated from recommended gamma-ray emission probabilities and the theoretical internal conversion coefficients of 1976Ba63 (latter estimated by interpolation of data). Log ft systematics can be applied to the beta-particle transition to the ground state of Fe-56, with a lower limit for log ft of 13.9 (1998Si17), to give a beta-particle emission probability of ¡ 0.0005 (set to zero).

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Decay Data Evaluation Project (DDEP)

8.3 Gamma Transitions and Conversion Electron Coefficients

Energies

A number of well-defined gamma-ray energies were adopted from the recommended standards of 2000He14. All other gamma-ray energies were calculated from the structural details of the proposed decay scheme and the nuclear level energies of 1999Hu04 (as derived from the energy measurements of 1973Ar15, 1974Ho25 and 1974Ti01). An additional gamma ray with an energy of 3119.3(5) keV was only detected by 1968Sh01, and has been discarded due to a lack of evidence in all of the other studies.

Emission Probabilities

Weighted mean relative emission probabilities were determined for all of the gamma rays assigned to the decay scheme, using the relevant data from the measurements of 1967Au01, 1968Sh07, 1973Ar15, 1974Ho25, 1974Ti01 and 2004MiXX. All gamma-ray emissions were expressed relative to the 846.7638 keV transition, which was arbitrarily assigned an uncertainty of 3% (100(3)%).

The normalisation factor for the gamma-ray emission probabilities was calculated from the proposed decay scheme via two routes:

(a) beta population of all Fe-56 nuclear levels derived from gamma-ray depopulation/population and summed, assuming beta decay to Fe-56 ground state is zero (spin and parity considerations). for all nuclear levels populated by beta decay sum P(beta) = 101.163(1479) NF = 100

NF = 0.9885(145)

etc.

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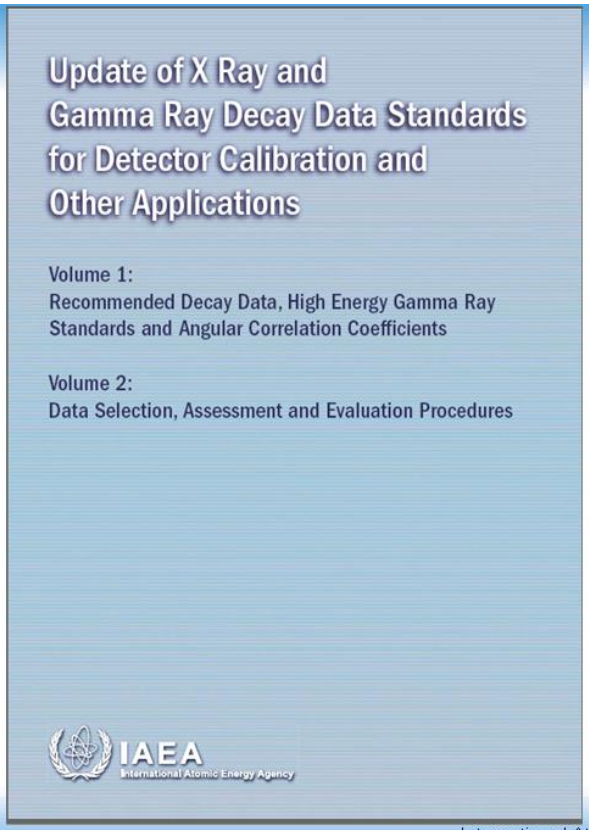

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Recommended radionuclide half-lives

Nuclide	Half-life (days) 1 year = 365.2422 days value	uncertainty
11-Na-22	950.57	± 0.23
11-Na-24	0.62329	± 0.00006
19-K-40	(4.563	± 0.013) 10^{+11}
21-Sc-46	83.79	± 0.04
24-Cr-51	27.7009	± 0.0020
25-Mn-54	312.29	± 0.26
25-Mn-56	0.107449	± 0.000019
26-Fe-55	1002.7	± 2.3
26-Fe-59	44.494	± 0.013
27-Co-56	77.236	± 0.026
27-Co-57	271.80	± 0.05
27-Co-58	70.86	± 0.06
27-Co-60	1925.23	± 0.27
29-Cu-64	0.52929	± 0.00018
30-Zn-65	243.86	± 0.20
31-Ga-66	0.3889	± 0.0034

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV) E_γ	uncertainty	Emission Probability per decay P_γ	uncertainty	Comments
11-Na-22	511	-	1.798	± 0.002	annihilation radiation
11-Na-22	1274.537	± 0.003	0.99940	± 0.00014	
11-Na-24	1368.626	± 0.005	0.999935	± 0.000005	
11-Na-24	2754.007	± 0.011	0.99872	± 0.00008	
19-K-40	1460.822	± 0.006	0.1066	± 0.0013	
21-Sc-46	889.271	± 0.002	0.999833	± 0.000005	
21-Sc-46	1120.537	± 0.003	0.99986	+0.00004 -0.00036	
24-Cr-51	320.0835	± 0.0004	0.0987	± 0.0005	
25-Mn-54	834.838	± 0.005	0.999746	± 0.000011	
25-Mn-56	846.7638	± 0.0019	0.9885	± 0.0003	
25-Mn-56	1810.726	± 0.004	0.269	± 0.004	
25-Mn-56	2113.092	± 0.006	0.142	± 0.003	
25-Mn-56	2523.06	± 0.05	0.0102	± 0.0002	
26-Fe-59	142.651	± 0.002	0.00972	± 0.00015	
26-Fe-59	192.349	± 0.005	0.0292	± 0.0003	
26-Fe-59	1099.245	± 0.003	0.5659	± 0.0021	
26-Fe-59	1291.590	± 0.006	0.4321	± 0.0025	

Decay Data of the Transactinium Nuclides

Technical Reports Series No. 261, May 1986

Objectives

- assess status of existing data
- identify data discrepancies and unfulfilled requirements
- encourage measurements to meet requirements
- evaluate the data
- assemble final set of recommended decay data (satisfy required accuracies)

International Atomic Energy Agency

Decay Data of the Transactinium Nuclides

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International Atomic Energy Agency

Decay Data of the Transactinium Nuclides

International Atomic Energy Agency,

Technical Reports Series No. 261, May 1986

- assessed the status of the existing data,
- identified data discrepancies and unfulfilled requirements,
- encouraged measurements to meet requirements, both within and beyond the project,
- recommended half-lives for 40 nuclides (^{228}Th to ^{253}Es) → extended to 125 nuclides (mainly based on three existing evaluated data files),
- recommended α-particle and γ-ray emission probabilities, many based directly on ENSDF (*Nuclear Data Sheets*):

  29 nuclides (α-particle emission probabilities),

  47 nuclides (γ-ray emission probabilities)

"……. much remains to be done."

Decay Data of the Transactinium Nuclides

International Atomic Energy Agency, Technical Reports Series No. 261, May 1986

Nuclide	Data type	Accuracy (%) Required	Achieved	Needs	CRP activities Measurements	Evaluations
Pu-239	$T_{1/2}$	0.5	0.1		AERE, CBNM, +	CBNM
	P_α	1	1–2	Mass determination,	+	JAERI
	P_γ	1	<1	non-destructive	INEL, LMRI, +	JAERI
	P_X	3	3	assay and environ-	–	–
				mental studies		
Pu-240	$T_{1/2}$	0.5	0.1		+	CBNM/LMRI
	$T_{1/2}$ (SF)	2	3	Mass determination,	CBNM	+
	P_α	1	1–2	non-destructive assay	+	LMRI
	P_γ	1	1–2	and environmental	INEL, LMRI	LMRI
	P_X	3	3	studies; $T_{1/2}$ (SF)	–	–
				for waste management		
Pu-241	$T_{1/2}$	0.5	0.7	Mass determination	AERE, CBNM, +	CBNM
	$T_{1/2}$ (α)	1	0.8	and non-destructive	CBNM	–
	P_γ	1	1–2	assay	INEL, +	LMRI
Pu-242	$T_{1/2}$	1	0.3	Mass determination,	+	+
	$T_{1/2}$ (SF)	5	1.5	non-destructive assay	–	+
	P_α	5	<1	and environmental	–	–
	P_γ	5	2–5	studies	CBNM	–
	P_X	3	unknown		–	–
Am-241	$T_{1/2}$	0.2	0.1	Non-destructive assay	–	CBNM
	P_α	not requested	1–2	and low energy gamma	+	CBNM
	P_γ	0.5–1	1–10	emission standard.	CBNM, LMRI	CBNM
	P_X	2	3	0.5% accuracy requested for 59.5 keV gamma emission probability	–	–

International Nuclear Data Committee, May 2002 and May 2004:

recommended "Updated Decay Data Library for Actinides" by means of a Co-ordinated Research Project

2005 to 2008/09

International Atomic Energy Agency

Updated Decay Data Library for Actinides (2005 – 2009)

M.A. Kellett
IAEA Nuclear Data Section

International Atomic Energy Agency

Updated Decay Data Library for Actinides

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Updated Decay Data Library for Actinides

- M.A. Kellett, *Summary Report of the First Research Coordination Meeting on Updated Decay Data Library for Actinides*, 17 – 19 October 2005, IAEA report INDC(NDS)-0479, IAEA, Vienna, Austria, 2006

  See *http://www-nds.iaea.org/reports-new/indc-reports/indc-nds/indc-nds-0479.pdf*

- M.A. Kellett, *Summary Report of the Second Research Coordination Meeting on Updated Decay Data Library for Actinides*, 28 – 30 March 2007, IAEA report INDC(NDS)-0508, IAEA, Vienna, Austria, 2007

  See *http://www-nds.iaea.org/reports-new/indc-reports/indc-nds/indc-nds-0508.pdf*

Radionuclides allocated to each CRP participant

Participant	Actinides	Decay daughters
M.-M. Bé	^{234,238}U, ^{243}Am, ^{252}Cf	^{210}Tl, ^{210,214}Pb, ^{210,214}Bi, ^{210,214,218}Po, ^{218}At, ^{218,222}Rn, ^{226}Ra
V.P. Chechev	^{233}Th, ^{233}Pa, ^{237,239}U, ^{236,236m,237,238,239}Np, ^{238,239,240,241,242}Pu, ^{241}Am, ^{242,244}Cm	^{227}Ac
Huang Xiaolong	^{231}Th, ^{235}U	^{213}Bi, ^{213}Po, ^{217}At, ^{217}Rn, ^{221,223}Fr, ^{225}Ra, ^{225}Ac
F.G. Kondev	^{243,245,246}Cm	^{206}Hg, ^{206,207,209}Tl, ^{209,211}Pb
A. Luca	^{234}Th, ^{236}U	^{228}Ra
G. Mukherjee	^{229}Th, ^{233}U	-
A.L. Nichols	^{228}Th, ^{242,242m,244,244m}Am	^{208}Tl, ^{212}Pb, ^{212,215}Bi, ^{212,216}Po, ^{211,219}At, ^{219,220}Rn, ^{224}Ra
A.K. Pearce	^{232}Th, ^{231}Pa, ^{232}U	^{223}Ra, ^{228}Ac

Unallocated, April 2007	-	^{211}Bi, ^{211,215}Po, ^{215}At

Updated Decay Data Library for Actinides

Measurements:

- F.G. Kondev, I. Ahmad, J.P. Greene, M.A. Kellett, A.L. Nichols, *Measurements of the half-life of ^{246}Cm and the α-decay emission probabilities of ^{246}Cm and ^{250}Cf*, Appl. Radiat. Isot. 65 (2007) 335-340
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- F.G. Kondev, M.A. Kellett, I. Ahmad, J.P. Greene, A.L. Nichols, *Experimental studies to improve specific actinide decay data*, Int. Conf. on Nuclear Data for Science and Technology (ND2007), 22 – 27 April 2007, Nice, France
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- F.G. Kondev, I. Ahmad, M.P. Carpenter, C.J. Chiara, J.P. Greene, R.V.F. Janssens, M.A. Kellett, C.J. Lister, A.L. Nichols, G. Savard, D. Seweryniak, S. Zhu, *Decay studies of minor actinide nuclides, and future opportunities for improving the decay data of neutron-rich fission products,* submitted for presentation at Int. Conf. Reactor Physics, Nuclear Power: a Sustainable Resource, PHYSOR-2008, 14-19 September 2008, Interlaken, Switzerland

Updated Decay Data Library for Actinides

Evaluations:

- V.P. Chechev, *Evaluation of ^{242}Cm and ^{244}Cm Decay Data*, Physics of Atomic Nuclei 69 (2006) 1188-1197
- V.P. Chechev and N.K. Kuzmenko, *Decay Data Evaluation Project (DDEP): Evaluation of the ^{237}U, ^{236}Np, ^{236m}Np and ^{241}Pu Decay Characteristics*, Int. Conf. on Nuclear Data for Science and Technology (ND2007), 22 – 27 April 2007, Nice, France
- V. Chisté, M.-M. Bé and C. Dulieu, *Evaluation of Decay Data of Radium-226 and Its Daughters*, Int. Conf. on Nuclear Data for Science and Technology (ND2007), 22 – 27 April 2007, Nice, France

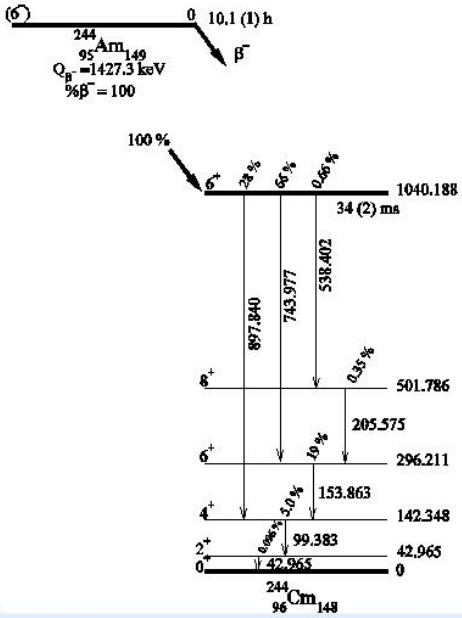
Updated Decay Data Library for Actinides

^{244}Am

100% β^- decay to 1040.188-keV nuclear level and of ^{244}Cm, followed by cascade of seven γ rays

International Atomic Energy Agency

Updated Decay Data Library for Actinides



Updated Decay Data Library for Actinides

Radionuclide	Anomalies and inadequacies
^{224}Ra	Discrepancy between related measurements of absolute emission probability of 240.99-keV γ ray and the α-particle emission probabilities to the ground and first excited states of ^{220}Rn
^{226}Ra	Modest discrepancy between related measurements of absolute emission probability of 186.21-keV γ ray and the α-particle emission probabilities to the ground and first excited states of ^{222}Rn
^{225}Ac	Only two measurements of the half-life (most recent in 1950)
^{233}Th	Measured γ-ray emission probabilities are reported without uncertainties
^{233}Pa	Precise measurements of low-energy γ rays and LX-rays would assist greatly in resolving difficulties in decay scheme evaluation.
^{237}U	Half-life measurements merited to fortify earlier experimental studies

International Atomic Energy Agency

Updated Decay Data Library for Actinides

Radionuclide	Anomalies and inadequacies
^{239}U	Large numbers of observed γ rays are unplaced in decay scheme
^{236}Np, $^{236}Np^{m}$	Inadequate experimental data
^{239}Pu	Determination of the multipolarities of the lower-energy γ rays would be beneficial
^{241}Am	Specific γ-ray transitions require more detailed measurements (27.0, 54.1 and 95.0 keV), including conversion-electron emission probabilities

Updated Decay Data Library for Actinides

Radionuclide	Anomalies and inadequacies
^{242}Am	Half-life studies merited to fortify the three existing measurements; γ-ray studies would also be beneficial
^{244}Am	Half-life studies required to fortify only one known measurement; γ-ray studies would also be beneficial
$^{244}Am^{m}$	Half-life measurements are required to quantify the value and uncertainty with much greater confidence; γ-ray studies would also be extremely beneficial (only one known decay data measurement)
^{242}Cm	Accurate measurements of 44-, 102-, 157- and 210-keV γ-ray emission probabilities merited

International Atomic Energy Agency

Updated Decay Data Library for Actinides

Recommended data files will be made available after completion and full review:

www-nds.iaea.org
and
www.nucleide.org/DDEP_WG/DDEPdata.htm

also in ENSDF and ENDF-6 formats for nuclear applications libraries

IAEA Co-ordinated Research Project (CRP)

Financial Support

1. Lump-sum cost-sharing contract
   - average IAEA contribution of $5,000,
   - also provision to attend RCMs

2. Cost-free agreement (Developed Countries)
   - only provision to attend RCMs

IAEA Co-ordinated Research Project (CRP)

1. Must assist Agency programmes (particularly CRPs)

2. Proposed project must be compatible with the Agency's approved programmes and functions

IAEA Co-ordinated Research Project (CRP)

Research contracts: one year – renewable up to total period of project (normally for 3 years (two one-year renewals))

Reports: yearly progress report and final report

Publications: acknowledge IAEA support of the work

Other provisions: equipment

4.

Nuclear Theory:
Nuclear Structure
(I) Single-particle Models

P. Van Isacker

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Nuclear Structure
(I) Single-particle models

P. Van Isacker, GANIL, France

NSDD Workshop, Trieste, April-May 2008

Overview of nuclear models

- *Ab initio* methods: Description of nuclei starting from the bare nn & nnn interactions.
- Nuclear shell model: Nuclear average potential + (residual) interaction between nucleons.
- Mean-field methods: Nuclear average potential with global parametrisation (+ correlations).
- Phenomenological models: Specific nuclei or properties with local parametrisation.

NSDD Workshop, Trieste, April-May 2008

Nuclear shell model

- Many-body quantum mechanical problem:

$$\hat{H} = \sum_{k=1}^{A} \frac{p_k^2}{2m_k} + \sum_{k<l}^{A} \hat{V}_2(\boldsymbol{r}_k, \boldsymbol{r}_l)$$

$$= \underbrace{\sum_{k=1}^{A} \left[\frac{p_k^2}{2m_k} + \hat{V}(\boldsymbol{r}_k) \right]}_{\text{mean field}} + \underbrace{\left[\sum_{k<l}^{A} \hat{V}_2(\boldsymbol{r}_k, \boldsymbol{r}_l) - \sum_{k=1}^{A} V(\boldsymbol{r}_k) \right]}_{\text{residualinteraction}}$$

- Independent-particle assumption. Choose V and neglect residual interaction:

$$\hat{H} \approx \hat{H}_{\text{IP}} = \sum_{k=1}^{A} \left[\frac{p_k^2}{2m_k} + \hat{V}(\boldsymbol{r}_k) \right]$$

Independent-particle shell model

- Solution for one particle:

$$\left[\frac{p^2}{2m} + \hat{V}(\boldsymbol{r}) \right] \phi_i(\boldsymbol{r}) = E_i \phi_i(\boldsymbol{r})$$

- Solution for many particles:

$$\Phi_{i_1 i_2 \mathrm{K}\, i_A}(\boldsymbol{r}_1, \boldsymbol{r}_2, \mathrm{K}\,, \boldsymbol{r}_A) = \prod_{k=1}^{A} \phi_{i_k}(\boldsymbol{r}_k)$$

$$\hat{H}_{\text{IP}} \Phi_{i_1 i_2 \mathrm{K}\, i_A}(\boldsymbol{r}_1, \boldsymbol{r}_2, \mathrm{K}\,, \boldsymbol{r}_A) = \left(\sum_{k=1}^{A} E_{i_k} \right) \Phi_{i_1 i_2 \mathrm{K}\, i_A}(\boldsymbol{r}_1, \boldsymbol{r}_2, \mathrm{K}\,, \boldsymbol{r}_A)$$

Independent-particle shell model

- Anti-symmetric solution for many particles (Slater determinant):

$$\Psi_{i_1 i_2 \mathrm{K}\, i_A}(\boldsymbol{r}_1,\boldsymbol{r}_2,\mathrm{K},\boldsymbol{r}_A)=\frac{1}{\sqrt{A!}}\begin{vmatrix}\phi_{i_1}(\boldsymbol{r}_1) & \phi_{i_1}(\boldsymbol{r}_2) & \mathrm{K} & \phi_{i_1}(\boldsymbol{r}_A)\\ \phi_{i_2}(\boldsymbol{r}_1) & \phi_{i_2}(\boldsymbol{r}_2) & \mathrm{K} & \phi_{i_2}(\boldsymbol{r}_A)\\ \mathrm{M} & \mathrm{M} & \mathrm{O} & \mathrm{M}\\ \phi_{i_A}(\boldsymbol{r}_1) & \phi_{i_A}(\boldsymbol{r}_2) & \mathrm{K} & \phi_{i_A}(\boldsymbol{r}_A)\end{vmatrix}$$

- Example for $A=2$ particles:

$$\Psi_{i_1 i_2}(\boldsymbol{r}_1,\boldsymbol{r}_2)=\frac{1}{\sqrt{2}}\left[\phi_{i_1}(\boldsymbol{r}_1)\phi_{i_2}(\boldsymbol{r}_2)-\phi_{i_1}(\boldsymbol{r}_2)\phi_{i_2}(\boldsymbol{r}_1)\right]$$

Hartree-Fock approximation

- Vary ϕ_i (*ie* V) to minimize the expectation value of H in a Slater determinant:

$$\delta\frac{\int \Psi^*_{i_1 i_2 \mathrm{K}\, i_A}(\boldsymbol{r}_1,\boldsymbol{r}_2,\mathrm{K},\boldsymbol{r}_A)\hat{H}\Psi_{i_1 i_2 \mathrm{K}\, i_A}(\boldsymbol{r}_1,\boldsymbol{r}_2,\mathrm{K},\boldsymbol{r}_A)d\boldsymbol{r}_1 d\boldsymbol{r}_2 \mathrm{K}\; d\boldsymbol{r}_A}{\int \Psi^*_{i_1 i_2 \mathrm{K}\, i_A}(\boldsymbol{r}_1,\boldsymbol{r}_2,\mathrm{K},\boldsymbol{r}_A)\Psi_{i_1 i_2 \mathrm{K}\, i_A}(\boldsymbol{r}_1,\boldsymbol{r}_2,\mathrm{K},\boldsymbol{r}_A)d\boldsymbol{r}_1 d\boldsymbol{r}_2 \mathrm{K}\; d\boldsymbol{r}_A}=0$$

- Application requires choice of H. Many global parametrizations (Skyrme, Gogny,…) have been developed.

Poor man's Hartree-Fock

- Choose a simple, analytically solvable V that approximates the microscopic HF potential:

$$\hat{H}_{\text{IP}} = \sum_{k=1}^{A}\left[\frac{p_k^2}{2m} + \frac{m\omega^2}{2}r_k^2 - \zeta \boldsymbol{l}_k \cdot \boldsymbol{s}_k - \kappa l_k^2\right]$$

- Contains
  - Harmonic oscillator potential with constant ω.
  - Spin-orbit term with strength ζ.
  - Orbit-orbit term with strength κ.
- Adjust ω, ζ and κ to best reproduce HF.

Harmonic oscillator solution

- Energy eigenvalues of the harmonic oscillator:

$$E_{nlj} = \left(N+\tfrac{3}{2}\right)\hbar\omega - \kappa\hbar^2 l(l+1) + \zeta\hbar^2 \begin{cases} -\frac{1}{2}l & j = l+\frac{1}{2} \\ \frac{1}{2}(l+1) & j = l-\frac{1}{2} \end{cases}$$

$N = 2n + l = 0, 1, 2, \text{K}$: oscillator quantum number

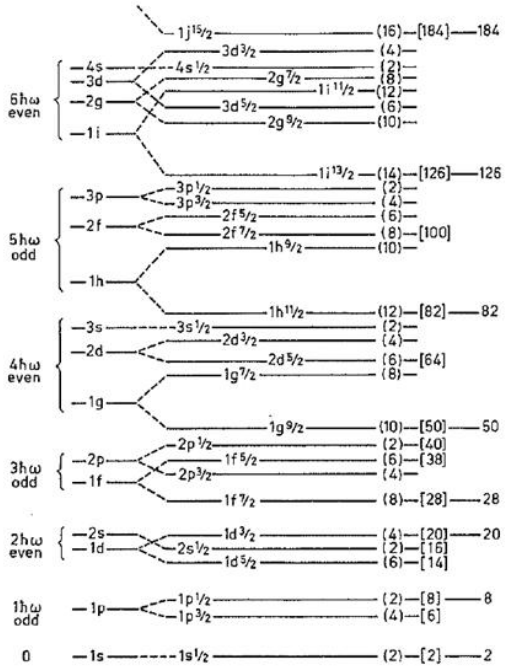
$n = 0, 1, 2, \text{K}$: radial quantum number

$l = N,\ N-2, \text{K}, 1 \text{ or } 0$: orbital angular momentum

$j = l \pm \frac{1}{2}$: total angular momentum

$m_j = -j, -j+1, \text{K}, +j$: z projection of j

Energy levels of harmonic oscillator



- Typical parameter values:

$$\hbar\omega \approx 41\,A^{-1/3}\ \text{MeV}$$

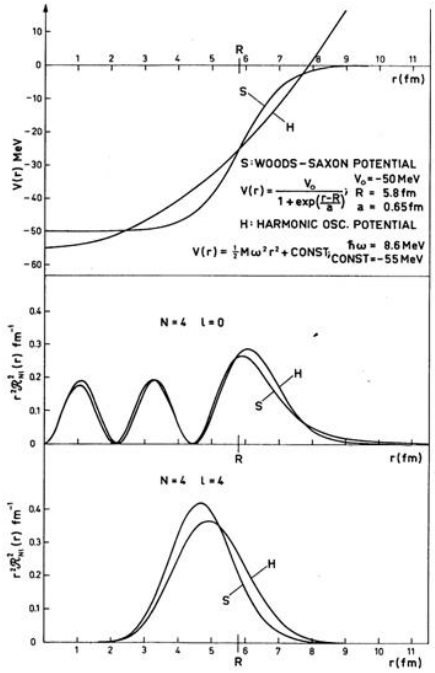
$$\zeta\hbar^2 \approx 20\,A^{-2/3}\ \text{MeV}$$

$$\kappa\hbar^2 \approx 0.1\ \text{MeV}$$

$$\therefore b \approx 1.0\,A^{1/6}\ \text{fm}$$

- 'Magic' numbers at 2, 8, 20, 28, 50, 82, 126, 184,…

Why an orbit-orbit term?



- Nuclear mean field is close to Woods-Saxon:

$$\hat{V}_{\text{ws}}(r) = \frac{V_0}{1+\exp\dfrac{r-R_0}{a}}$$

- $2n+l=N$ degeneracy is lifted $\Rightarrow E_l < E_{l-2} < \ldots$

Why a spin-orbit term?

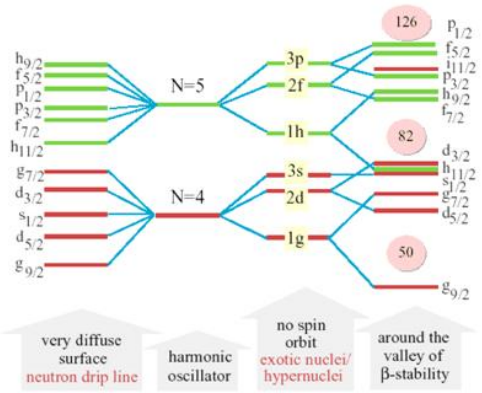
- Relativistic origin (*ie* Dirac equation).
- From general invariance principles:

$$\hat{V}_{\rm so} = \zeta(r)\boldsymbol{l}\cdot\boldsymbol{s}, \quad \zeta(r) = \frac{r_0^2}{r}\frac{\partial V}{\partial r} [= \zeta \text{ in HO}]$$

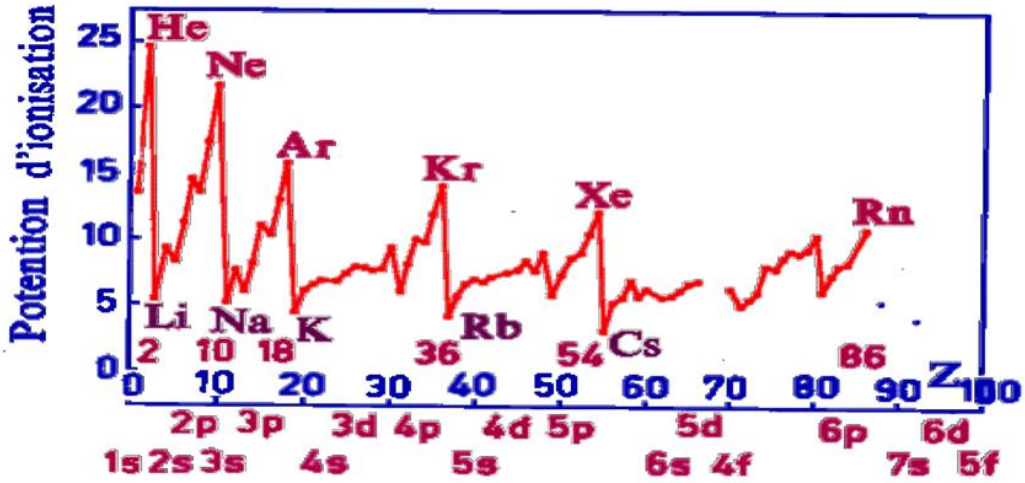
- Spin-orbit term is surface peaked ⇒ diminishes for diffuse potentials.

Evidence for shell structure

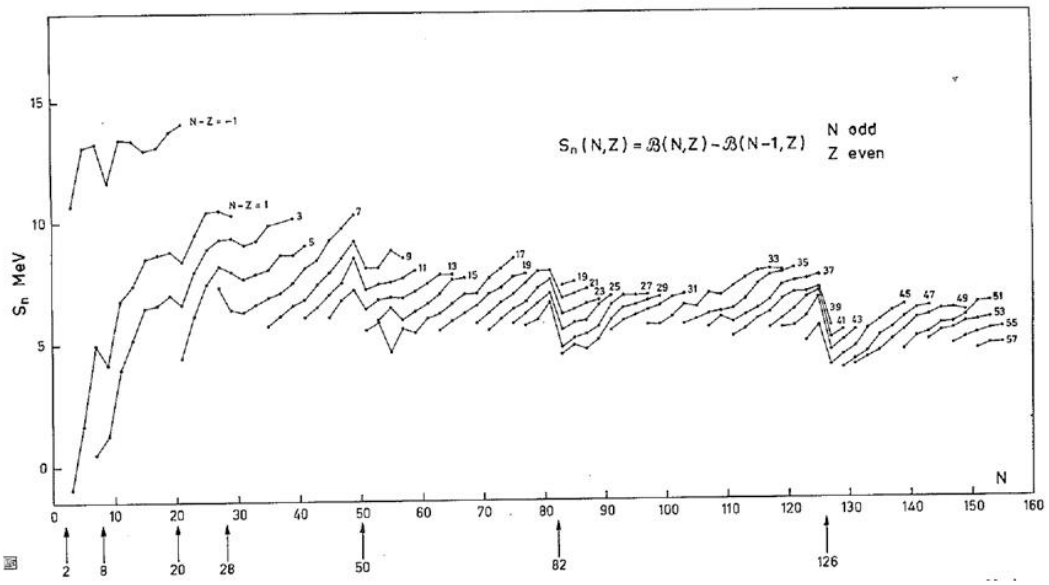
- Evidence for nuclear shell structure from
  - 2^+ in even-even nuclei [E_x, B(E2)].
  - Nucleon-separation energies & nuclear masses.
  - Nuclear level densities.
  - Reaction cross sections.
- *Is nuclear shell structure modified away from the line of stability?*



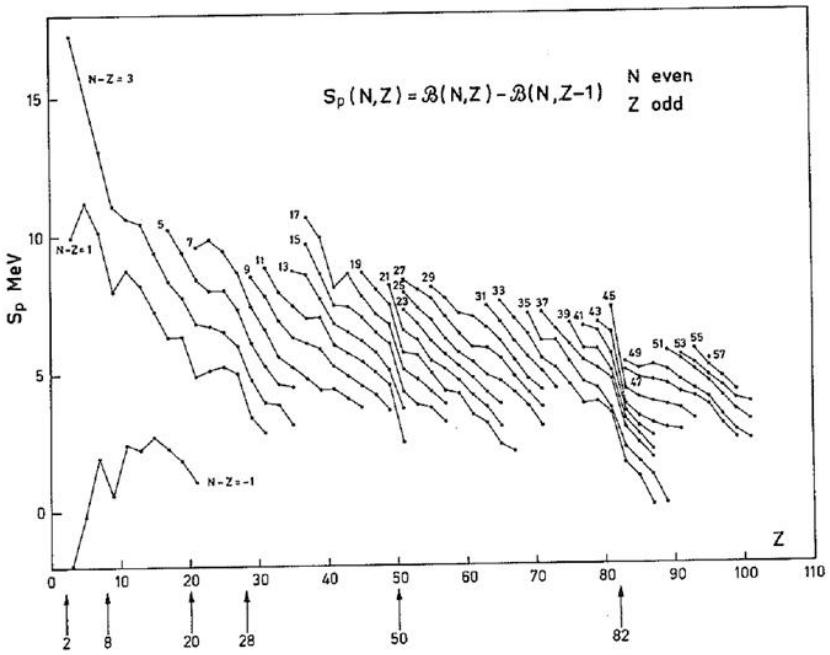
Ionisation potential in atoms



Neutron separation energies



Proton separation energies



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Liquid-drop mass formula

- Binding energy of an atomic nucleus:

$$B(N,Z) = a_v A - a_s A^{2/3} - a_c \frac{Z(Z-1)}{A^{1/3}} - a'_s \frac{(N-Z)^2}{A} + a_p \frac{\Delta(N,Z)}{A^{1/3}}$$

- For 2149 nuclei ($N,Z \geq 8$) in AME03:
  $a_v \approx 16$, $a_s \approx 18$, $a_c \approx 0.71$, $a'_s \approx 23$, $a_p \approx 6$
  $\Rightarrow \sigma_{rms} \approx 2.93$ MeV.

C.F. von Weizsäcker, Z. Phys. **96** (1935) 431
H.A. Bethe & R.F. Bacher, Rev. Mod. Phys. **8** (1936) 82

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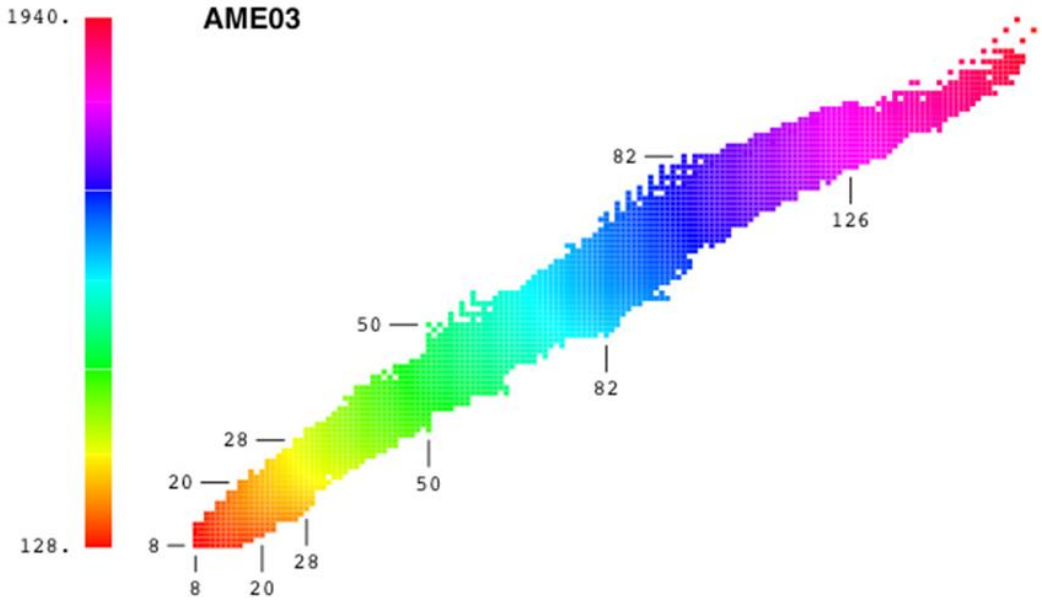
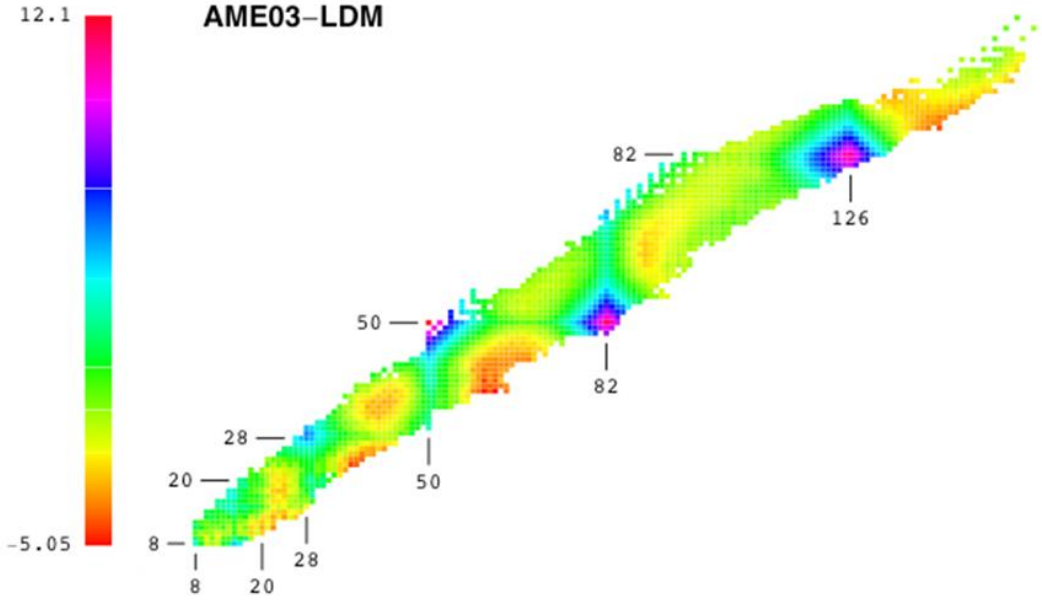
Nuclear mass surface



‘Unfolding’ of the mass surface



Modified liquid-drop formula

- Add surface, Wigner and 'shell' corrections:

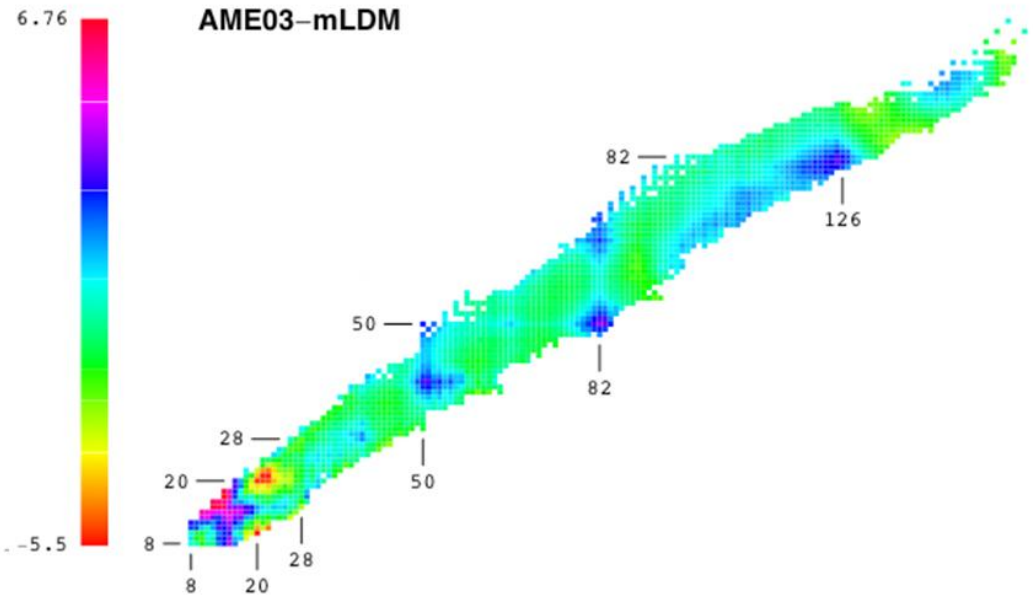
$$B(N,Z) = a_v A - a_s A^{2/3} - a_c \frac{Z(Z-1)}{A^{1/3}} + a_p \frac{\Delta(N,Z)}{A^{1/3}}$$
$$- \frac{S_v}{1+y_s A^{-1/3}} \frac{4T(T+1)}{A} - a_f (n_\nu + n_\pi) + a_{ff} (n_\nu + n_\pi)^2$$

- For 2149 nuclei ($N,Z \geq 8$) in AME03:

  $a_v \approx 16$, $a_s \approx 18$, $a_c \approx 0.71$, $S_v \approx 35$, $y_s \approx 2.9$, $a_p \approx 5.5$, $a_f \approx 0.85$, $a_{ff} \approx 0.016$

  $\Rightarrow \sigma_{rms} \approx 1.16$ MeV.

Shell-corrected LDM



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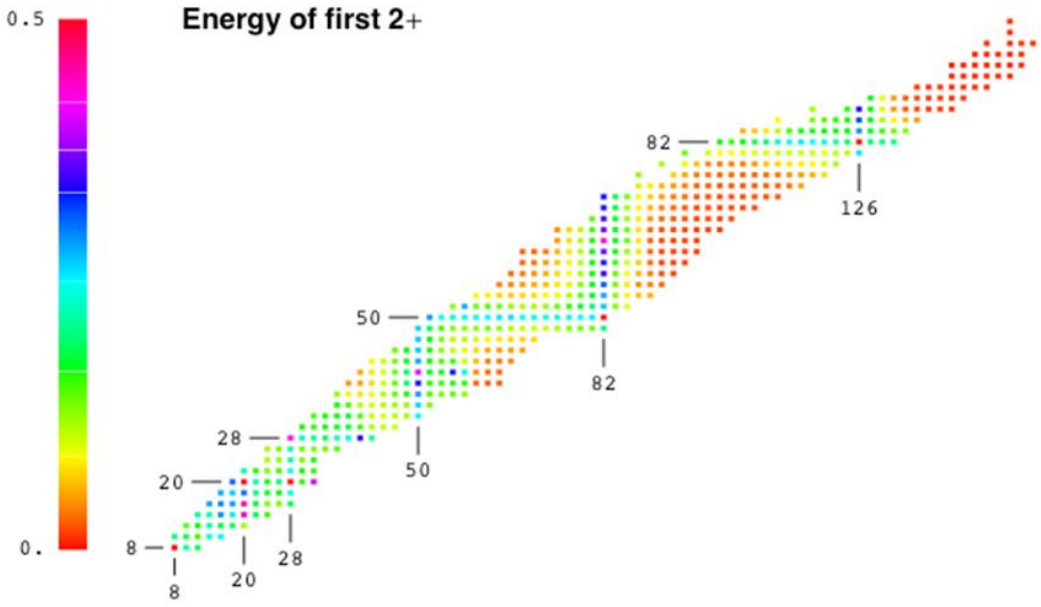
Shell structure from $E_x(2_1)$



Evidence for IP shell model

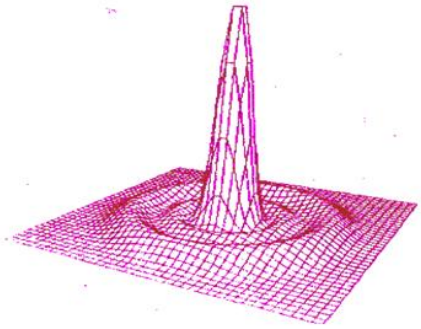
Z	Isotope	Observed J^π	Shell model nlj
3	^{9}Li	$(3/2^-)$	$1p_{3/2}$
5	^{13}B	$3/2^-$	$1p_{3/2}$
7	^{17}N	$1/2^-$	$1p_{1/2}$
9	^{21}F	$5/2^+$	$1d_{5/2}$
11	^{25}Na	$5/2^+$	$1d_{5/2}$
13	^{29}Al	$5/2^+$	$1d_{5/2}$
15	^{33}P	$1/2^+$	$2s_{1/2}$
17	^{37}Cl	$3/2^+$	$1d_{3/2}$
19	^{41}K	$3/2^+$	$1d_{3/2}$
21	^{45}Sc	$7/2^-$	$1f_{7/2}$
23	^{49}Va	$7/2^-$	$1f_{7/2}$
25	^{53}Mn	$7/2^-$	$1f_{7/2}$
27	^{57}Co	$7/2^-$	$1f_{7/2}$
29	^{61}Cu	$3/2^-$	$2p_{3/2}$
31	^{65}Ga	$3/2^-$	$2p_{3/2}$
33	^{69}As	$(5/2^-)$	$1f_{5/2}$
35	^{73}Br	$(3/2^-)$	$1f_{5/2}$

- Ground-state spins and parities of nuclei:

$$\left.\begin{array}{l} j \text{ in } \phi_{nljm_j} \Rightarrow J \\ l \text{ in } \phi_{nljm_j} \Rightarrow (-)^l = \pi \end{array}\right\} \Rightarrow J^\pi$$

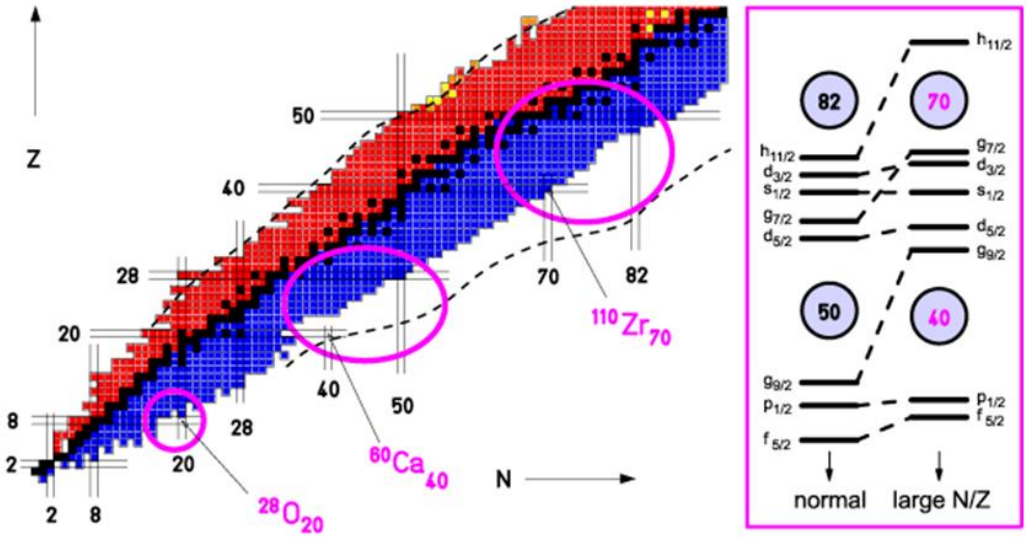
Validity of SM wave functions

- Example: Elastic electron scattering on ^{206}Pb and ^{205}Tl, differing by a 3*s* proton.
- Measured ratio agrees with shell-model prediction for 3*s* orbit.



J.M. Cavedon *et al.*, Phys. Rev. Lett. **49** (1982) 978

Variable shell structure



Beyond Hartree-Fock

- Hartree-Fock-Bogoliubov (HFB): Includes pairing correlations in mean-field treatment.
- Tamm-Dancoff approximation (TDA):
  - Ground state: closed-shell HF configuration
  - Excited states: mixed 1p-1h configurations
- Random-phase approximation (RPA): Correlations in the ground state by treating on the same footing as 1p-1h excitations.

Nuclear shell model

- Full shell-model Hamiltonian:

$$\hat{H} = \sum_{k=1}^{A}\left[\frac{p_k^2}{2m} + \hat{V}(\boldsymbol{r}_k)\right] + \sum_{k<l}^{A}\hat{V}_{\mathrm{RI}}(\boldsymbol{r}_k, \boldsymbol{r}_l)$$

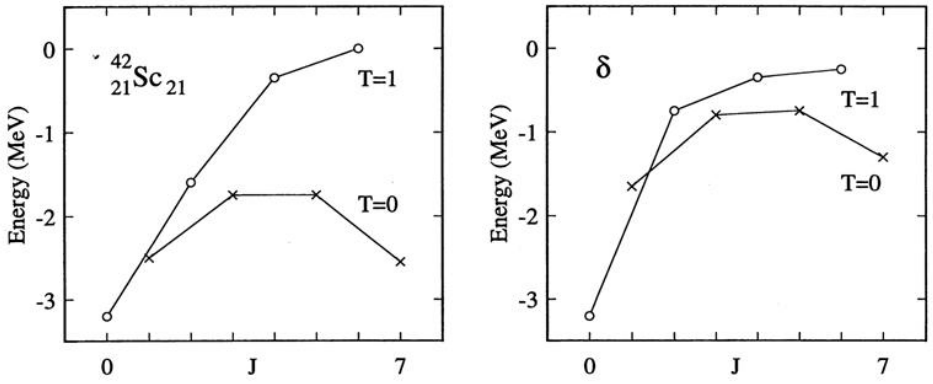
- Valence nucleons: Neutrons or protons that are in excess of the last, completely filled shell.
- Usual approximation: Consider the residual interaction V_{RI} among valence nucleons only.
- Sometimes include selected core excitations ('intruder' states).

Residual shell-model interaction

- Four approaches:
  - Effective: Derive from free nn interaction taking account of the nuclear medium.
  - Empirical: Adjust matrix elements of residual interaction to data. Examples: *p*, *sd* and *pf* shells.
  - Effective-empirical: Effective interaction with some adjusted (monopole) matrix elements.
  - Schematic: Assume a simple spatial form and calculate matrix elements on harmonic-oscillator basis. Example: δ interaction.

Schematic short-range interaction

- Delta interaction in harmonic-oscillator basis:
- Example of $^{42}Sc_{21}$ (1 neutron + 1 proton):



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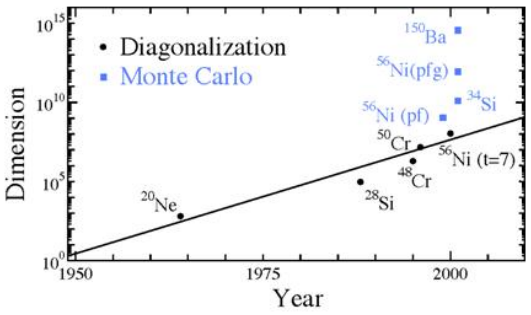
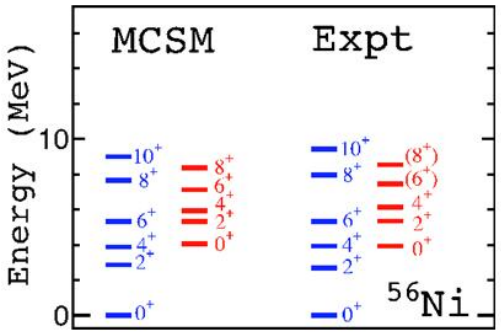
Large-scale shell model

- Large Hilbert spaces:

$$\left\langle \Psi_{i'_1 i'_2 \mathrm{K}\, i'_A} \left| \sum_{k<l}^{n} \hat{V}_{\mathrm{RI}}(\boldsymbol{r}_k, \boldsymbol{r}_l) \right| \Psi_{i_1 i_2 \mathrm{K}\, i_A} \right\rangle$$

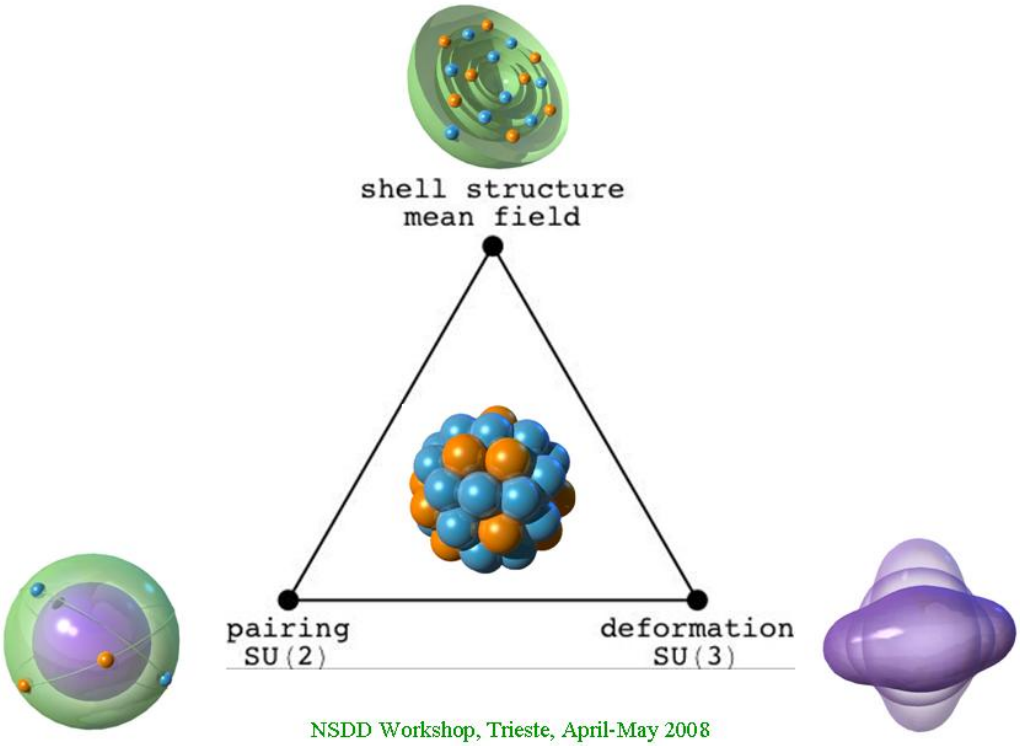
  - Diagonalisation : ~10^9.
  - Monte Carlo : ~10^{15}.
- Example : 8n + 8p in $pfg_{9/2}$ (^{56}Ni).





M. Honma *et al.*, Phys. Rev. C **69** (2004) 034335

Three faces of the shell model

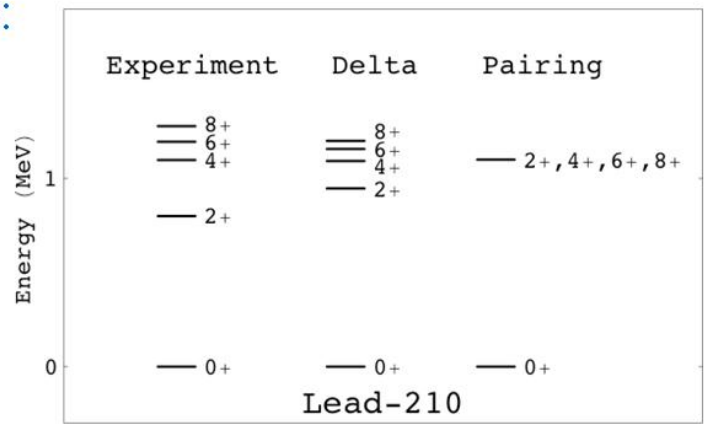


Racah's SU(2) pairing model

- Assume pairing interaction in a single-j shell:

$$\left\langle j^2 JM_J \left| \hat{V}_{\text{pairing}}(\boldsymbol{r}_1, \boldsymbol{r}_2) \right| j^2 JM_J \right\rangle = \begin{cases} -\frac{1}{2}(2j+1)g_0, & J=0 \\ 0, & J \neq 0 \end{cases}$$

- Spectrum ^{210}Pb:



Solution of the pairing Hamiltonian

- Analytic solution of pairing Hamiltonian for identical nucleons in a single-j shell:

$$\left\langle j^n \omega J \left| \sum_{1 \le k < l}^{n} \hat{V}_{\text{pairing}}(\boldsymbol{r}_k, \boldsymbol{r}_l) \right| j^n \omega J \right\rangle = -g_0 \tfrac{1}{4}(n-\upsilon)(2j-n-\upsilon+3)$$

- Seniority υ (number of nucleons not in pairs coupled to J=0) is a good quantum number.
- Correlated ground-state solution (*cf.* BCS).

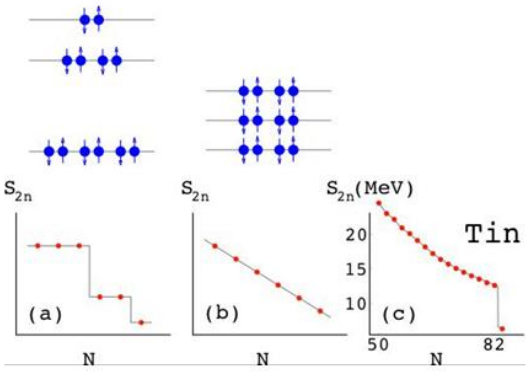
G. Racah, Phys. Rev. **63** (1943) 367

Nuclear superfluidity

- Ground states of pairing Hamiltonian have the following *correlated* character:
  - Even-even nucleus (υ=0): $\left(\hat{S}_+\right)^{n/2}|\mathrm{o}\rangle, \quad \hat{S}_+ = \sum_m \hat{a}^+_{m\downarrow}\hat{a}^+_{m\uparrow}$
  - Odd-mass nucleus (υ=1): $\hat{a}^+_{mb}\left(\hat{S}_+\right)^{n/2}|\mathrm{o}\rangle$
- Nuclear superfluidity leads to
  - Constant energy of first 2^+ in even-even nuclei.
  - Odd-even staggering in masses.
  - Smooth variation of two-nucleon separation energies with nucleon number.
  - Two-particle (2n or 2p) transfer enhancement.

Two-nucleon separation energies

- Two-nucleon separation energies S_{2n}:
  - (a) Shell splitting dominates over interaction.
  - (b) Interaction dominates over shell splitting.
  - (c) S_{2n} in tin isotopes.



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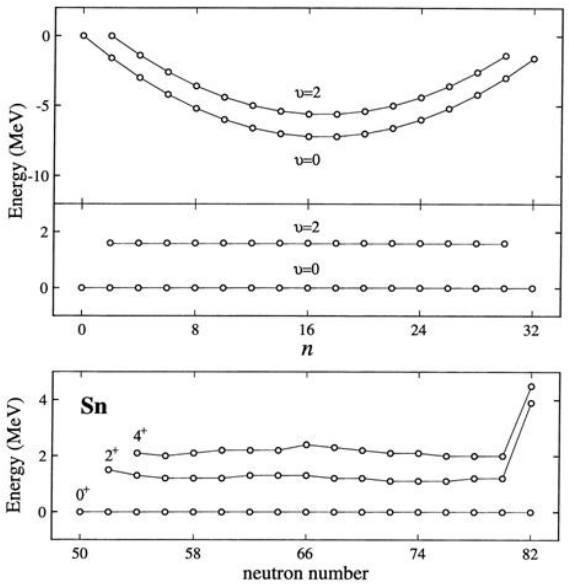
Pairing gap in semi-magic nuclei

- Even-even nuclei:
  - Ground state: $\upsilon=0$.
  - First-excited state: $\upsilon=2$.
  - Pairing produces constant energy gap:

$$E_x\left(2_1^+\right)=\tfrac{1}{2}(2j+1)G$$

- Example of Sn isotopes

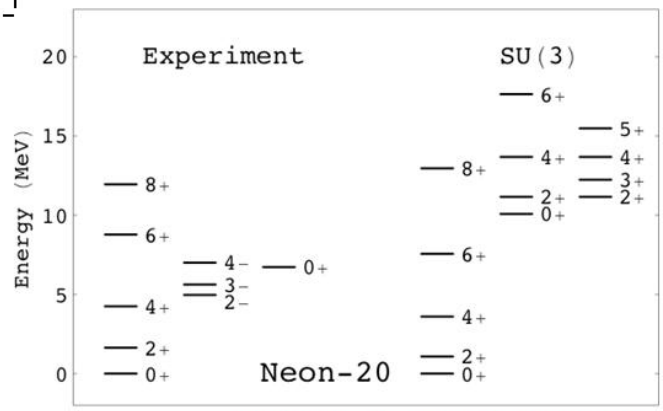


Elliott's SU(3) model of rotation

- Harmonic oscillator mean field (*no* spin-orbit) with residual interaction of quadrupole type:

$$\hat{H}=\sum_{k=1}^{A}\left[\frac{p_k^2}{2m}+\frac{1}{2}m\omega^2 r_k^2\right]-g_2\hat{Q}\cdot\hat{Q},$$

$$\hat{Q}_\mu \propto \sum_{k=1}^{A} r_k^2 Y_{2\mu}(\hat{\mathbf{r}}_k) + \sum_{k=1}^{A} p_k^2 Y_{2\mu}(\hat{\mathbf{p}}_k)$$



J.P. Elliott, Proc. Roy. Soc. A **245** (1958) 128; 562

Nuclear Theory:
Nuclear Structure
(II) Collective Models

P. Van Isacker

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Nuclear Structure
(II) Collective models

P. Van Isacker, GANIL, France

NSDD Workshop, Trieste, April-May 2008

Overview of collective models

- (Rigid) rotor model
- (Harmonic quadrupole) vibrator model
- Liquid-drop model of vibrations and rotations
- Interacting boson model
- Particle-core coupling model
- Nilsson model

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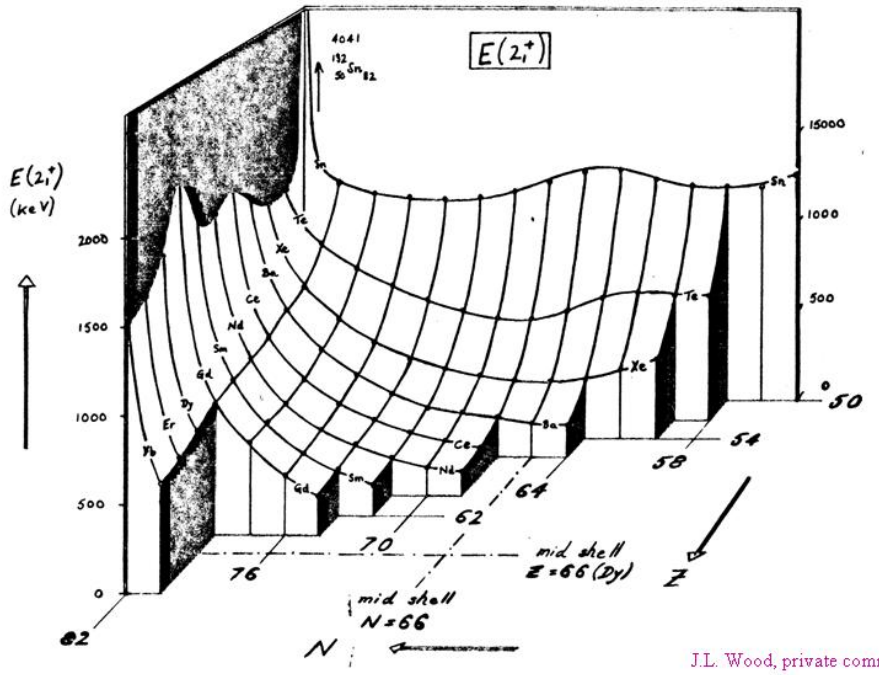
Evolution of $E_x(2^+)$



J.L. Wood, private communication

Quantum-mechanical symmetric top

- Energy spectrum:

$$E_{\text{rot}}(I) = \frac{\hbar^2}{2\Im} I(I+1)$$

$$\equiv A\, I(I+1), \quad I = 0, 2, 4, \text{K}$$

- Large deformation $\Rightarrow$ large $\Im \Rightarrow$ low $E_x(2^+)$.
- R_{42} energy ratio:

$$E_{\text{rot}}(4^+)/E_{\text{rot}}(2^+) = 3.333\text{K}$$

E(I)-E(I-2)

6^+ 42A

22A

4^+ 20A

14A

2^+ 6A

0^+ 0

6A

Rigid rotor model

- Hamiltonian of quantum-mechanical rotor in terms of 'rotational' angular momentum $\boldsymbol{R}$:

$$\hat{H}_{\text{rot}} = \frac{\hbar^2}{2}\left[\frac{R_1^2}{\mathfrak{I}_1} + \frac{R_2^2}{\mathfrak{I}_2} + \frac{R_3^2}{\mathfrak{I}_3}\right] = \frac{\hbar^2}{2}\sum_{i=1}^{3}\frac{R_i^2}{\mathfrak{I}_i}$$

- Nuclei have an additional intrinsic part H_{intr} with 'intrinsic' angular momentum $\boldsymbol{J}$.
- Total angular momentum is $\boldsymbol{I} = \boldsymbol{R} + \boldsymbol{J}$

Rigid axially symmetric rotor

- For $\mathfrak{I}_1 = \mathfrak{I}_2 = \mathfrak{I} \neq \mathfrak{I}_3$ the rotor Hamiltonian is

$$\hat{H}_{\text{rot}} = \sum_{i=1}^{3}\frac{\hbar^2}{2\mathfrak{I}_i}(I_i - J_i)^2 = \underbrace{\sum_{i=1}^{3}\frac{\hbar^2}{2\mathfrak{I}_i}I_i^2}_{\hat{H}'_{\text{rot}}} - \underbrace{\sum_{i=1}^{3}\frac{\hbar^2}{\mathfrak{I}_i}I_iJ_i}_{\text{Coriolis}} + \underbrace{\sum_{i=1}^{3}\frac{\hbar^2}{2\mathfrak{I}_i}J_i^2}_{\text{intrinsic}}$$

- Eigenvalues of H'_{rot}:

$$E'_{KI} = \frac{\hbar^2}{2\mathfrak{I}}I(I+1) + \frac{\hbar^2}{2}\left(\frac{1}{\mathfrak{I}_3} - \frac{1}{\mathfrak{I}}\right)K^2$$

- Eigenvectors $|KIM\rangle$ of H'_{rot} satisfy:

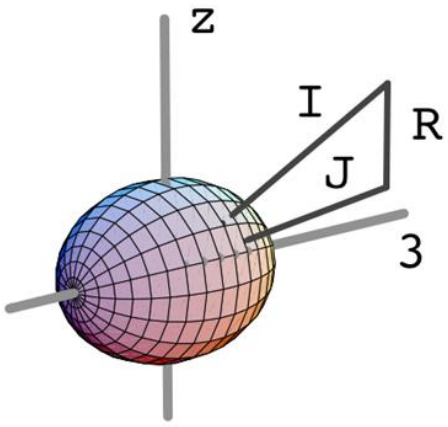
$$I^2|KIM\rangle = I(I+1)|KIM\rangle,$$

$$I_z|KIM\rangle = M|KIM\rangle, \quad I_3|KIM\rangle = K|KIM\rangle$$

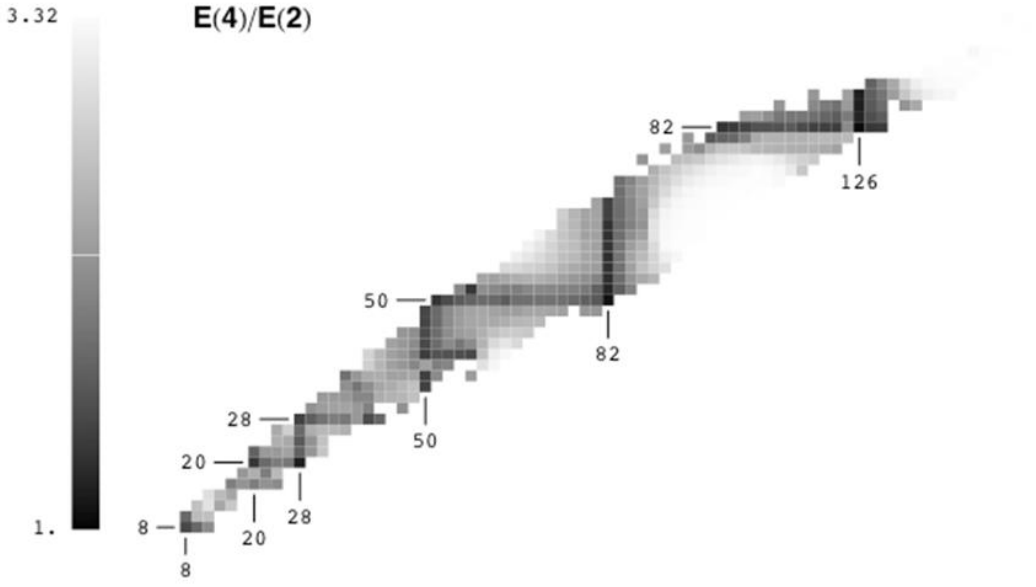
Ground-state band of an axial rotor

- Ground-state spin of even-even nuclei is $I = 0$. Hence $K = 0$ for ground-state band:

$$E_I = \frac{\hbar^2}{2\Im} I(I+1)$$



Ratio R_{42}



Electric (quadrupole) properties

- Partial γ-ray half-life:

$$T_{1/2}^{\gamma}(\mathrm{E}\lambda) = \ln 2 \left\{ \frac{8\pi}{\mathrm{h}} \frac{\lambda+1}{\lambda[(2\lambda+1)!!]^2} \left(\frac{E_\gamma}{\mathrm{hc}} \right)^{2\lambda+1} B(\mathrm{E}\lambda) \right\}^{-1}$$

- Electric quadrupole transitions:

$$B(\mathrm{E2}; I_\mathrm{i} \rightarrow I_\mathrm{f}) = \frac{1}{2I_\mathrm{i}+1} \sum_{M_\mathrm{i}} \sum_{M_\mathrm{f}\mu} \left| \langle I_\mathrm{f} M_\mathrm{f} | \sum_{k=1}^{A} e_k r_k^2 Y_{2\mu}(\theta_k, \varphi_k) | I_\mathrm{i} M_\mathrm{i} \rangle \right|^2$$

- Electric quadrupole moments:

$$eQ(I) = \langle IM = I | \sqrt{\frac{16\pi}{5}} \sum_{k=1}^{A} e_k r_k^2 Y_{20}(\theta_k, \varphi_k) | IM = I \rangle$$

Magnetic (dipole) properties

- Partial γ-ray half-life:

$$T_{1/2}^{\gamma}(\mathrm{M}\lambda) = \ln 2 \left\{ \frac{8\pi}{\mathrm{h}} \frac{\lambda+1}{\lambda[(2\lambda+1)!!]^2} \left(\frac{E_\gamma}{\mathrm{hc}} \right)^{2\lambda+1} B(\mathrm{M}\lambda) \right\}^{-1}$$

- Magnetic dipole transitions:

$$B(\mathrm{M1}; I_\mathrm{i} \rightarrow I_\mathrm{f}) = \frac{1}{2I_\mathrm{i}+1} \sum_{M_\mathrm{i}} \sum_{M_\mathrm{f}\mu} \left| \langle I_\mathrm{f} M_\mathrm{f} | \sum_{k=1}^{A} \left(g_k^l l_{k,\mu} + g_k^s s_{k,\mu} \right) | I_\mathrm{i} M_\mathrm{i} \rangle \right|^2$$

- Magnetic dipole moments:

$$\mu(I) = \langle IM = I | \sum_{k=1}^{A} \left(g_k^l l_{k,z} + g_k^s s_{k,z} \right) | IM = I \rangle$$

E2 properties of rotational nuclei

- *Intra*-band E2 transitions:

$$B(\mathrm{E2};KI_\mathrm{i}\to KI_\mathrm{f})=\frac{5}{16\pi}\langle I_\mathrm{i}K\ 20|I_\mathrm{f}K\rangle^2 e^2Q_0(K)^2$$

- E2 moments:

$$Q(KI)=\frac{3K^2-I(I+1)}{(I+1)(2I+3)}Q_0(K)$$

- $Q_0(K)$ is the 'intrinsic' quadrupole moment:

$$e\hat{Q}_0\equiv\int\rho(\boldsymbol{r}')r'^2\left(3\cos^2\theta'-1\right)d\boldsymbol{r}',\quad Q_0(K)=\langle K|\hat{Q}_0|K\rangle$$

E2 properties of ground-state bands

- For the ground state (usually $K = I$):

$$Q(K=I)=\frac{I(2I-1)}{(I+1)(2I+3)}Q_0(K)$$

- For the gsb in even-even nuclei ($K = 0$):

$$B(\mathrm{E2};I\to I-2)=\frac{15}{32\pi}\frac{I(I-1)}{(2I-1)(2I+1)}e^2Q_0^2$$

$$Q(I)=-\frac{I}{2I+3}Q_0$$

$$\Rightarrow\left|eQ\left(2_1^+\right)\right|=\frac{2}{7}\sqrt{16\pi\cdot B\left(\mathrm{E2};2_1^+\to 0_1^+\right)}$$

Generalized intensity relations

- Mixing of K arises from
  - Dependence of Q_0 on I (stretching)
  - Coriolis interaction
  - Triaxiality
- Generalized *intra*- and *inter*-band matrix elements (*eg* E2):

$$\frac{\sqrt{B(\mathrm{E2};K_\mathrm{i}I_\mathrm{i}\rightarrow K_\mathrm{f}I_\mathrm{f})}}{\langle I_\mathrm{i}K_\mathrm{i}\ 2K_\mathrm{f}-K_\mathrm{i}|I_\mathrm{f}K_\mathrm{f}\rangle} = M_0 + M_1\Delta + M_2\Delta^2 + \mathrm{L}$$

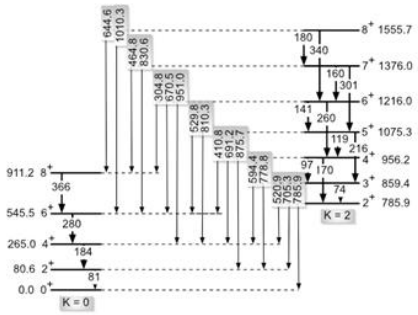
with $\Delta = I_\mathrm{f}(I_\mathrm{f}+1) - I_\mathrm{i}(I_\mathrm{i}+1)$

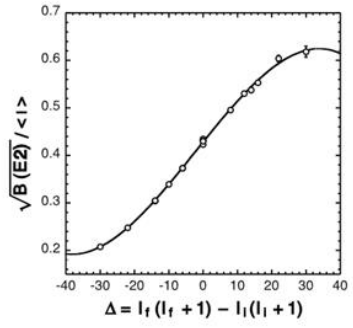
Inter-band E2 transitions

- Example of $\gamma \rightarrow$ g transitions in ^{166}Er:

$$\frac{\sqrt{B(\mathrm{E2};I_\gamma \rightarrow I_\mathrm{g})}}{\langle I_\gamma 2\ 2-2|I_\mathrm{g}0\rangle} = M_0 + M_1\Delta + M_2\Delta^2 + \mathrm{L}$$

$$\Delta = I_\mathrm{g}(I_\mathrm{g}+1) - I_\gamma(I_\gamma+1)$$





W.D. Kulp *et al.*, Phys. Rev. C **73** (2006) 014308

Modes of nuclear vibration

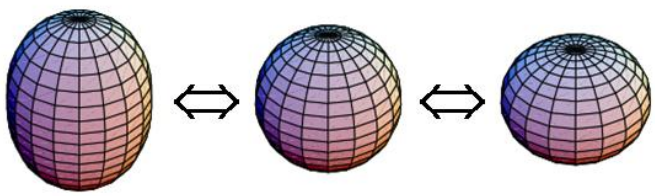
- Nucleus is considered as a droplet of nuclear matter with an equilibrium shape. Vibrations are modes of excitation around that shape.
- Character of vibrations depends on symmetry of equilibrium shape. Two important cases in nuclei:
  - Spherical equilibrium shape
  - Spheroidal equilibrium shape

Vibrations about a spherical shape

- Vibrations are characterized by a multipole quantum number λ in surface parametrization:

$$R(\theta,\varphi)=R_0\left(1+\sum_{\lambda}\sum_{\mu=-\lambda}^{+\lambda}\alpha_{\lambda\mu}Y^*_{\lambda\mu}(\theta,\varphi)\right)$$

  - λ=0: compression (high energy)
  - λ=1: translation (not an intrinsic excitation)
  - λ=2: quadrupole vibration



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Properties of spherical vibrations

- Energy spectrum:

  $E_{\text{vib}}(n) = \left(n + \frac{5}{2}\right)\hbar\omega,\ n = 0,1\text{K}$

- R_{42} energy ratio:

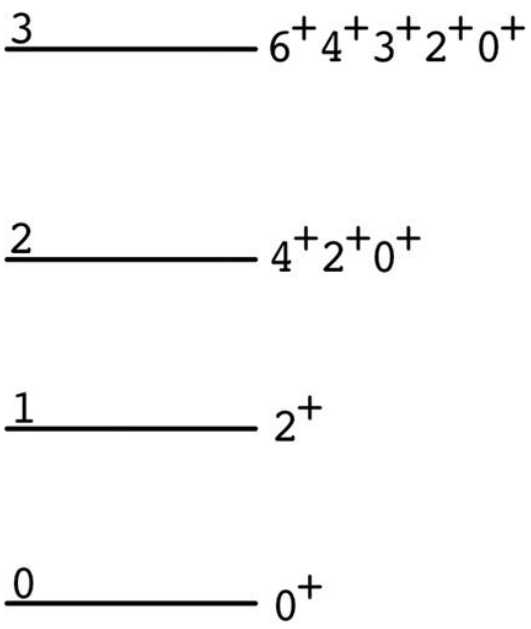
  $E_{\text{vib}}(4^+)/E_{\text{vib}}(2^+) = 2$

- E2 transitions:

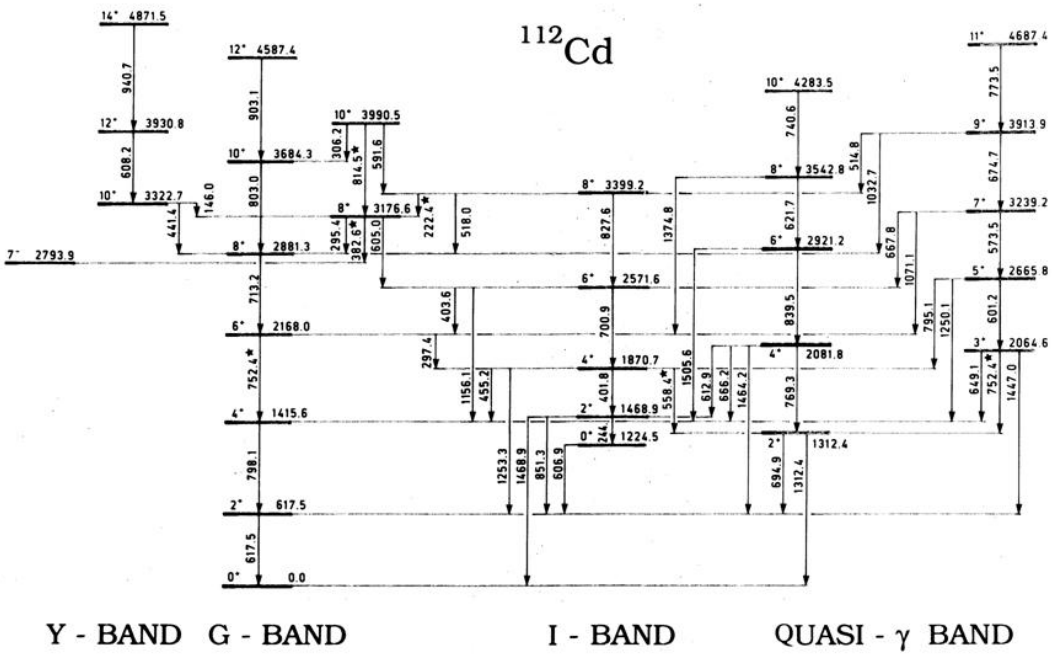
  $B(\text{E2}; 2_1^+ \rightarrow 0_1^+) = \alpha^2$

  $B(\text{E2}; 2_2^+ \rightarrow 0_1^+) = 0$

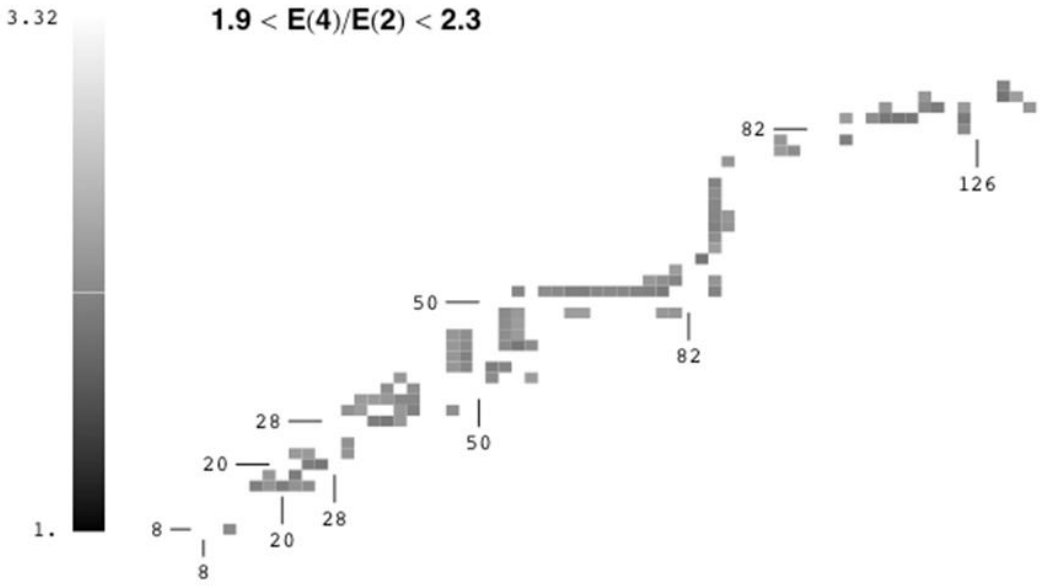
  $B(\text{E2}; n = 2 \rightarrow n = 1) = 2\alpha^2$



Example of ^{112}Cd

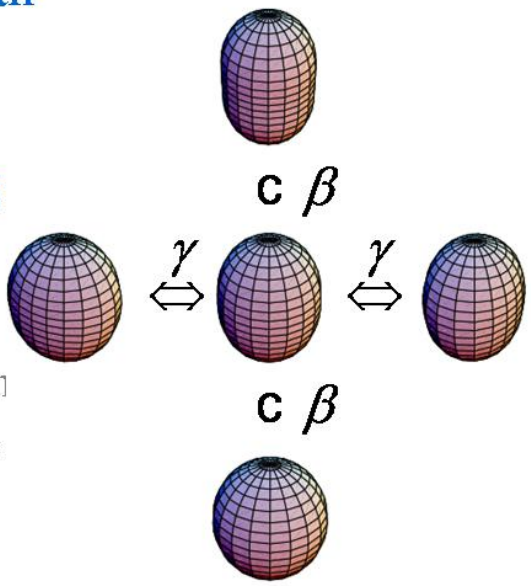


Possible vibrational nuclei from R_{42}

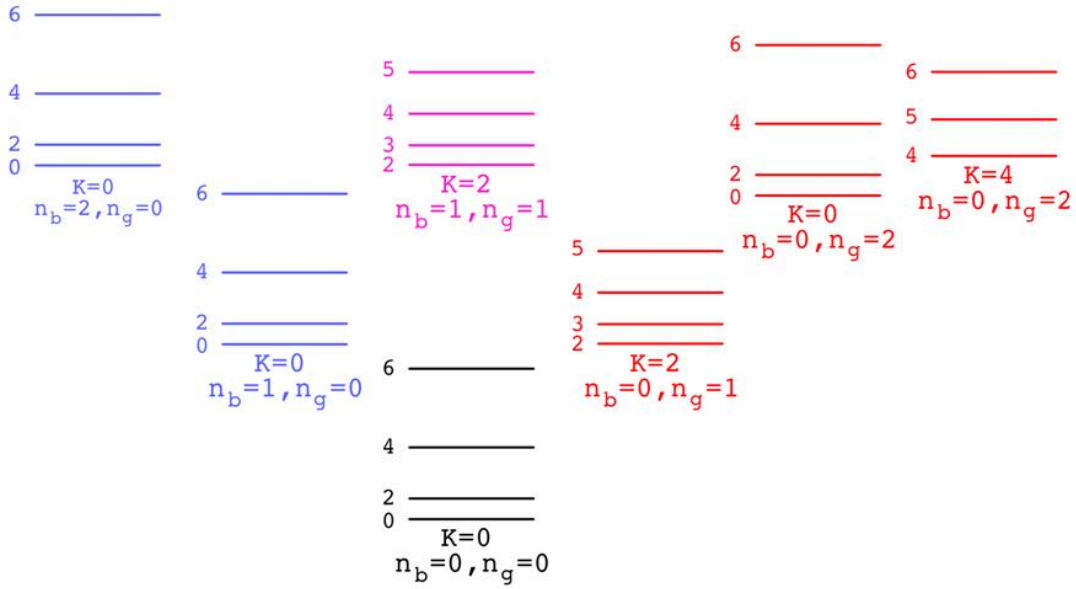


Vibrations about a spheroidal shape

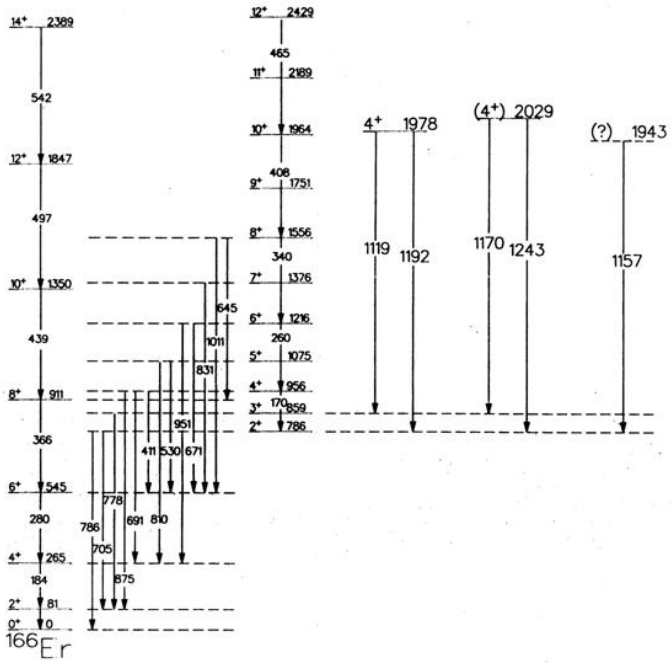
- Vibration of a shape with axial symmetry is characterized by $a_{\lambda\nu}$
- Quadrupole oscillations
  - $\nu = 0$: along the axis of symmetry (β)
  - $\nu = \pm 1$: spurious rotation
  - $\nu = \pm 2$: perpendicular to axis of symmetry (γ)



Spectrum of spheroidal vibrations



Example of ^{166}Er



Rigid triaxial rotor

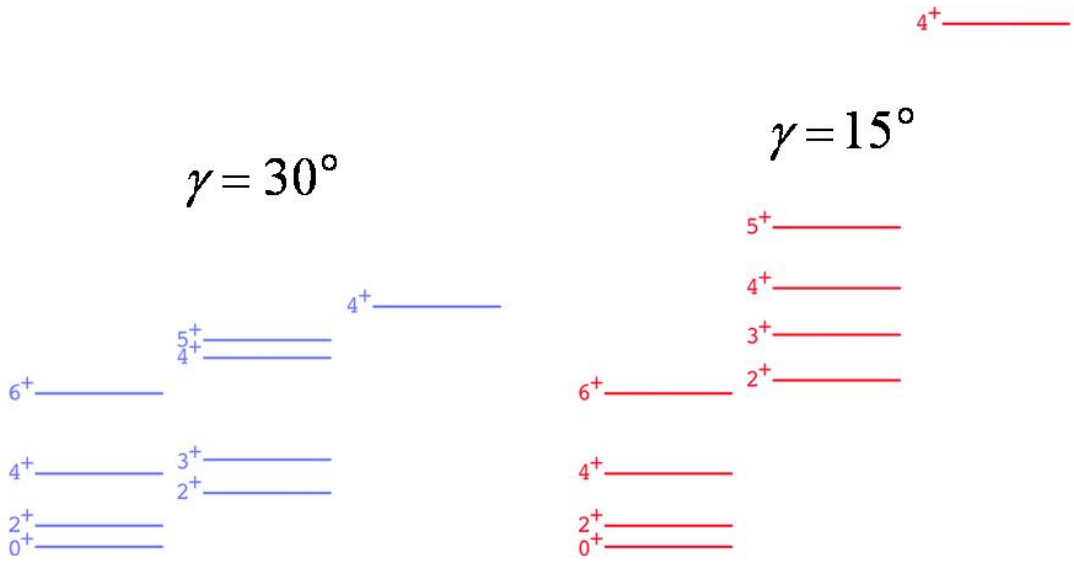
- Triaxial rotor Hamiltonian $\mathfrak{I}_1 \neq \mathfrak{I}_2 \neq \mathfrak{I}_3$:

$$\hat{H}'_{\text{rot}} = \sum_{i=1}^{3} \frac{\hbar^2}{2\mathfrak{I}_i} I_i^2 = \underbrace{\frac{\hbar^2}{2\mathfrak{I}} I^2 + \frac{\hbar^2}{2\mathfrak{I}_f} I_3^2}_{\hat{H}'_{\text{axial}}} + \underbrace{\frac{\hbar^2}{2\mathfrak{I}_g}\left(I_+^2 + I_-^2\right)}_{\hat{H}'_{\text{mix}}}$$

$$\frac{1}{\mathfrak{I}} = \frac{1}{2}\left(\frac{1}{\mathfrak{I}_1} + \frac{1}{\mathfrak{I}_2}\right), \frac{1}{\mathfrak{I}_f} = \frac{1}{\mathfrak{I}_3} - \frac{1}{\mathfrak{I}}, \frac{1}{\mathfrak{I}_g} = \frac{1}{4}\left(\frac{1}{\mathfrak{I}_1} - \frac{1}{\mathfrak{I}_2}\right)$$

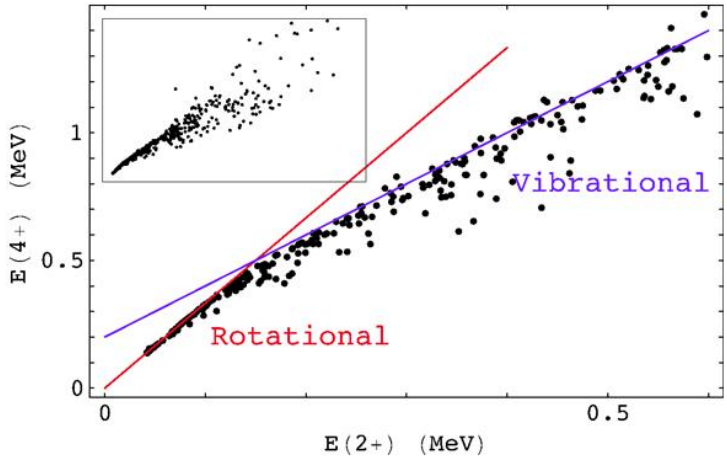
- H'_{mix} non-diagonal in axial basis $|KIM\rangle \Rightarrow K$ is *not* a conserved quantum number

Rigid triaxial rotor spectra



Tri-partite classification of nuclei

- Empirical evidence for seniority-type, vibrational- and rotational-like nuclei:



- Need for model of *vibrational* nuclei.

N.V. Zamfir *et al.*, Phys. Rev. Lett. **72** (1994) 3480

Interacting boson model

- Describe the nucleus as a system of N interacting s and d bosons. Hamiltonian:

$$\hat{H}_{\mathrm{IBM}} = \sum_{i=1}^{6} \varepsilon_i \hat{b}_i^{+} \hat{b}_i + \sum_{i_1 i_2 i_3 i_4 = 1}^{6} \upsilon_{i_1 i_2 i_3 i_4} \hat{b}_{i_1}^{+} \hat{b}_{i_2}^{+} \hat{b}_{i_3} \hat{b}_{i_4}$$

- Justification from
  - Shell model: s and d bosons are associated with S and D fermion (*Cooper*) pairs.
  - Geometric model: for large boson number the IBM reduces to a liquid-drop Hamiltonian.

Dimensions

- Assume Ω available 1-fermion states. Number of n-fermion states is $\binom{\Omega}{n} = \frac{\Omega!}{n!(\Omega-n)!}$
- Assume Ω available 1-boson states. Number of n-boson states is $\binom{\Omega+n-1}{n} = \frac{(\Omega+n-1)!}{n!(\Omega-1)!}$
- Example: $^{162}Dy_{96}$ with 14 neutrons (Ω = 44) and 16 protons (Ω = 32) ($^{132}Sn_{82}$ inert core).
  - SM dimension: ~$7 \cdot 10^{19}$
  - IBM dimension: 15504

Dynamical symmetries

- Boson Hamiltonian is of the form

$$\hat{H}_{\mathrm{IBM}} = \sum_{i=1}^{6} \varepsilon_i \hat{b}_i^{+} \hat{b}_i + \sum_{i_1 i_2 i_3 i_4 = 1}^{6} \upsilon_{i_1 i_2 i_3 i_4} \hat{b}_{i_1}^{+} \hat{b}_{i_2}^{+} \hat{b}_{i_3} \hat{b}_{i_4}$$

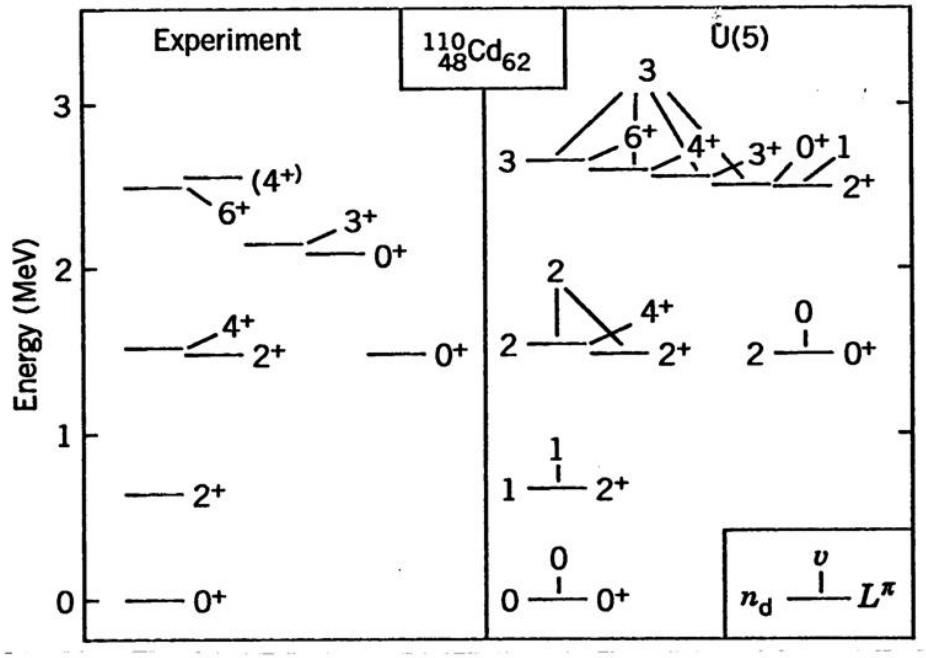
- In general not solvable analytically.
- Three solvable cases with SO(3) symmetry:

$\mathrm{U}(6) \supset \mathrm{U}(5) \supset \mathrm{SO}(5) \supset \mathrm{SO}(3)$

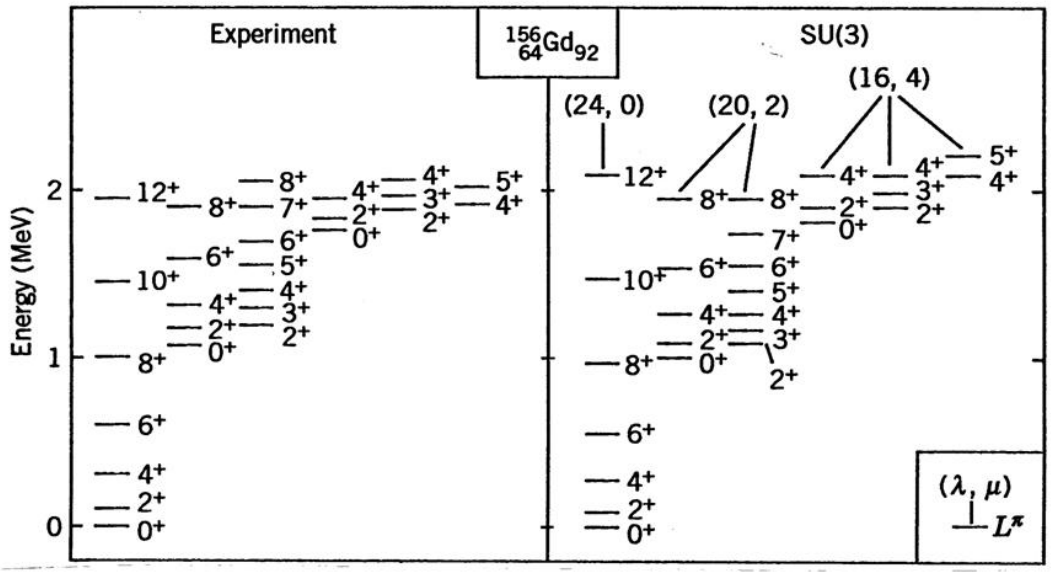
$\mathrm{U}(6) \supset \mathrm{SU}(3) \supset \mathrm{SO}(3)$

$\mathrm{U}(6) \supset \mathrm{SO}(6) \supset \mathrm{SO}(5) \supset \mathrm{SO}(3)$

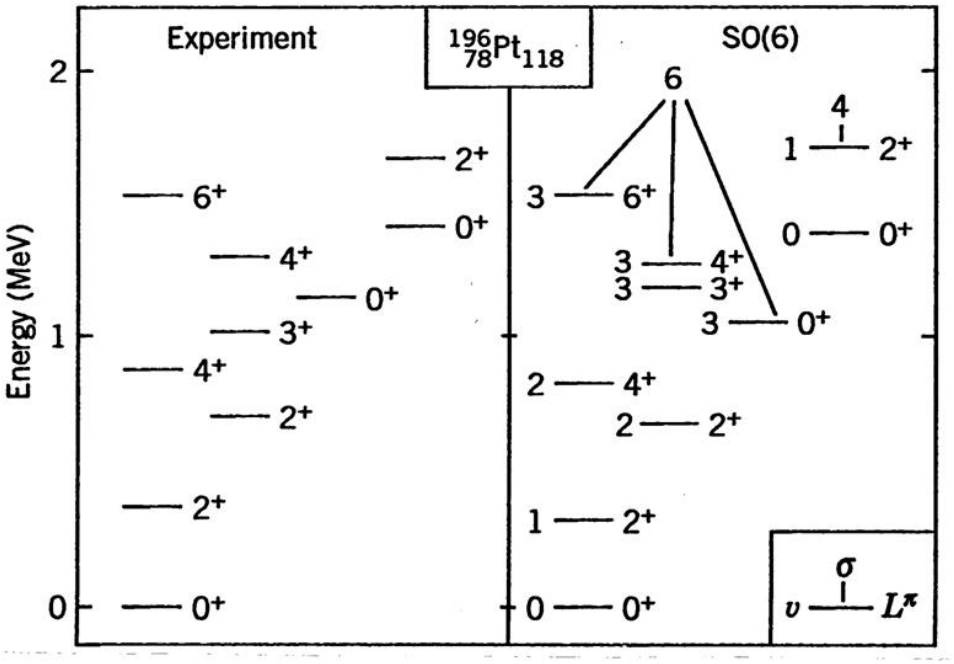
U(5) vibrational limit: $^{110}Cd_{62}$



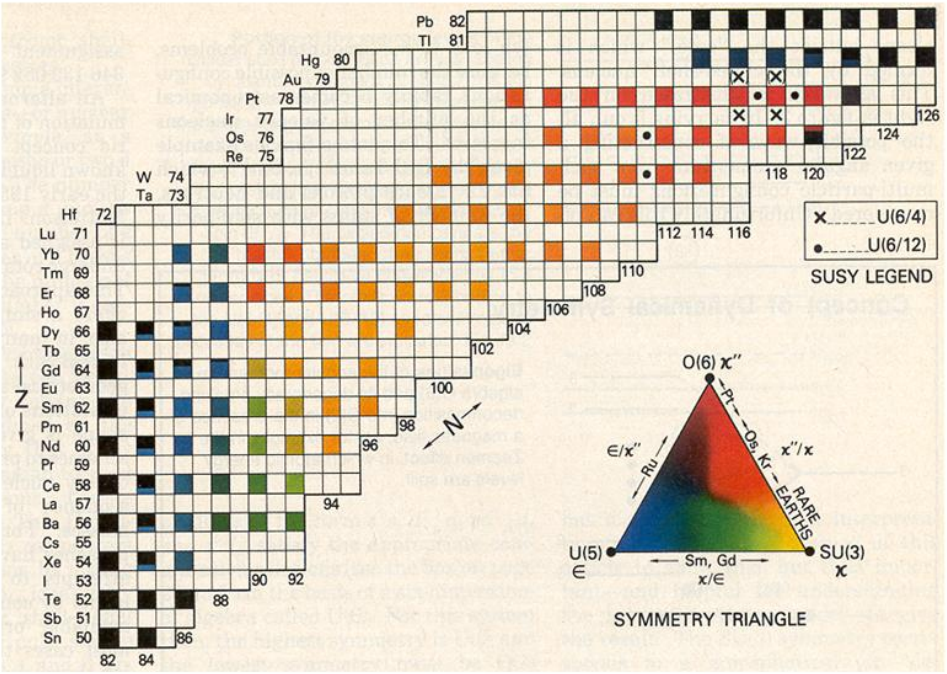
SU(3) rotational limit: $^{156}Gd_{92}$



SO(6) γ-unstable limit: $^{196}Pt_{118}$



Applications of IBM

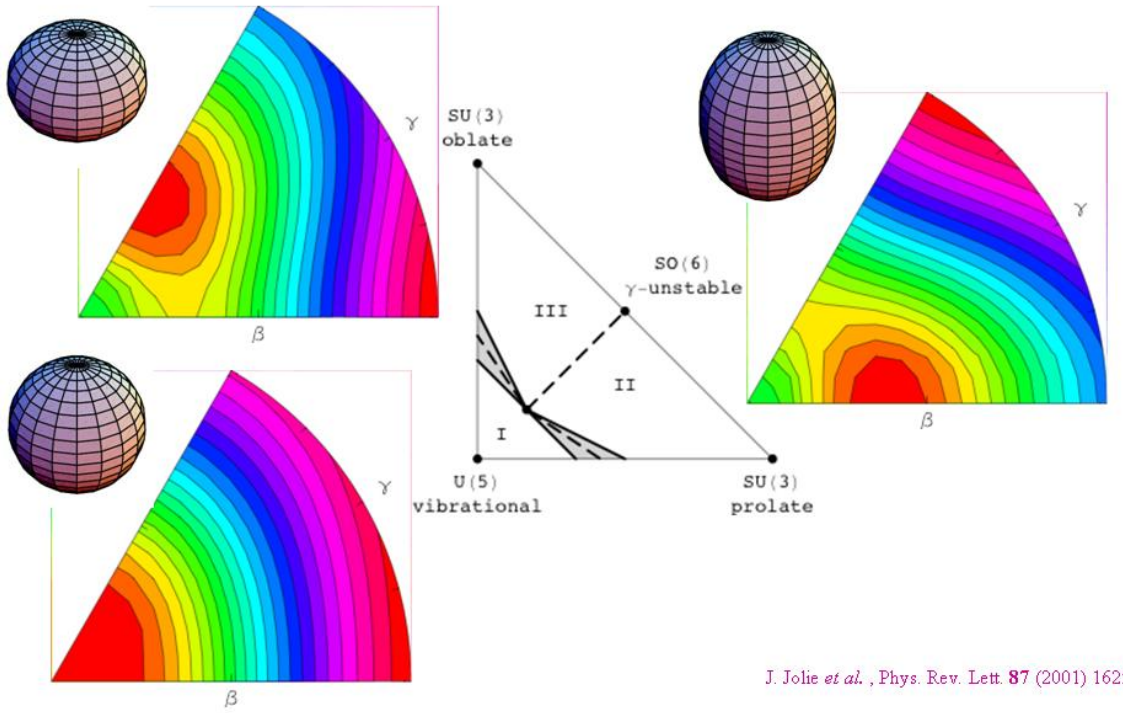


Classical limit of IBM

- For large boson number N, the minimum of $V(\beta,\gamma)=\langle N;\beta\gamma \mid H \mid N;\beta\gamma\rangle$ approaches the exact ground-state energy:

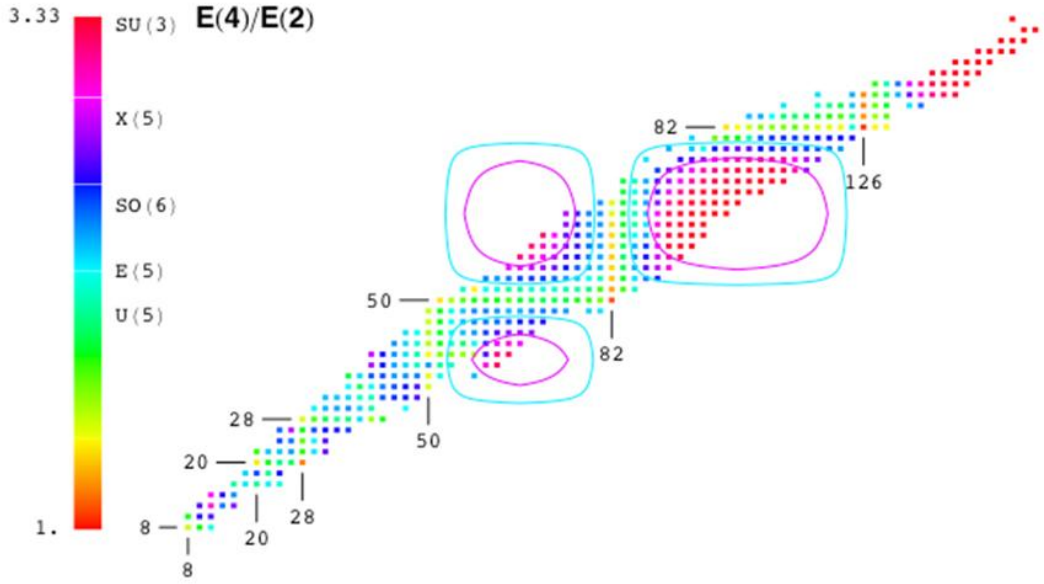
$$V(\beta,\gamma)\propto\begin{cases}\text{U(5)}: & \dfrac{\beta^2}{1+\beta^2}\\ \text{SU(3)}: & \dfrac{\beta^4-4\sqrt{2}\beta^3\cos 3\gamma+8\beta^2}{8\left(1+\beta^2\right)^2}\\ \text{SO(6)}: & \left(\dfrac{1-\beta^2}{1+\beta^2}\right)^2\end{cases}$$

Phase diagram of IBM



J. Jolie *et al.* , Phys. Rev. Lett. **87** (2001) 162501.

Ratio R_{42}

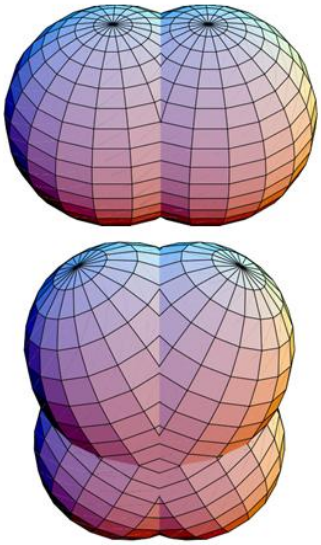


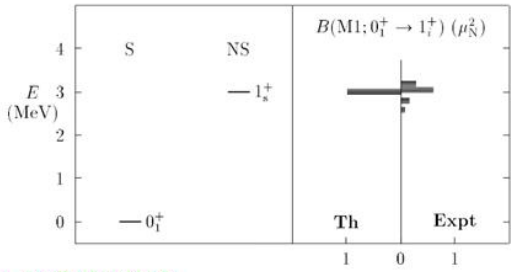
Extensions of IBM

- Neutron and proton degrees of freedom (IBM-2):
  - F-spin multiplets (N_ν+N_π=constant)
  - Scissors excitations
- Fermion degrees of freedom (IBFM):
  - Odd-mass nuclei
  - Supersymmetry (doublets and quartets)
- Other boson degrees of freedom:
  - Isospin T = 0 and T = 1 pairs (IBM-3 and IBM-4)
  - Higher multipole (g,…) pairs

Scissors mode

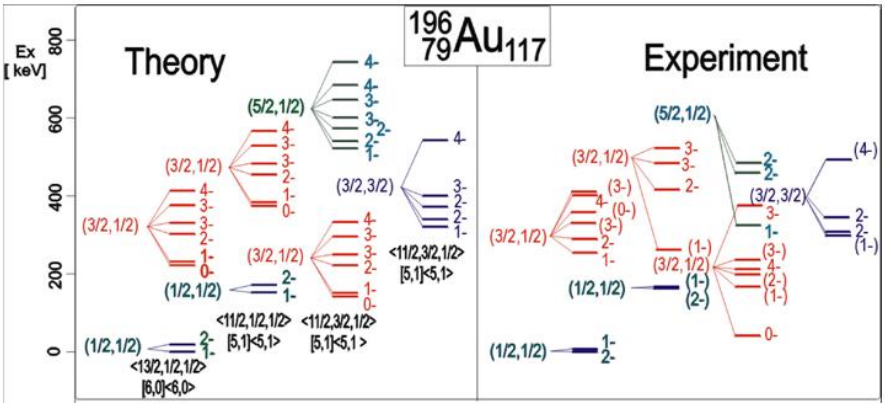
- Collective displacement modes between neutrons and protons:
  - Linear displacement (giant dipole resonance): R_ν-$R_\pi \Rightarrow$ E1 excitation.
  - Angular displacement (scissors resonance): L_ν-$L_\pi \Rightarrow$ M1 excitation.





Supersymmetry

- A simultaneous description of even- and odd-mass nuclei (doublets) or of even-even, even-odd, odd-even and odd-odd nuclei (quartets).
- Example of ^{194}Pt, ^{195}Pt, ^{195}Au and ^{196}Au:



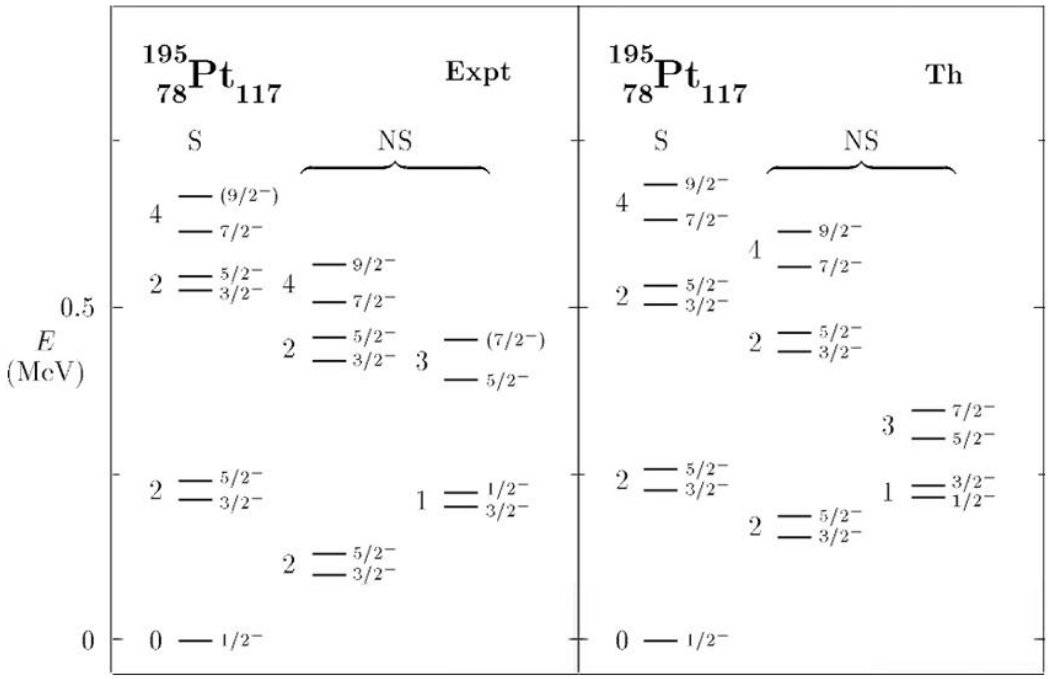
Bosons + fermions

- Odd-mass nuclei are fermions.
- Describe an odd-mass nucleus as N bosons + 1 fermion mutually interacting. Hamiltonian:

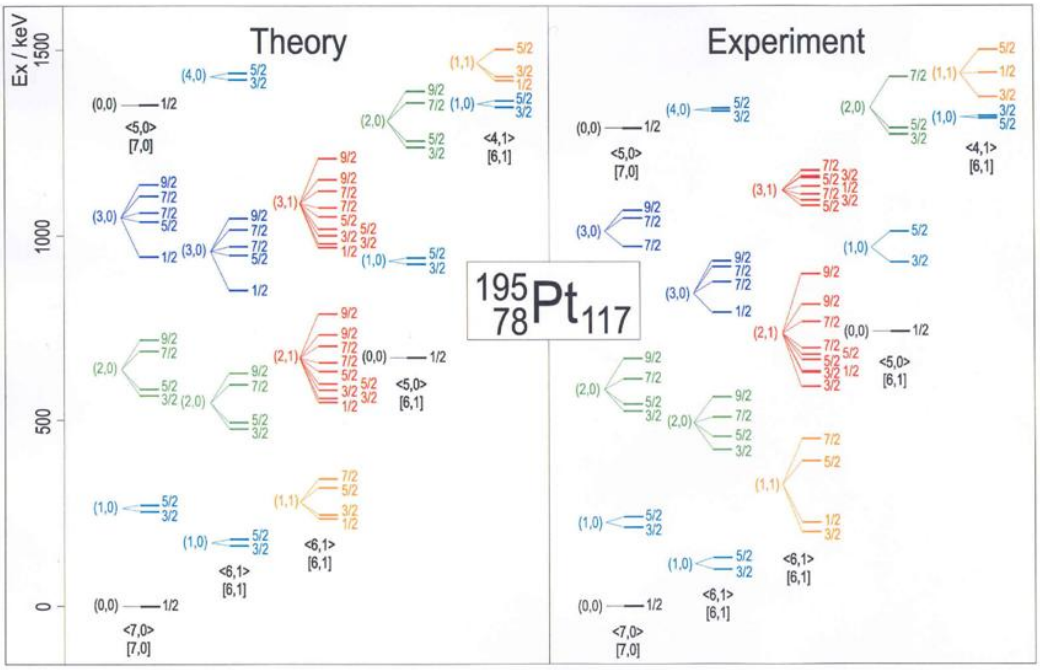
$$\hat{H}_{\mathrm{IBFM}} = \hat{H}_{\mathrm{IBM}} + \sum_{j=1}^{\Omega} \bar{\varepsilon}_j \hat{a}_j^+ \hat{a}_j + \sum_{i_1 i_2 = 1}^{6} \sum_{j_1 j_2 = 1}^{\Omega} \bar{\upsilon}_{i_1 j_1 i_2 j_2} \hat{b}_{i_1}^+ \hat{a}_{j_1}^+ \hat{b}_{i_2} \hat{a}_{j_2}$$

- Algebra: $\mathrm{U}(6) \oplus \mathrm{U}(\Omega) = \left\{ \begin{matrix} \hat{b}_{i_1}^+ \hat{b}_{i_2} & \\ & \hat{a}_{j_1}^+ \hat{a}_{j_2} \end{matrix} \right\}$
- Many-body problem is solved analytically for certain energies ε and interactions υ.

Example: $^{195}\mathrm{Pt}_{117}$



Example: $^{195}Pt_{117}$ (new data)



Nuclear supersymmetry

- Up to now: separate description of even-even and odd-mass nuclei with the algebra

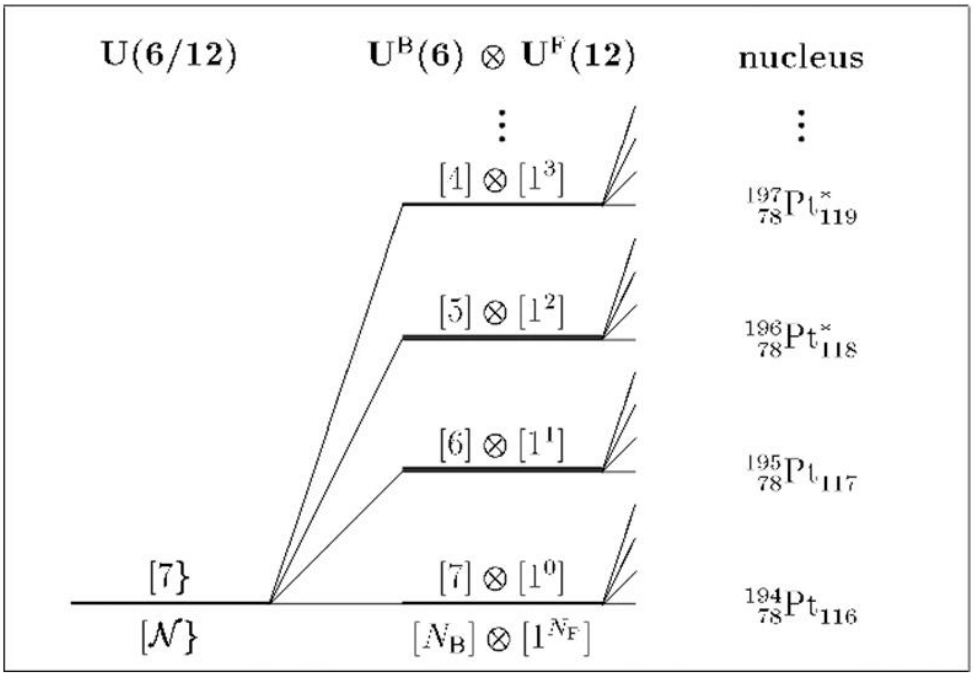
$$U(6) \oplus U(\Omega) = \left\{ \begin{matrix} \hat{b}_{i_1}^{+} \hat{b}_{i_2} & \\ & \hat{a}_{j_1}^{+} \hat{a}_{j_2} \end{matrix} \right\}$$

- Simultaneous description of even-even and odd-mass nuclei with the superalgebra

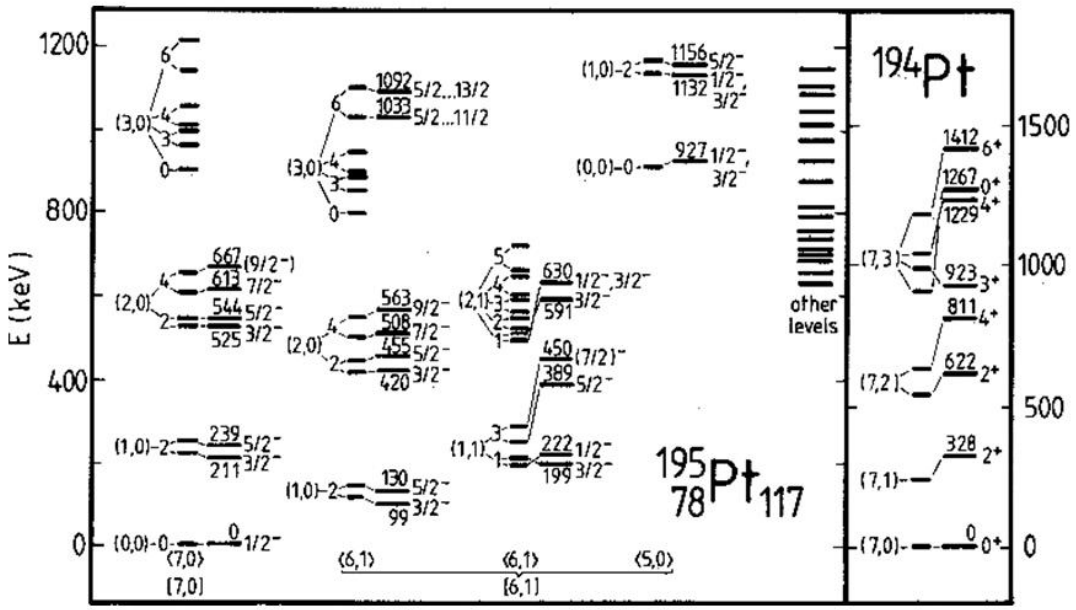
$$U(6/\Omega) = \left\{ \begin{matrix} \hat{b}_{i_1}^{+} \hat{b}_{i_2} & \hat{b}_{i_1}^{+} \hat{a}_{j_2} \\ \hat{a}_{j_1}^{+} \hat{b}_{i_2} & \hat{a}_{j_1}^{+} \hat{a}_{j_2} \end{matrix} \right\}$$

NSDD Workshop, Trieste, April-May 2008

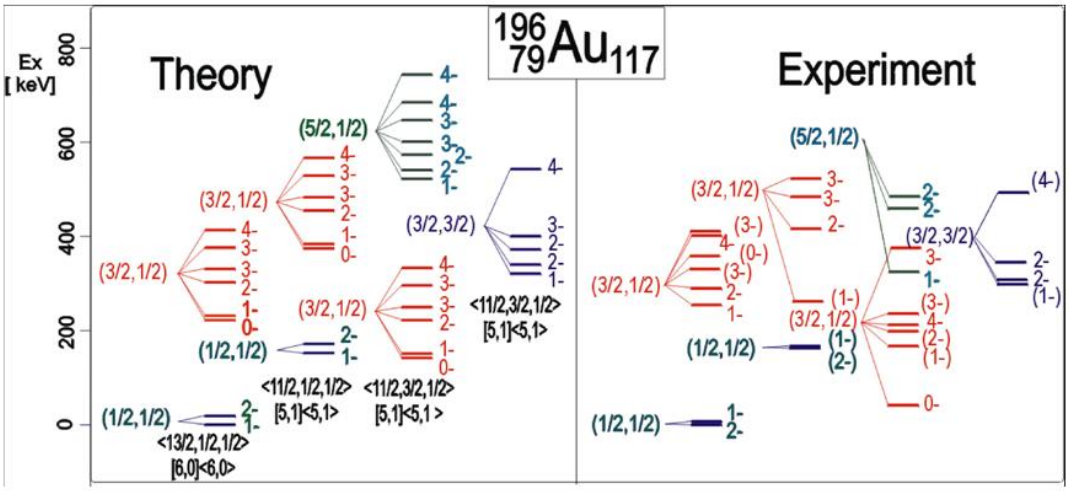
U(6/12) supermultiplet



Example: $^{194}Pt_{116}$ and $^{195}Pt_{117}$



Example: $^{196}Au_{117}$



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Nuclear Theory:
Structure of the Odd-Even Nuclei in the Interacting Boson Model

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Fermion degrees of freedom in the interacting boson model

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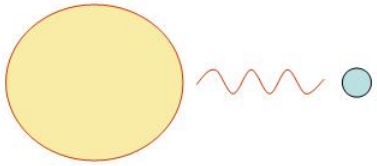
Zagreb
Croatia

1. Structure of odd-even nuclei in the interacting boson-fermion model
2. High spin states in the interacting boson and interacting boson-fermion model
3. Structure of odd-odd nuclei in the interacting boson-fermion-fermion model
4. β decay in the interacting boson-fermion model

1.

Structure of odd-even nuclei in the interacting boson fermion model



CORE		INTERACTION	FERMION
Spherical Soft Transitional Deformed Laboratory coordinates Intrinsic coordinates	Microscopic Geometrical Phenomenological Algebraic …….. ……..	?	Particle Hole Quasiparticle

IBM CORE

Origin : Microscopic

Symmetries : Algebraic

Applications : Phenomenologic

FERMION

Quasiparticle

INTERACTION

Origin : Microscopic

Symmetries : Algebraic
and supersymmetry in some cases

Applications : Phenomenologic

On the same basis,
applicable for nuclei :

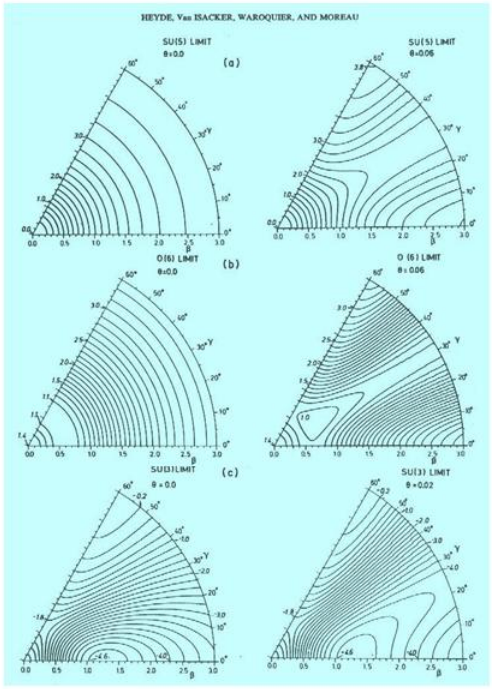
Spherical
Soft
Transitional
Deformed

Coordinates : Laboratory

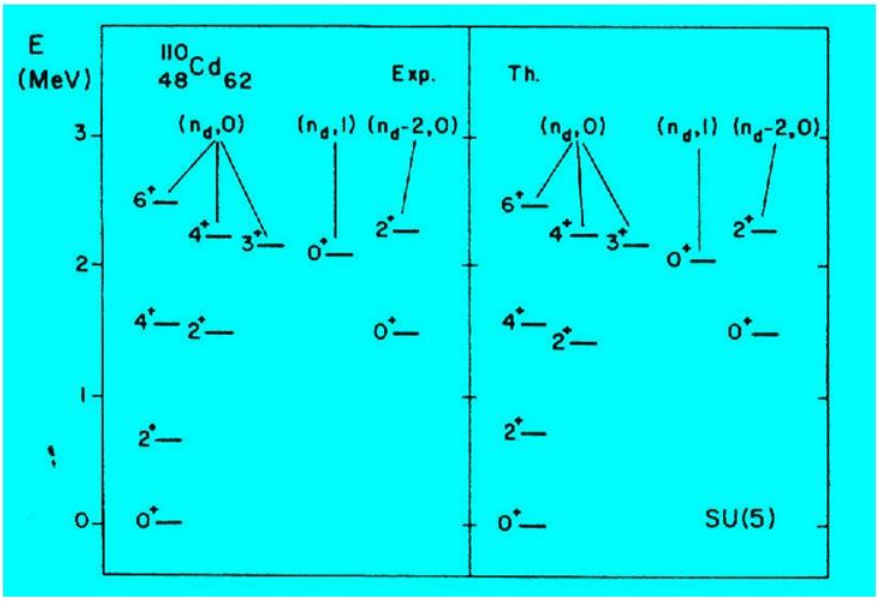
SPHERICAL →

γ – SOFT →

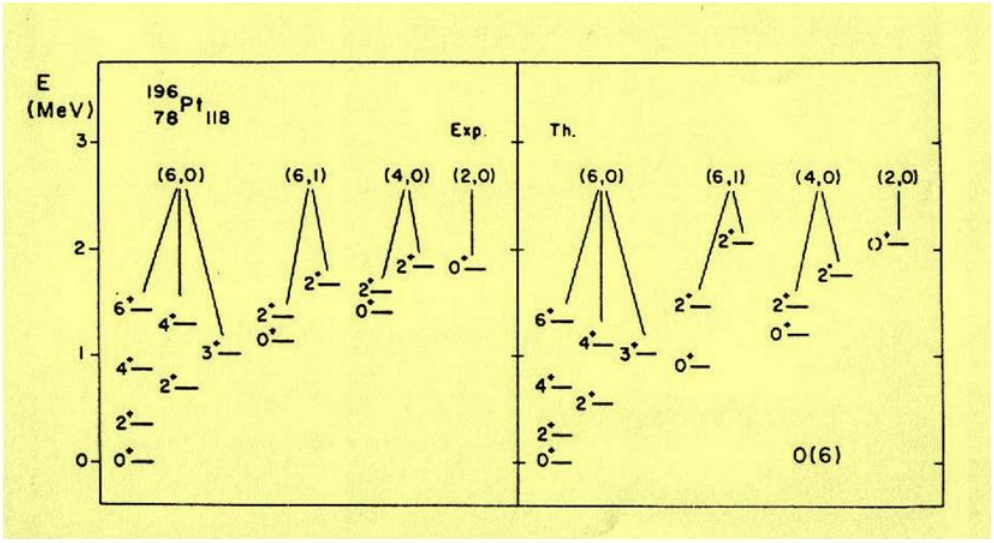
DEFORMED →



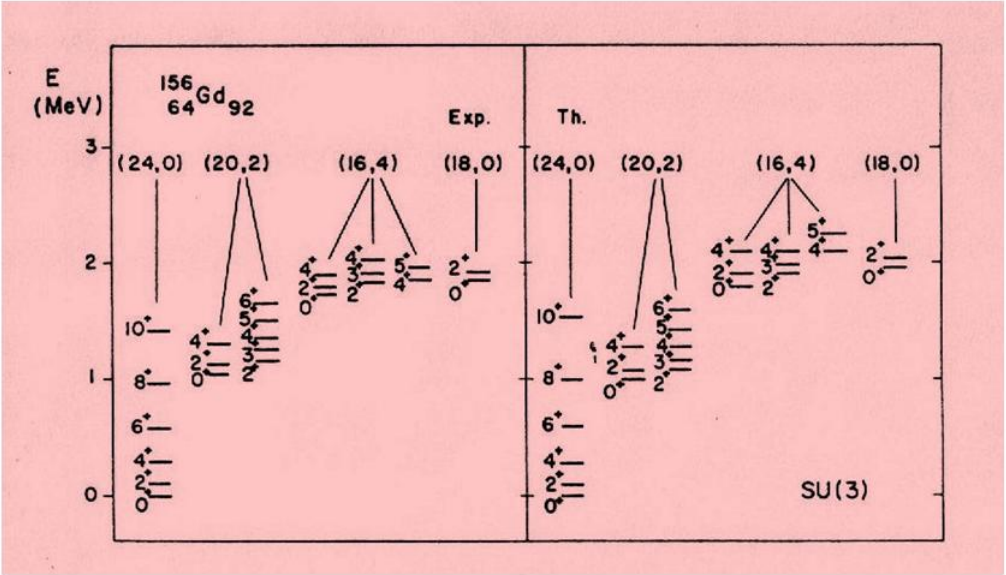
Spherical core



γ - soft core



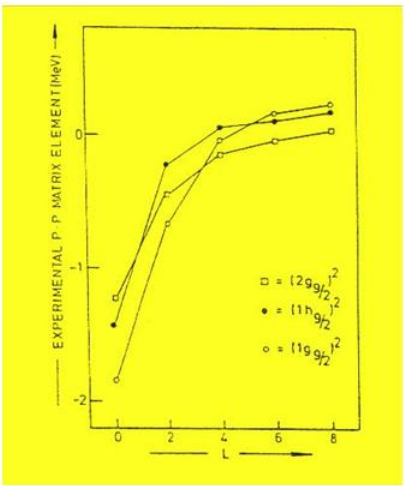
Deformed core



Microscopic origin

Shell model $\longrightarrow$ matrix elements of the effective interaction between identical nucleons are strongly attractive when the two nucleons are in a $J = 0$ state, and remain attractive when the two nucleons are in a $J = 2$ state. They become repulsive for $J \geq 4$.

Nucleons tend to form pairs with angular momentum $J = 0$ or $J = 2$



Generalized seniority scheme: generalization of the seniority scheme to several non-degenerate orbits. The number of active nucleons is counted in respect to the nearest closed shell (valence nucleons), Contributions from orbits outside the valence shell can be neglected sine they lie at too high an energy

A collective $J = 0$ pair is generated by the operator

$$S^\dagger = \sum_j \alpha_j S_j^\dagger$$
$$S_j^\dagger = \frac{1}{2}\sqrt{2j+1}\ (c_j^\dagger \tilde{c}_j)^{(0)}$$

State with generalized seniority $w = 0$ and $n = 2N$ particles

$$|n,\ J = 0,\ w = 0\rangle = (S^\dagger)^N\ |0\rangle$$

An excited 2^+ state is generated by the operator that creates a collective state with $J = 2$ and $w = 2$

$$D^\dagger = \sum_{jj'} \frac{1}{2}\beta_{jj'}\sqrt{1+\delta_{jj'}}\ (c_j^\dagger \tilde{c}_{j'})^{(2)}$$

State with generalized seniority $w = 2$, $J = 2$ and $n = 2N$ particles

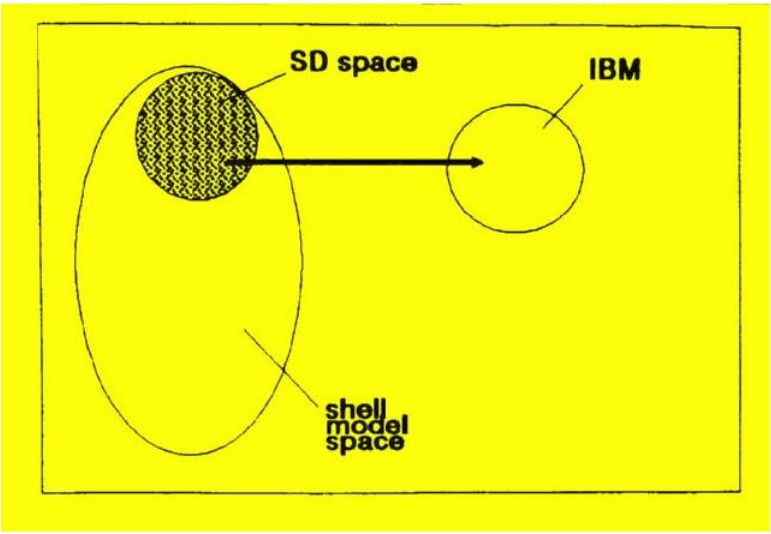
$$|n,\ J = 2,\ w = 2\rangle = D^\dagger (S^\dagger)^{N-1}\ |0\rangle$$

The structure coefficients α_j and $\beta_{jj'}$ can be obtained by diagonalizing the shell model interaction in the space of all $w = 0, 2$ states.

Instead of having to use the full shell model space, it is sufficient to consider the much smaller (S, D) subspace.

- Low-lying collective states can be described very well
- Non collective states can not be described
- Matrix elements of the fermion operators in the (S,D) subspace can be cumbersome
- Space built on S and D fermion pairs is mapped onto a corresponding space built on s and d boson degrees of freedom
- For states containing more than one D fermion pair, we have to map the component of the state which is orthogonal to all states containing fewer D fermion pairs

$$
\begin{aligned}
|S^N,\ L=0\rangle &\longrightarrow |s^N,\ L=0\rangle \\
|D\ S^{N-1},\ L=2\rangle &\longrightarrow |d\ s^{N-1},\ L=2\rangle \\
|D^m\ S^{N-m},\ L\rangle_{\ orth} &\longrightarrow |d^m\ s^{N-m},\ L\rangle
\end{aligned}
$$



- By equating matrix elements in (S, D) and (s, d) spaces, operators in the (s, d) space are obtained.
- Since the S and D fermion pairs are always pairs of like nucleons (two protons or two neutrons), one has proton (s_π, d_π) and neutron (s_ν, d_ν) bosons. The model is called IBM-2.

$$H_B = \epsilon_d \left(\hat{n}_{d_\nu} + \hat{n}_{d_\pi}\right) + \kappa \left(Q_\nu^B \cdot Q_\pi^B\right) + M_{\nu\pi} + V_{\nu\nu} + V_{\pi\pi}$$

$$\begin{aligned} Q_\nu^B &= d_\nu^\dagger s_\nu + s_\nu^\dagger \tilde{d}_\nu + \chi_\nu \left[d_\nu^\dagger \tilde{d}_\nu\right]^{(2)} \\ Q_\pi^B &= d_\pi^\dagger s_\pi + s_\pi^\dagger \tilde{d}_\pi + \chi_\pi \left[d_\pi^\dagger \tilde{d}_\pi\right]^{(2)} \end{aligned}$$

$$\begin{aligned} M_{\nu\pi} &= \frac{1}{2}\xi_2 \left(\left(d_\nu^\dagger s_\pi^\dagger - d_\pi^\dagger s_\nu^\dagger\right) \cdot \left(\tilde{d}_\nu s_\pi - \tilde{d}_\pi s_\nu\right)\right) \\ &\quad - \sum_{K=1,3} \xi_K \left(\left[d_\nu^\dagger d_\pi^\dagger\right]^{(K)} \cdot \left[\tilde{d}_\nu \tilde{d}_\pi\right]^{(K)}\right) \end{aligned}$$

$$V_{\nu\nu} = \frac{1}{2} \sum_{L=0,2,4} c_L^\nu \left(\left[d_\nu^\dagger d_\nu^\dagger\right]^{(L)} \cdot \left[\tilde{d}_\nu \tilde{d}_\nu\right]^{(L)}\right)$$

$$V_{\pi\pi} = \frac{1}{2} \sum_{L=0,2,4} c_L^\pi \left(\left[d_\pi^\dagger d_\pi^\dagger\right]^{(L)} \cdot \left[\tilde{d}_\pi \tilde{d}_\pi\right]^{(L)}\right)$$

- A major part of the interaction between like particles is contained in the boson energies and a smaller part in the $V_{\nu\nu}$ and $V_{\pi\pi}$ terms
- The $Q_\nu^B \cdot Q_\pi^B$ interaction is the boson image of the neutron-proton quadrupole-quadrupole interaction.
- $M_{\nu\pi}$ (Majorana term) shifts up all states that are not totally symmetric in the neutron-proton degree of freedom. This is a consequence of the truncation of the basis to s and d bosons only.

Introducing the concept of F spin, the IBM-1 Hamiltonian can be obtained by projecting out the part that acts only on the maximal F spin subspace (on states that are totally symmetric in the neutron-proton degree of freedom).

$$\begin{aligned} H_B &= \varepsilon\, \hat{N} + \frac{1}{2}\, v_0 \, \left([d^\dagger d^\dagger]_{(0)} [\tilde{s}\tilde{s}]_{(0)} + h.c.\right)_{(0)} \\ &+ \frac{1}{\sqrt{2}}\, v_2 \, \left([d^\dagger d^\dagger]_{(2)} [\tilde{d}\tilde{s}]_{(2)} + h.c.\right)_{(0)} \\ &+ \sum_{L=0,2,4} \frac{1}{2}\, C_L \, \sqrt{2L+1} \, \left([d^\dagger d^\dagger]_{(L)} [\tilde{d}\tilde{d}]_{(L)}\right)_{(0)} \end{aligned}$$

LIMITS

$$
\begin{array}{lll}
U(6) \supset & U(5) \supset O(5) \supset O(3) \supset O(2) & \textit{vibrational limit} \\
U(6) \supset & SU(3) \supset O(3) \supset O(2) & \textit{rotational limit} \\
U(6) \supset & O(6) \supset O(5) \supset O(3) \supset O(2) & \gamma - \textit{soft limit}
\end{array}
$$

Lie algebra U(6) admits

- Schwinger boson realization in terms of 6 bosons s, d_μ
- Holstein-Primakoff boson realization in terms of 5 bosons b_μ

$$
\begin{aligned}
d^\dagger_{2\mu} &\longleftrightarrow b^\dagger_{2\mu} \\
s^\dagger &\longleftrightarrow \sqrt{N - \sum_\mu b^\dagger_{2\mu} b_{2\mu}}
\end{aligned}
$$

- In the IBFM, an odd-nucleon operator $a^\dagger_j$ is introduced in addition to the s and d boson operators.
- States in the IBFM model space can be related to the shell model basis by using the generalized seniority scheme
- The odd-nucleon operator $a^\dagger_j$ should not be regarded as a nucleon creation operator (in the shell model sense), but as a generalized seniority raising operator

$$
\begin{aligned}
a^\dagger_j |s^N\rangle = |js^N\rangle &\longleftrightarrow |n = 2N+1, J = j, w = 1\rangle \\
(a^\dagger_j d^\dagger)^{(J)} |s^{N-1}\rangle = |(jd)^{(J)} s^{N-1}\rangle &\longleftrightarrow |n = 2N+1, J, w = 3\rangle
\end{aligned}
$$

- Operator $a^\dagger_j$ operating on an N boson state with n_d d -bosons creates a state which corresponds to a shell model state with $n = 2N + 1$ and $w = 2n_d + 1$.
- Shell model single-nucleon operator $c^\dagger_j$
  $c^\dagger_j |w = 2\rangle = \alpha|w = 1\rangle + \beta|w = 3\rangle$
- Odd-nucleon operator $a^\dagger_j$
  $a^\dagger_j |w = 2\rangle = |w = 3\rangle$

A microscopic theory for a system that includes both fermionic and bosonic degrees of freedom is complicated.

The dominant interaction in the coupling of the odd-particle to the bosons is the proton-neutron quadrupole interaction → construction of the IBFM image of the shell model quadrupole operator.

There are several methods for obtaining the IBFM image of the shell model quadrupole operator. One of them is to introduce the pseudo particle operator $\check{c}_j^\dagger$ (Scholten).

Condition:

Matrix elements of $c_j^\dagger$ in the IBFM space are equal to the matrix elements of $c_j^\dagger$ In the shell model space

For $w \leq 1$ (α_j are the coefficients which enter in the definition of the S pair operator):

$$\hat{n} = \sum_j \alpha_j^2 \sum_m c_{jm}^\dagger c_{jm} = \sum_j \alpha_j^2 \hat{n}_j$$

$$\langle S^N | \hat{n} | S^N \rangle = 2N$$

Effective degeneracy

$$\Omega_e = \sum_j \alpha_j^2 \Omega_j$$

Spherical shell model OCCUPATION PROBABILITIES v_j^2 are introduced ($u_j^2 + v_j^2 = 1$).

$$v_j^2 = n_j/(2j+1)$$
$$n_j = \langle S^N | \hat{n}_j | S^N \rangle \approx 2N\alpha_j^2 \frac{\Omega_j}{\Omega_e}$$
$$v_j^2 = \alpha_j^2 N/\Omega_e$$

$$\langle S^N j' \parallel c_j^\dagger \parallel S^N \rangle = -\hat{j} u_j \delta_{jj'} = u_j \langle s^N j' \parallel a_j^\dagger \parallel s^N \rangle$$
$$\langle S^N \parallel c_j^\dagger \parallel S^{N-1} j' \rangle = \hat{j} v_j \delta_{jj'} = v_j \langle s^N \parallel (s^\dagger \tilde{a}_j)^{(j)} \parallel s^{N-1} j' \rangle / \sqrt{N}$$

Similar expressions can be obtained for $\omega \leq 3$. Finally, the IBFM image of the shell model single-nucleon creation operator is

$$\begin{aligned} \check{c}_j^\dagger &= u_j a_j^\dagger - \sum_{j'} \frac{v_j}{\sqrt{N}} \sqrt{\frac{10}{2j+1}} \beta_{j'j} (K_\beta)^{-1} s^\dagger (\tilde{d}\, a_{j'}^\dagger)^{(j)} \\ &+ \frac{v_j}{\sqrt{N}} (s^\dagger \tilde{a}_j)^{(j)} + \sum_{j'} u_j \sqrt{\frac{10}{2j+1}} \beta_{j'j} (K_\beta)^{-1} (d^\dagger \tilde{a}_{j'})^{(j)} \end{aligned}$$

$$K_\beta^2 = \sum_{jj'} \beta_{j'j}^2$$

The coefficients $\beta_{j'j}$ define the microscopic structure of the d-boson.

The matrix elements of the quadrupole operator $\sum_{jj'} Q_{jj'}\ (c_j^\dagger \tilde{c}_{j'})^{(2)}$ in the fermion space are replaced by the matrix elements of the pseudo particle operator $\check{c}_j^\dagger$ acting in the boson space , giving the quadrupole operator expressed in terms of boson and odd-particle operators.

$$\begin{aligned} Q^{(2)} &= Q_B^{(2)} + Q_F^{(2)} \\ Q_B^{(2)} &= [s^\dagger \tilde{d} + d^\dagger \tilde{s}]^{(2)} + \chi [d^\dagger \tilde{d}]^{(2)} \\ Q_F^{(2)} &= \sum_{jj'} Q_{jj'}\ (u_j u_{j'} - v_j v_{j'})\ (a_j^\dagger \tilde{a}_{j'})^{(2)} \\ &- \sqrt{\frac{10}{N}} \sum_{jj'j''} Q_{jj'} (u_j v_{j'} + v_j u_{j'}) \beta_{j''j} [(d^\dagger \tilde{a}_{j''})^{(j)} (\tilde{s} a_{j'}^\dagger)^{(j')}]^{(2)} (\hat{j} K_\beta)^{-1} \end{aligned}$$

The boson-fermion interaction can be generated by the interaction between like particles or by the proton-neutron quadrupole interaction. The structure of the interactions is identical. The product of $Q_B^{(2)}$ and $Q_F^{(2)}$ contributes to the boson-fermion interaction. By mapping the basis from IBM-2 onto IBM-1 and taking terms up to second order in d-boson operators, the standard form of the boson-fermion interaction is obtained.

The IBFM-1 Hamiltonian for an odd-even nucleus

$$H = H_B + H_F + V_{BF}$$

H_B is the boson Hamiltonian of IBM-1 describing a system of N interacting bosons (correlated S and D pairs) that approximate the valence nucleon pairs:

$$\begin{aligned} H_B &= \varepsilon\, \hat{N} + \frac{1}{2}\, v_0 \left([d^\dagger \times d^\dagger]_{(0)} \times [\tilde{s} \times \tilde{s}]_{(0)} + h.c. \right)_{(0)} \\ &+ \frac{1}{\sqrt{2}}\, v_2 \left([d^\dagger \times d^\dagger]_{(2)} \times [\tilde{d} \times \tilde{s}]_{(2)} + h.c. \right)_{(0)} \\ &+ \sum_{L=0,2,4} \frac{1}{2}\, C_L \sqrt{2L+1} \left([d^\dagger \times d^\dagger]_{(L)} \times [\tilde{d} \times \tilde{d}]_{(L)} \right)_{(0)} \end{aligned}$$

$$n_s = N - n_d$$

H_F is the fermion Hamiltonian containing quasiparticle energies of odd protons or neutrons. The quasiparticle energies and occupation probabilities contained in the fermion Hamiltonian and other terms are obtained in a BCS calculation with a standard set of single fermion energies.

$$H_F = \sum_i \varepsilon_i\, a_i^\dagger \tilde{a}_i$$

V_{BF} is the IBFM-1 boson-fermion interaction containing the dynamical, exchange and monopole term.

- The dynamical interaction V_{DYN} represents the direct component of the quadrupole interaction between the odd particle and bosons
- The exchange interaction V_{EXC} arises from the two-particle nature of the bosons, bringing the Pauli exclusion principle into play.
- The monopole interaction V_{MON} can result from a variety of causes, in particular from the blocking of certain degrees of freedom by the odd particle.

$$V_{BF} = V_{DYN} + V_{EXC} + V_{MON}$$

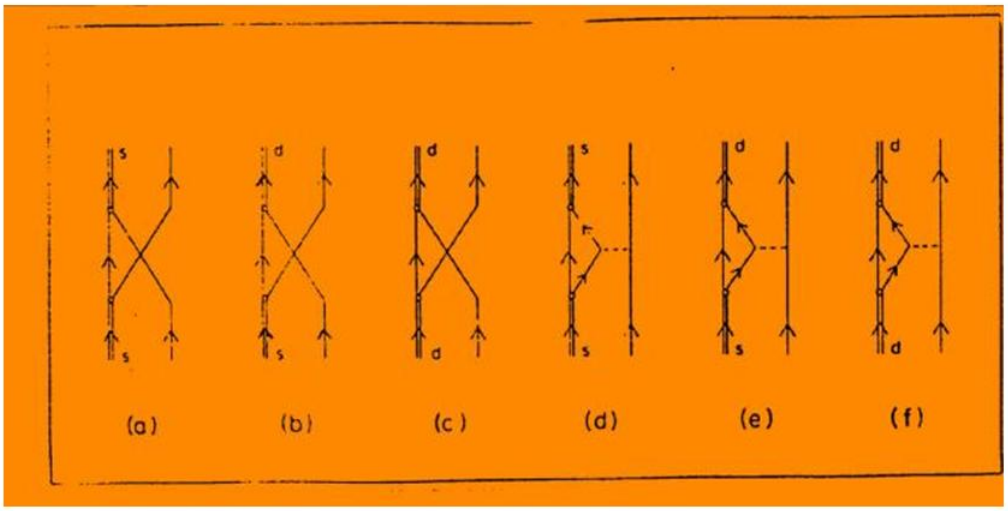
$$V_{DYN} = \Gamma_0 \sum_{j_1 j_2} \sqrt{5}\,(u_{j_1}u_{j_2} - v_{j_1}v_{j_2})\,\langle j_1 \parallel Y_2 \parallel j_2\rangle\,\left([a^\dagger_{j_1} \times \tilde{a}_{j_2}]^{(2)} \times Q_B^{(2)}\right)^{(0)}$$

$Q_B^{(2)}$ is the standard boson quadrupole operator

$$Q_B^{(2)} = [s^\dagger \times \tilde{d} + d^\dagger \times \tilde{s}]^{(2)} + \chi[d^\dagger \times \tilde{d}]^{(2)}$$

$$V_{EXC} = \Lambda_0 \sum_{j_1 j_2 j_3} (-2)\sqrt{\frac{5}{2j_3+1}}\,(u_{j_1}v_{j_3} + v_{j_1}u_{j_3})\;(u_{j_2}v_{j_3} + v_{j_2}u_{j_3})$$
$$\langle j_3 \parallel Y_2 \parallel j_1\rangle\,\langle j_3 \parallel Y_2 \parallel j_2\rangle\;:\left([a^\dagger_{j_1} \times \tilde{d}\,]_{j_3} \times [\tilde{a}_{j_2} \times d^\dagger\,]_{j_3}\right)^{(0)}:$$

$$V_{MON} = A_0 \sum_j \sqrt{5}\,(2j+1)\,\left([a^\dagger_j \times \tilde{a}_j]^{(0)} \times [d^\dagger \times \tilde{d}]^{(0)}\right)^{(0)}$$



(a), (b), (c) exchange terms
(d), (e), (f) direct terms

Structure coefficients:

- The coefficients v_j are related to the structure coefficients of the fermion S-pair state, which is the microscopic equivalent of the s boson. In practice, they are the occupation probabilities of the single-particle orbits, as follows from a spherical BCS calculation.

- The coefficients $\beta_{j_a j_b} = (u_{j_a} v_{j_b} + v_{j_a} u_{j_b}) \langle j_a \parallel Y_2 \parallel j_b \rangle$ are the structure coefficients of the d boson.

The electromagnetic operators have the form:

$$M(E2) = M_B(E2) + M_F(E2)$$

$$M_B(E2) = \frac{3}{4\pi} R_0^2 \, e^{VIB} \left([s^\dagger \times \tilde{d} + d^\dagger \times \tilde{s}]^{(2)} + \chi [d^\dagger \times \tilde{d}]^{(2)} \right)$$

$$R_0^2 = 0.0144 \, A^{\frac{2}{3}} \qquad barn$$

$$M_F(E2) = \frac{3}{5} R_0^2 \, e_F \, Y_2$$

Common notation:

$$\frac{3}{4\pi} R_0^2 \, e^{VIB} = e_B$$

$$\vec{M}(M1) = \vec{M}_B(M1) + \vec{M}_F(M1)$$

$$\vec{M}_B(M1) = \sqrt{\frac{3}{4\pi}}\,\sqrt{10}\,g_R\,[d^\dagger \times \tilde{d}]^{(1)}$$

$$\vec{M}_F(M1) = \sqrt{\frac{3}{4\pi}}\,[\,g_l\,\vec{l} + g_s\,\vec{s} + g_T\,(Y_2 \times \vec{s}\,)_1\,]$$

Common notations:

$$\sqrt{\frac{3}{4\pi}}\,g_R = g_B$$

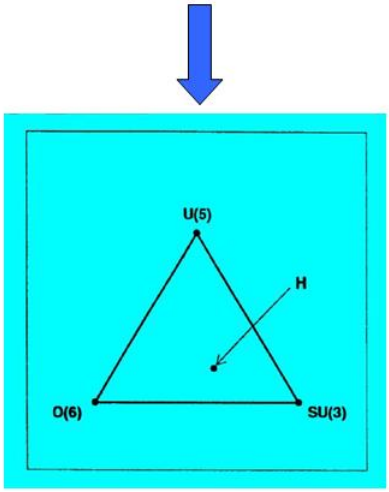
IBFM (and extensions) provide a consistent description of nuclear structure phenomena in:

- spherical nuclei
- deformed nuclei
- transitional nuclei

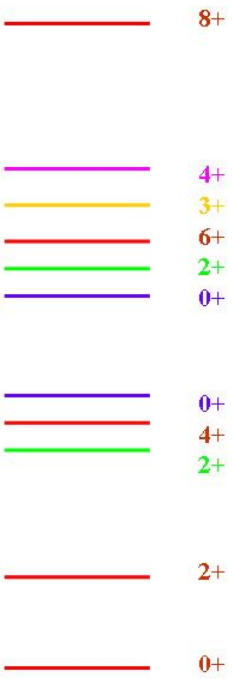
Procedure

1. Boson Hamiltonian

Place the core nucleus in the Casten triangle



Important levels

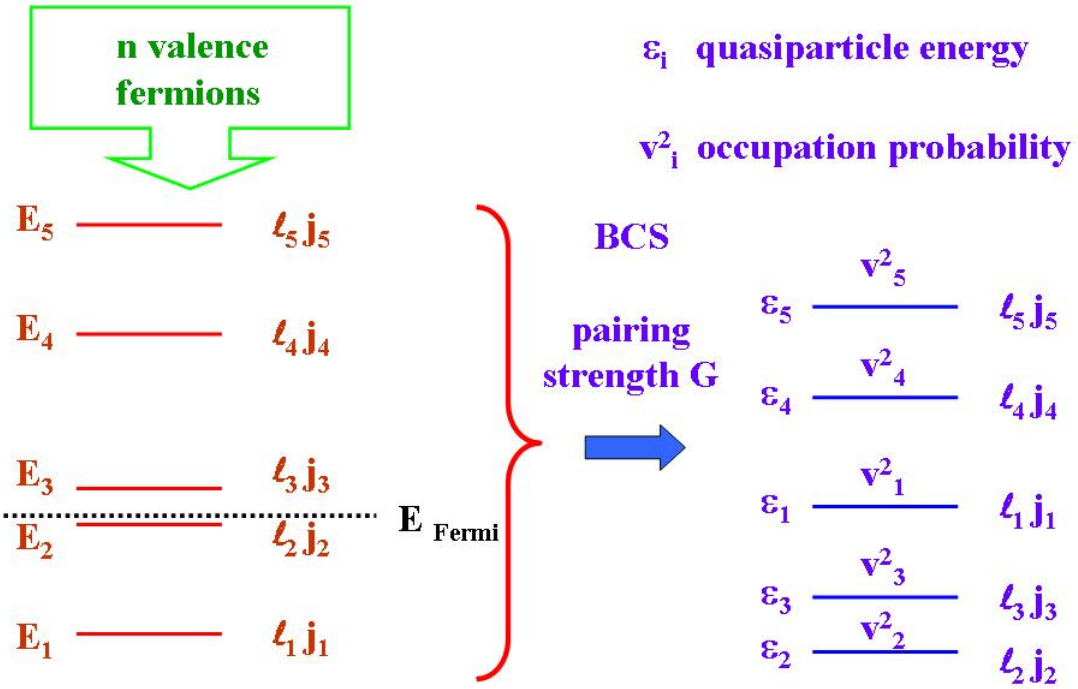


Important data

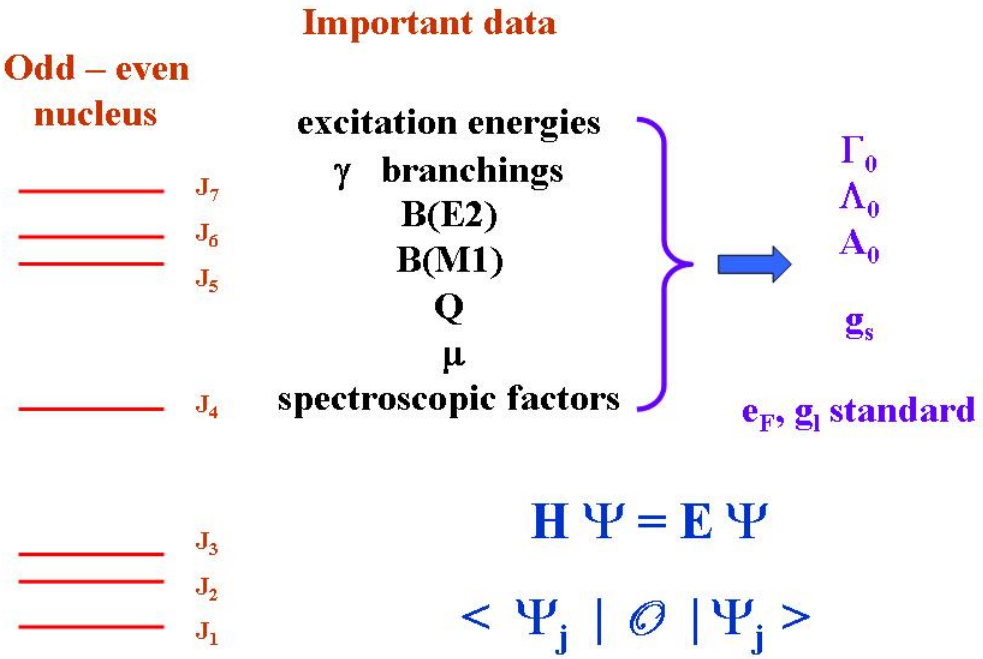
excitation energies
γ branchings
B(E2)
$Q(2^+_1)$
$\mu(2^+_1)$

ε
v_0
v_2 χ e_b
C_0 g_b
C_2
C_4

2. Fermion Hamiltonian



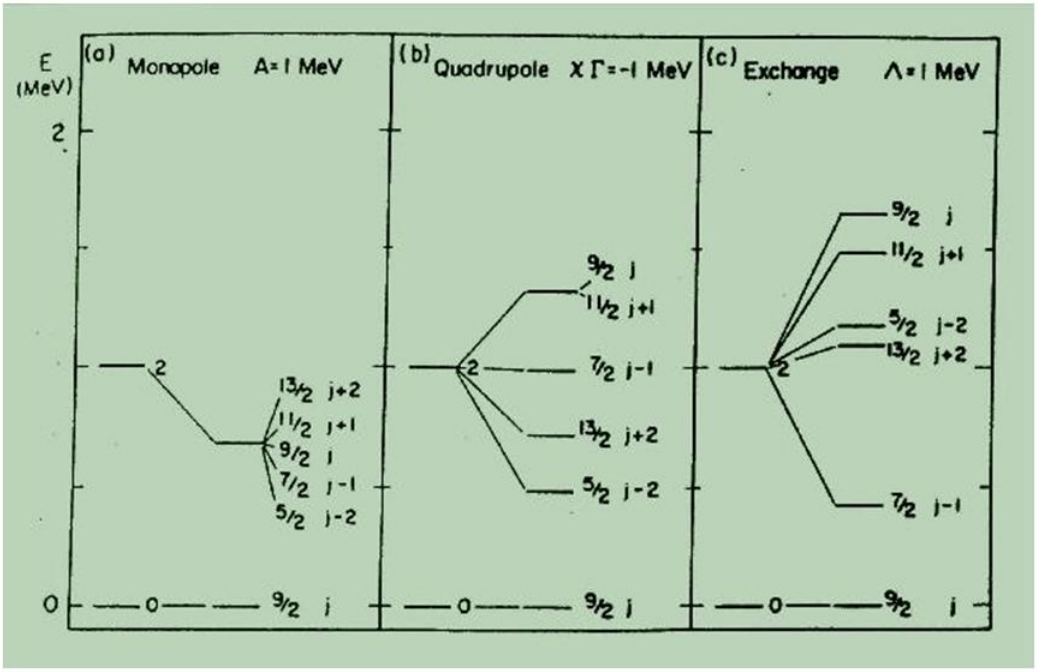
3. Boson – Fermion Hamiltonian



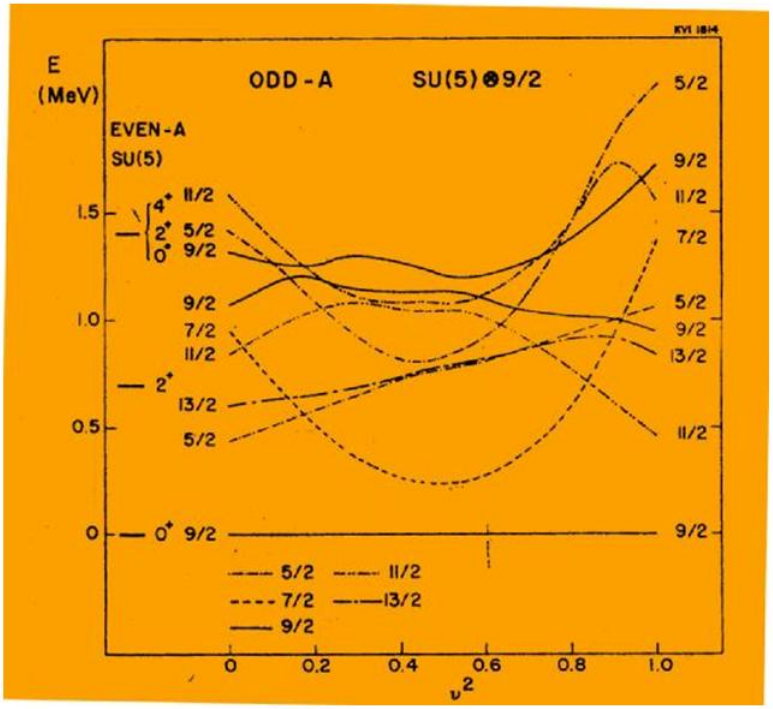
$$H\,\Psi = E\,\Psi$$

$$< \Psi_j \mid \mathcal{O} \mid \Psi_j >$$

Spherical nuclei

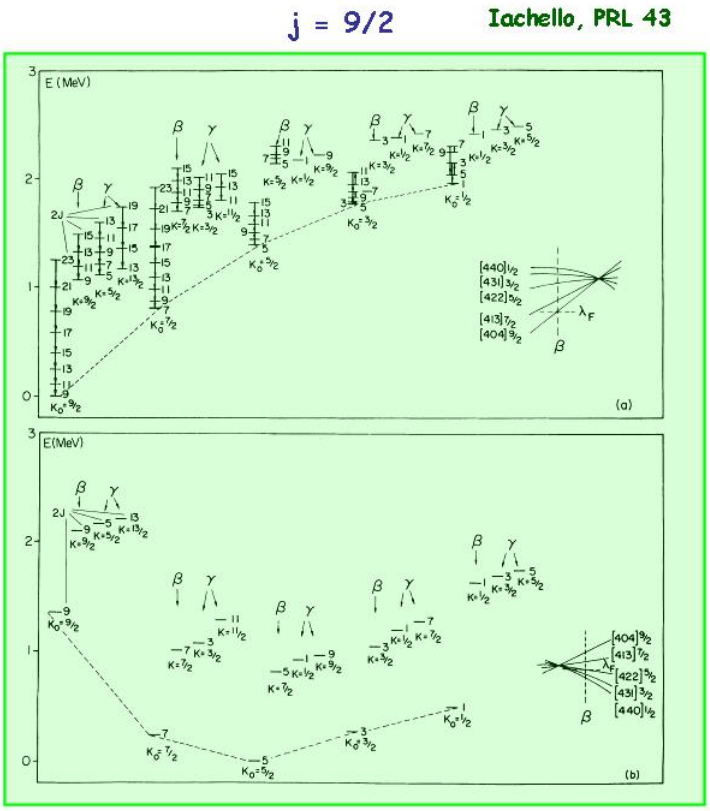


Scholten



Scholten

Deformed nuclei



$\Lambda = 0$

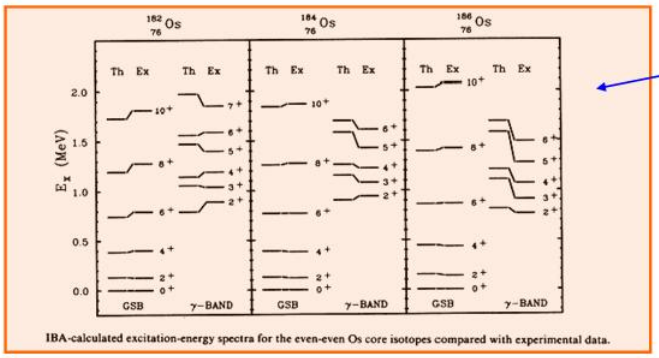
The levels are arranged into bands denoted by the lowest value of the angular momentum K contained in the band.

This quantum number is only approximately equivalent to the quantum number K in the Nilsson model.

The corresponding situation in the Nilsson model is shown in the inset.

$\Lambda \neq 0$

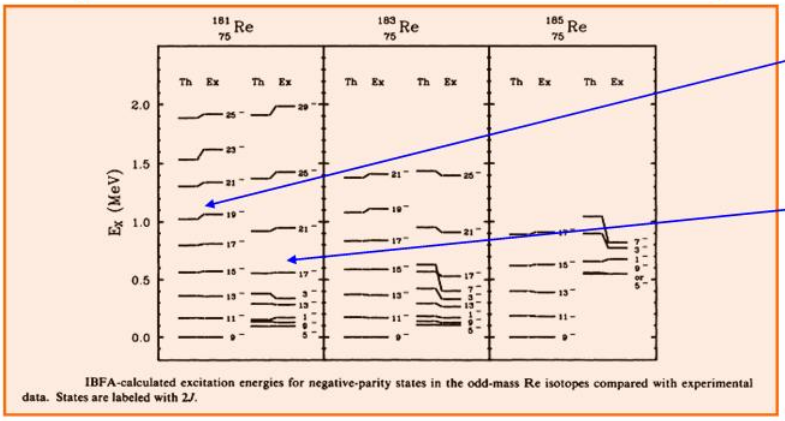
The IBFM generates bands that are analogous to the bands which can be constructed in the Nilsson model. In addition this model generates bands that could be called β and γ bands. While they arise automatically in the IBFM, they must be either placed ad hoc or calculated by use of other methods in the Nilsson model.



IBA-calculated excitation-energy spectra for the even-even Os core isotopes compared with experimental data.

Prolate

Scholten, PRC 37



IBFA-calculated excitation energies for negative-parity states in the odd-mass Re isotopes compared with experimental data. States are labeled with 2*J*.

$K^{\pi} = 9/2^-$

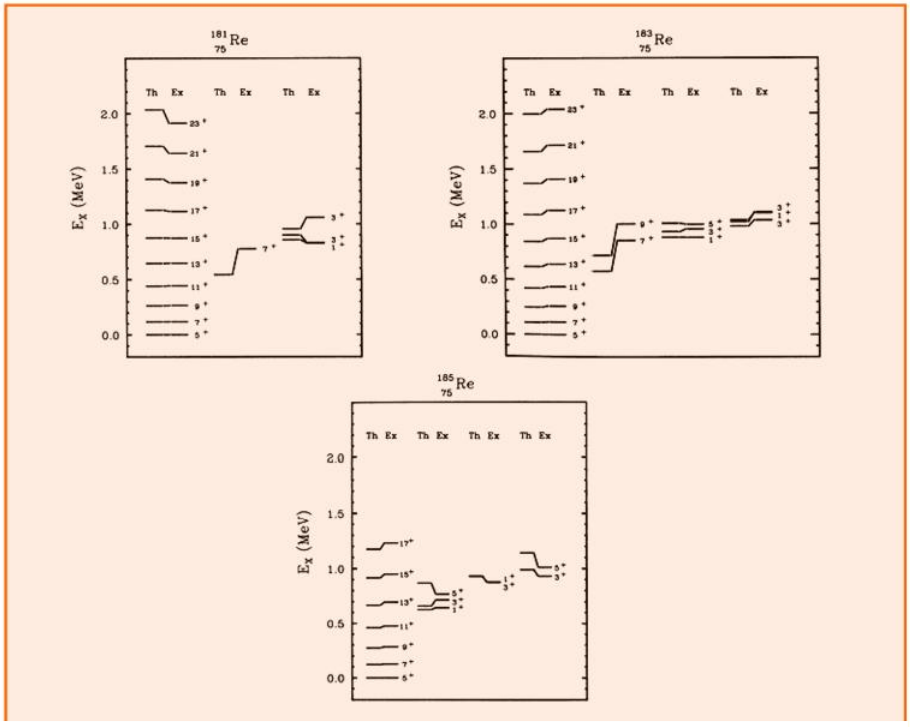
$(\pi\, h_{11/2})$

$v^2 = 0.62$

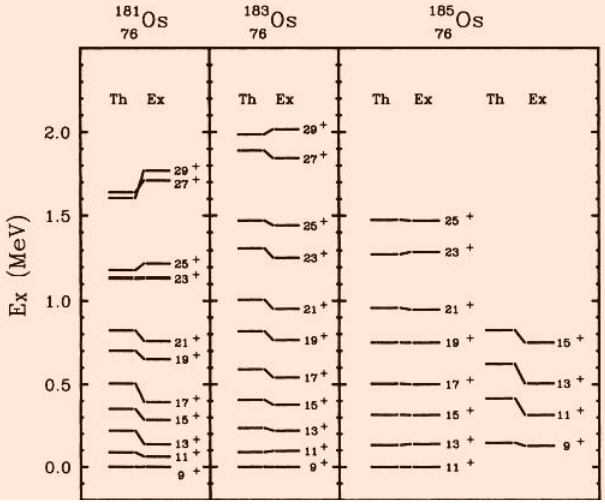
$K^{\pi} = 1/2^-$

$(\pi\, h_{9/2})$

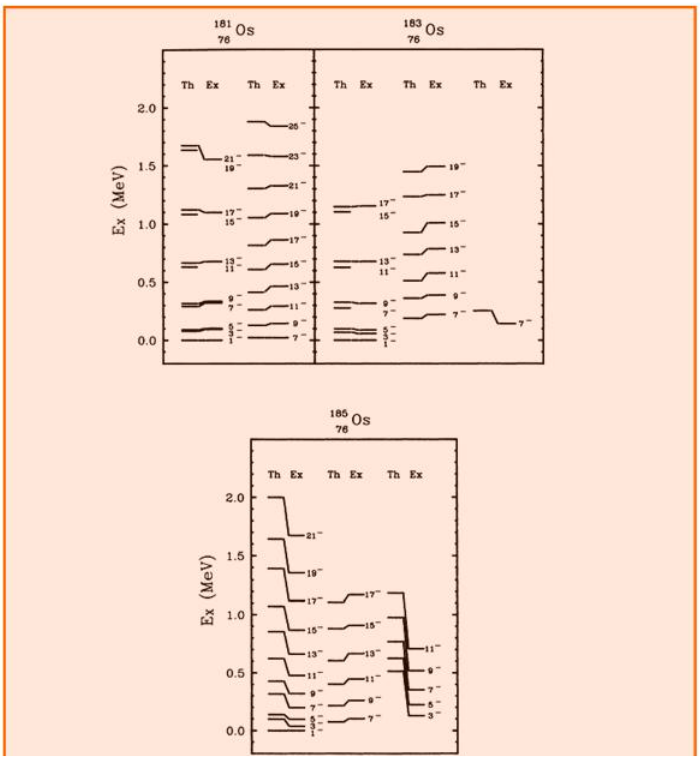
$V^2 = 0.05$



IBFA-calculated excitation energies for positive-parity states in the odd-mass Re isotopes compared with experimental data. States are labelled with 2*J*



IBFA-calculated excitation energies for positive-parity states in the odd-mass Os isotopes compared with experimental data. States are labelled with 2*J*



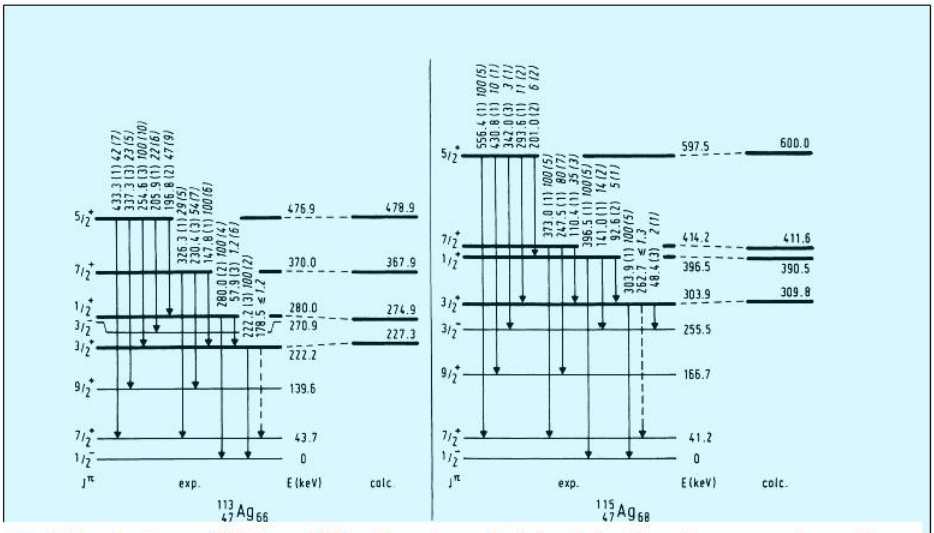
IBFA-calculated excitation energies for negative-parity states in the odd-mass Os isotopes compared with experimental data. States are labelled with 2*J*

The IBFM states for odd-A Re and Os nuclei are obtained in multi-j calculations.

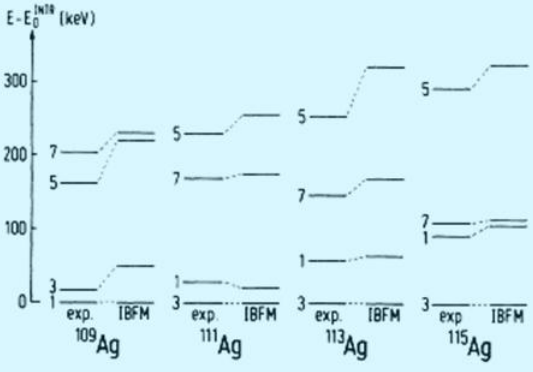
The choice of model space has a strong influence on the model parameters. Even if there is a large separation between shells, the mixing due to the strong core-particle quadrupole interaction does not allow for restricting the model space to a single j shell, for example, levels based on the $g_{9/2}$ particle. Here the $d_{5/2}$ particle from the next major shell has to be included due to the large non-spinflip matrix element $\langle d_{5/2} \parallel Y_2 \parallel g_{9/2} \rangle$. The same situation arises in the case of $h_{11/2}$ ($f_{7/2}$ has to be included in the model space). Restricting the model space requires a renormalization of the interactions. For unique-parity states:

- Strengths of boson-fermion interactions obtained in a single j calculation are effective strengths
- Strengths of boson-fermion interactions obtained in a multi j calculation are real strengths

Intruder deformed bands in odd Ag isotopes



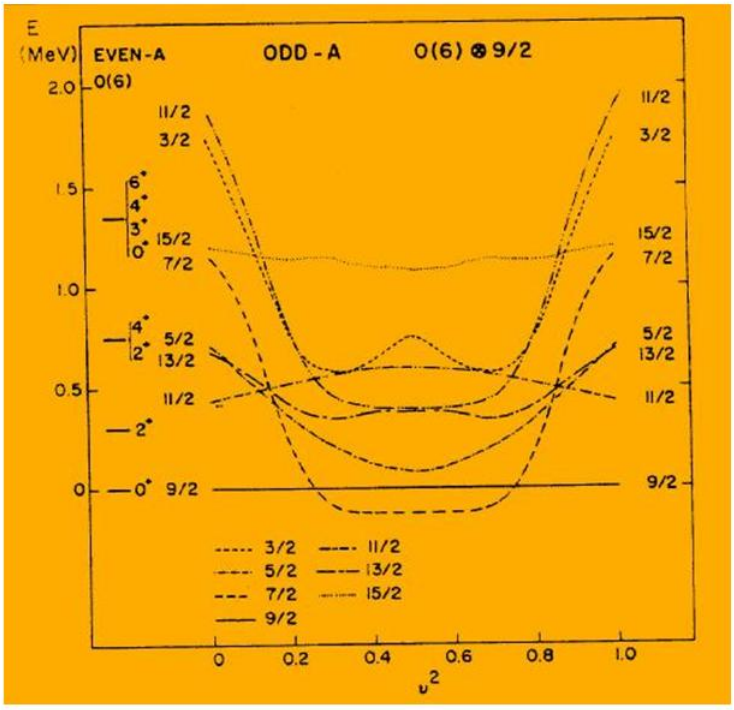
Partial level scheme of ^{113}Ag and ^{115}Ag. Energies and relative intensities of γ rays are given with their uncertainties in parentheses. The energies of the intruder band members are compared to the values calculated with the rotational formula K = ½.



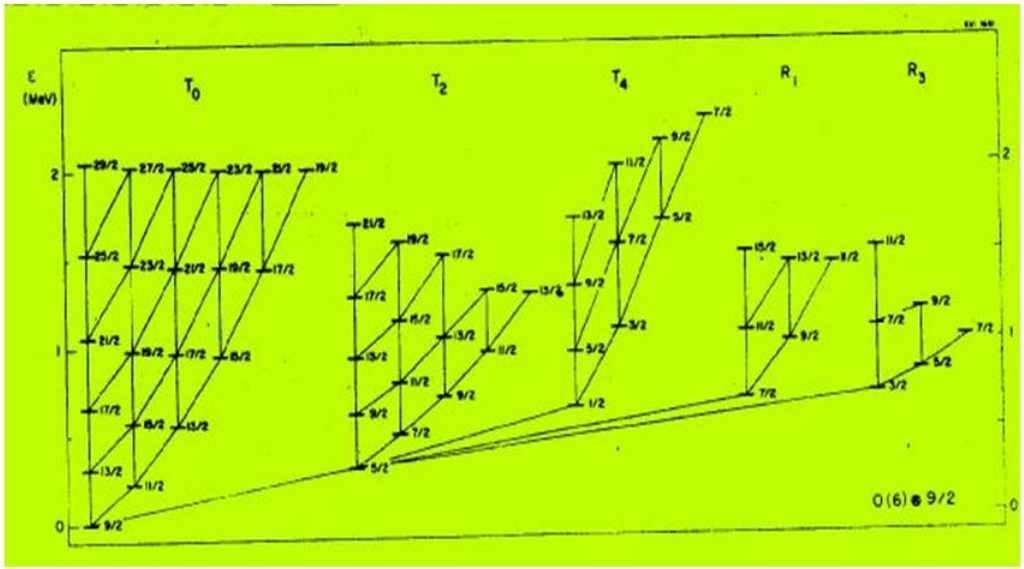
Intruder positive-parity states of ^{109,111,113,115}Ag in comparison to IBFM calculations. Indicated spin values are twice the actual value.

Only the monopole fermion-boson interaction strength is slightly changed from isotope to isotope. All other interaction strengths and occupation probabilities are the same for all isotopes.

O(6) nuclei



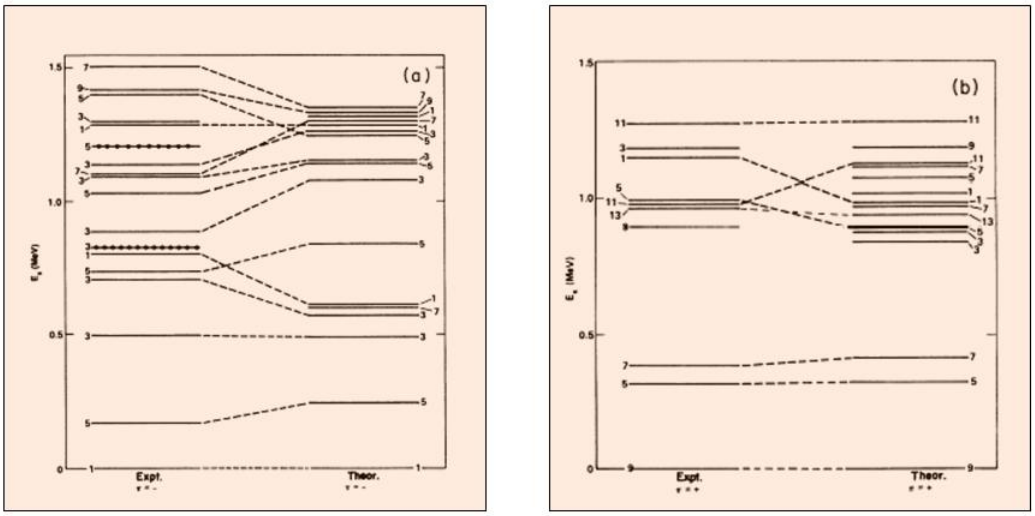
Scholten



Scholten

Transitional nuclei

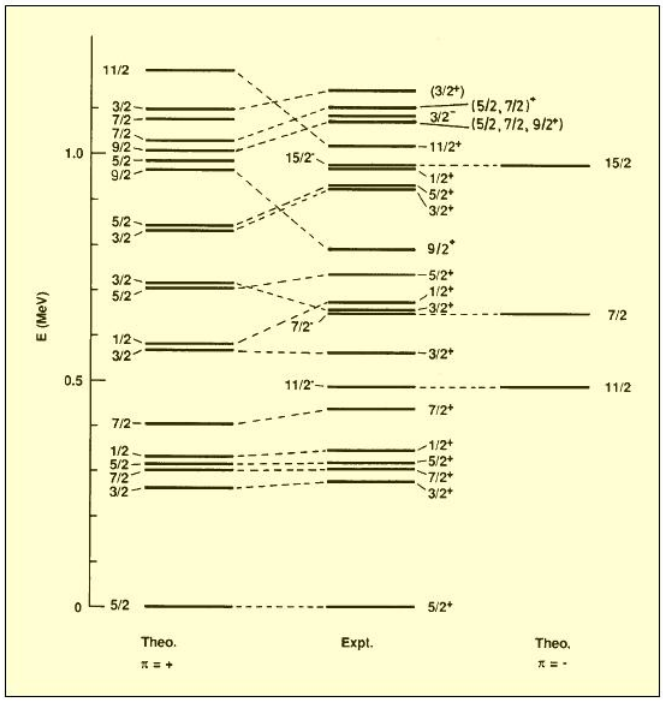
^{71}Ge



Negative parity levels Positive parity levels

Angular momentum x 2

^{105}Pd



From	J of Level To	I_γ Expt.	I_γ Theor.
$3/2_1^+$	$5/2_1^+$	100	100
$7/2_1^+$	$3/2_1^+$		0.0005
	$5/2_1^+$	100	100
$5/2_2^+$	$7/2_1^+$		0.0002
	$3/2_1^+$	0.12	0.7
	$5/2_1^+$	100	100
$1/2_1^+$	$5/2_2^+$		0
	$3/2_1^+$	27	93
	$5/2_1^+$	100	100
$7/2_2^+$	$5/2_2^+$		2
	$7/2_1^+$		0.0006
	$3/2_1^+$		0.03
	$5/2_1^+$	100	100
$3/2_2^+$	$7/2_2^+$		0.0005
	$1/2_1^+$	2.4	1
	$5/2_2^+$		2
	$7/2_1^+$		0.005
	$3/2_1^+$		0.4
	$5/2_1^+$	100	100
$3/2_3^+$	$3/2_2^+$	0.8	0.4
	$7/2_2^+$		0.08

Half-lives

J	Expt. [a]	Theor.
$3/2_1^+$	0.067 ns	0.03 ns
$5/2_2^+$	0.04 ns	0.1 ns
$7/2_2^+$	3.8 ps	7.7 ps
$1/2_1^+$	0.88 ns	0.22 ns
$3/2_2^+$	1.9 ps	6.3 ps
$1/2_2^+$	>2 ps	1.6 ps

BOSON-FERMION SYMMETRIES
SUPERSYMMETRIES

If the Hamiltonian can be expressed in terms of Casimir invariants of the chain of subgroups, the energy spectrum can be obtained ANALYTICALLY. Other observables (B(E2), B(M1), static moments, spectroscopic factors, ...) can be expressed in analytical form, too.

The symmetry group related to IBM-1 is $U(6)$. The six dimensions are formed by the s boson and five components of d_μ boson. Since the number of bosons is invariant, the group is unitary. There are three chains of subgroups:

$$\begin{aligned}
U(6) &\supset U(5) \supset O(5) \supset O(3) \supset O(2) && \textit{vibrational limit}\\
U(6) &\supset SU(3) \supset O(3) \supset O(2) && \textit{rotational limit}\\
U(6) &\supset O(6) \supset O(5) \supset O(3) \supset O(2) && \gamma - \textit{soft limit}
\end{aligned}$$

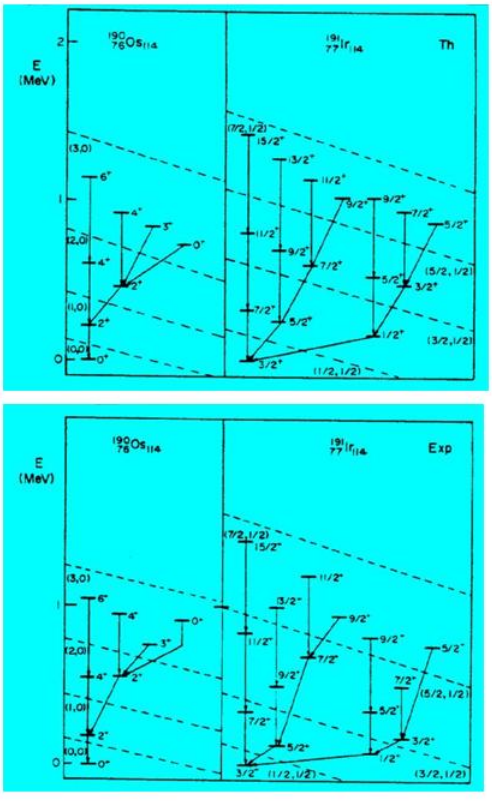
For boson-fermion systems, many group chains have been investigated. Example: A $j = 3/2$ particle coupled to an $O(6)$ core ($j = 3/2$ has four different m-states, and therefore forms a representation of the $U(4)$ group).

$$U^B(6) \otimes U^F(4) \supset O^B(6) \otimes U^F(4) \supset Spin(6) \supset Spin(5) \supset Spin(3) \supset Spin(2)$$

$$E = -\frac{A}{4}[\sigma_1(\sigma_1+4) + \sigma_2(\sigma_2+2) + \sigma_3^2] + \frac{B}{6}[\tau_1(\tau_1+3) + \tau_2(\tau_2+1)] + CJ(J+1) + D\Sigma(\Sigma+4)$$

$U^B(6)$	*quantum numbers*	$[N]$
$U^F(4)$	*quantum numbers*	$\{M\}$
$O^B(6)$	*quantum numbers*	Σ
$Spin(6)$	*quantum numbers*	$(\sigma_1, \sigma_2, \sigma_3)$
$Spin(5)$	*quantum numbers*	(τ_1, τ_2)
$Spin(3)$	*quantum numbers*	J
$Spin(2)$	*quantum numbers*	M_J

$O^B(6) \otimes U^F(4) \supset Spin(6) \longrightarrow$ Parameters describing the boson system are **uniquely related** to the parameters describing the boson-fermion system.



Problems:

- The symmetry approach to boson-fermion systems is more phenomenological in nature
- **Can be applied only in special cases when one or few fermion configurations are coupled to boson cores in one of the symmetry limits of IBM**

Advantages:

- This approach was extended to boson-fermion-fermion systems (odd-odd nuclei)
- **Spectra of neighbouring even-even, odd-even and odd-odd nuclei can** be described with the same set of parameters
- Analytical expressions are available
- Evidence that collective and single-particle degrees of freedom are closely related

Nuclear Theory:
High Spin States in the Interacting Boson and Interacting Boson-Fermion Model

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2.

High spin states in the interacting boson and interacting boson-fermion model

Models based on the Interacting Boson Model (IBM-1) constructed to describe the physics of high-spin states in nuclei ($10\ \hbar \leq J \leq 30\ \hbar$):

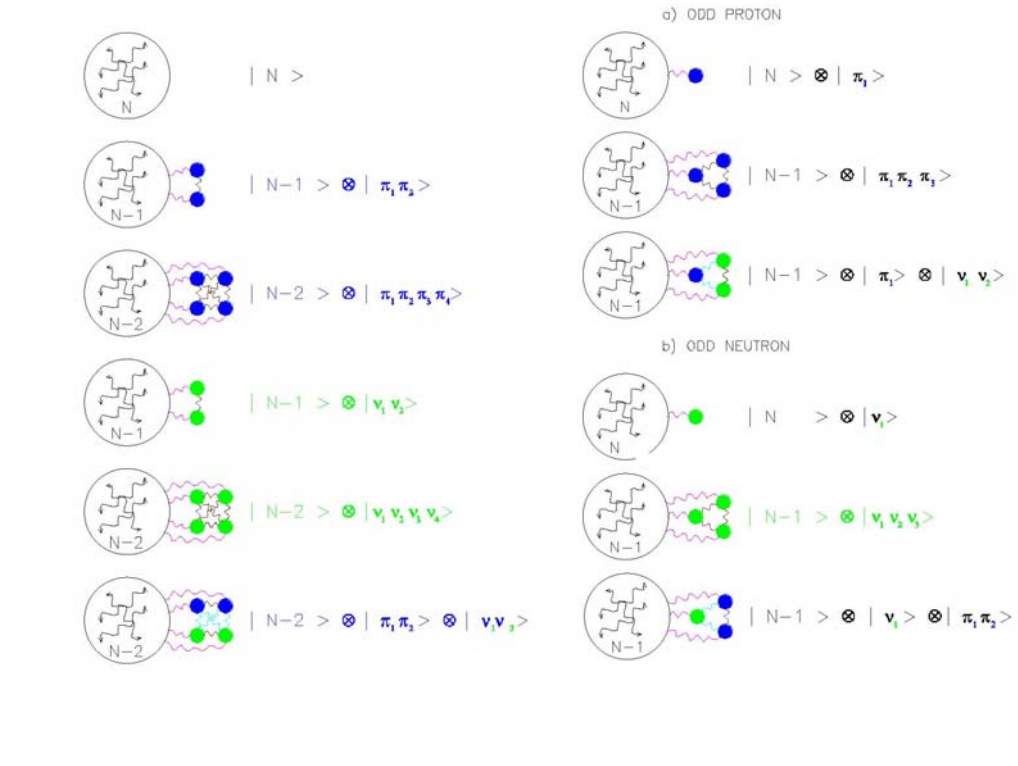
- **Interacting boson plus broken pairs model (IBBPM) for even-even nuclei**
- **Interacting boson fermion plus broken pairs model (IBFBPM) for odd-even nuclei**

One has to go beyond the boson approximation and include selected non-collective fermion degrees of freedom. By including part of the original shell-model fermion space through successive breaking of correlated S and D pairs, IBM can describe the structure of high-spin states.

The models are based on IBM-1; boson space consists of s and d bosons, with no distinction between protons and neutrons. To generate high-spin states, the models allow one or two bosons to be destroyed and form non-collective fermion pairs, represented by two- and four-quasiparticle states which recouple to the boson core. High-spin states are described in terms of broken pairs. High spin states are described in terms of broken pairs.

Advantages of using models based on IBM over more traditional approaches based on the cranking approximations:

- No assumption has to be made about the geometrical picture of high-spin bands
- The bands result from a consistent calculation of the complete excitation **spectrum which also includes the ground state band**
- Polarization effects directly result from the model fermion-boson interactions
- All calculations are performed in the laboratory frame, and therefore the results can be directly compared with experimental data
- This extension of the model is especially relevant for transitional regions, where single-particle excitations and vibrational collectivity are dominant modes, and the traditional cranking approach to high-spin physics is not adequate

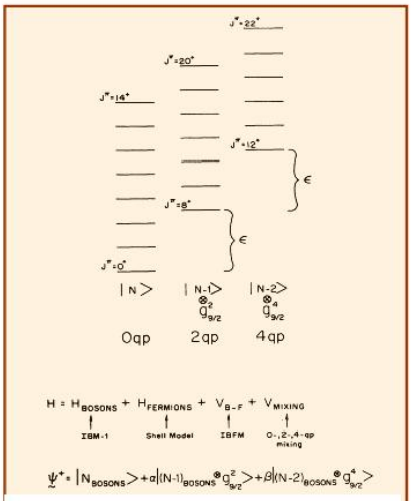


The model space for an even-even nucleus with $2N$ valence nucleons is

$$| \, N \; bosons \; > \oplus | \, (N-1) \; bosons \otimes 1 \; broken \; pair > \oplus | \, (N-2) \; bosons \otimes 2 \; broken \; pairs >$$

This means that the fermion basis can contain two-proton, two-neutron, four-proton, four-neutron and two-proton-two-neutron configurations.

For odd-A nuclei, two-broken pair configurations are not included in the model space. They would generate five-quasiparticle configurations resulting in exhaustive numerical calculations. The IBFBPM can describe one- and three-fermion structures. The two fermions in a broken pair can be of the same type as the unpaired fermion, resulting in a space with three identical fermions. If the fermions in the broken pair are different from the unpaired fermion, **the basis of the fermion contains two protons and one neutron or vice versa**



Schematic picture of our theoretical model and Hamiltonian.

The interacting boson plus broken pairs model (IBBPM) Hamiltonian for an even-even nucleus:

$$H \;\; = \;\; H_B + H_{\nu F} + H_{\pi F} + V_{\nu BF} + V_{\pi BF} + V_{\nu}^{mix} + V_{\pi}^{mix} + V_{\nu\pi}$$

The label π stands for protons and ν for neutrons. If broken pairs contain both protons and neutrons, the full model Hamiltonian is used. Otherwise, when broken pairs contain only protons ($\alpha = \pi$) or neutrons ($\alpha = \nu$), the model Hamiltonian is reduced to:

$$H \;\; = \;\; H_B + H_{\alpha F} + V_{\alpha BF} + V_{\alpha}^{mix}$$

The description of high spin states in odd-even nuclei employs the interacting boson fermion plus broken pairs model (IBFBPM).

- When the two fermions in a broken pair are of the same type as the unpaired fermion, the reduced Hamiltonian is used, where α **defines the** type of fermion (proton or neutron).
- If the fermions in the broken pair are different from the unpaired fermion, the full Hamiltonian is used, without the pair breaking interaction of the unpaired fermion and with the fermion Hamiltonian of the unpaired fermion containing only single-fermion energies.

H_B is the boson Hamiltonian of IBM-1 describing a system of N interacting bosons (correlated S and D pairs) that approximate the valence nucleon pairs:

$$\begin{aligned} H_B &= \varepsilon\, \hat{N} + \frac{1}{2} v_0 \left([d^\dagger \times d^\dagger]_{(0)} \times [\tilde{s} \times \tilde{s}]_{(0)} + h.c. \right)_{(0)} \\ &+ \frac{1}{\sqrt{2}} v_2 \left([d^\dagger \times d^\dagger]_{(2)} \times [\tilde{d} \times \tilde{s}]_{(2)} + h.c. \right)_{(0)} \\ &+ \sum_{L=0,2,4} \frac{1}{2} C_L \sqrt{2L+1} \left([d^\dagger \times d^\dagger]_{(L)} \times [\tilde{d} \times \tilde{d}]_{(L)} \right)_{(0)} \end{aligned}$$

$$n_s = N - n_d$$

$H_{\alpha F}$ is the fermion Hamiltonian which contains single-fermion (quasiparticle) energies and fermion-fermion interactions. The quasiparticle energies and occupation probabilities contained in the fermion Hamiltonian and other terms, are obtained in a BCS calculation with some standard set of single fermion energies.

$$H_{\alpha F} = \sum_i \varepsilon_{\alpha_i} a^\dagger_{\alpha_i} \tilde{a}_{\alpha_i} + \frac{1}{4} \sum_{abcd} \sum_{JM} V^J_{\alpha abcd} A^\dagger_{JM}(\alpha_a \alpha_b) A_{JM}(\alpha_c \alpha_d)$$

$$A^\dagger_{JM}(\alpha_a \alpha_b) = \frac{1}{\sqrt{1+\delta_{ab}}} [a^\dagger_{\alpha_a} a^\dagger_{\alpha_b}]^M_J$$

$$V^J_{\alpha abcd} = (u_{\alpha_a} u_{\alpha_b} u_{\alpha_c} u_{\alpha_d} + v_{\alpha_a} v_{\alpha_b} v_{\alpha_c} v_{\alpha_d})\, G(\alpha_a \alpha_b \alpha_c \alpha_d J) + 4\, v_{\alpha_a} u_{\alpha_b} v_{\alpha_c} u_{\alpha_d}\, F(\alpha_a \alpha_b \alpha_c \alpha_d J)$$

$V_{\alpha BF}$ is the interaction between the unpaired fermions and the boson core containing the dynamical, exchange and monopole interactions of the IBFM-1:

$$V_{\alpha BF} = V_{\alpha DYN} + V_{\alpha EXC} + V_{\alpha MON}$$

$$V_{\alpha DYN} = \Gamma_0 \sum_{\alpha j_1 \alpha j_2} \sqrt{5}\,(u_{\alpha j_1} u_{\alpha j_2} - v_{\alpha j_1} v_{\alpha j_2})\,\langle \alpha j_1 \parallel Y_2 \parallel \alpha j_2 \rangle \left([a^\dagger_{\alpha j_1} \times \tilde{a}_{\alpha j_2}]^{(2)} \times Q_B^{(2)} \right)^{(0)}$$

$Q_B^{(2)}$ is the standard boson quadrupole operator

$$Q_B^{(2)} = [s^\dagger \times \tilde{d} + d^\dagger \times \tilde{s}]^{(2)} + \chi [d^\dagger \times \tilde{d}]^{(2)}$$

$$V_{\alpha EXC} = A_0 \sum_{\alpha j_1 \alpha j_2 \alpha j_3} (-2) \sqrt{\frac{5}{2\,\alpha j_3 + 1}}\,(u_{\alpha j_1} v_{\alpha j_3} + v_{\alpha j_1} u_{\alpha j_3})\;\; (u_{\alpha j_2} v_{\alpha j_3} + v_{\alpha j_2} u_{\alpha j_3})$$
$$\langle \alpha j_3 \parallel Y_2 \parallel \alpha j_1 \rangle\, \langle \alpha j_3 \parallel Y_2 \parallel \alpha j_2 \rangle\; : \left([a^\dagger_{\alpha j_1} \times \tilde{d}\,]_{\alpha j_3} \times [\tilde{a}_{\alpha j_2} \times d^\dagger\,]_{\alpha j_3} \right)^{(0)} :$$

$$V_{\alpha MON} = A_0 \sum_{\alpha j} \sqrt{5}\,(2\alpha j + 1)\,\left([a^\dagger_{\alpha j} \times \tilde{a}_{\alpha j}]^{(0)} \times [d^\dagger \times \tilde{d}]^{(0)} \right)^{(0)}$$

The pair breaking interaction V_α^{mix} which mixes states with different number of fermions, conserving the total nucleon number only:

$$V_\alpha^{mix} = -U_0 \left\{ \sum_{\alpha j_1 \alpha j_2} u_{\alpha j_1} u_{\alpha j_2} (u_{\alpha j_1} v_{\alpha j_2} + u_{\alpha j_2} v_{\alpha j_1}) \langle \alpha j_1 \parallel Y_2 \parallel \alpha j_2 \rangle^2 \frac{1}{\sqrt{2\,\alpha j_2 + 1}} \left([a^\dagger_{\alpha j_2} \times a^\dagger_{\alpha j_2}]^{(0)} \cdot \tilde{s} \right) + hc \right\}$$
$$-U_2 \left\{ \sum_{\alpha j_1 \alpha j_2} (u_{\alpha j_1} v_{\alpha j_2} + u_{\alpha j_2} v_{\alpha j_1}) \langle \alpha j_1 \parallel Y_2 \parallel \alpha j_2 \rangle \left([a^\dagger_{\alpha j_1} \times a^\dagger_{\alpha j_2}]^{(2)} \cdot \tilde{d} \right) + hc \right\}$$

The proton-neutron interaction is:

$$V_{\nu\pi} = \sum_{\nu\nu'\pi\pi'} \sum_J h_J(\nu\nu'\pi\pi')(u_\nu u_{\nu'} - v_\nu v_{\nu'})(u_\pi u_{\pi'} - v_\pi v_{\pi'}) \left(\left[a^\dagger_\nu \times \tilde{a}_{\nu'} \right]^{(J)} \cdot \left[a^\dagger_\pi \times \tilde{a}_{\pi'} \right]^{(J)} \right)$$

The coefficients $h_J(\nu\nu'\pi\pi')$ are connected to the two-body matrix elements of the residual proton-neutron interaction by:

$$h_J(\nu\nu'\pi'\pi) = (-)^{j_\nu + j_\pi} \sum_{J'} (-)^{J'} \sqrt{2J'+1}\,\langle (j_\nu j_\pi) J' \parallel V(1,2) \parallel (j_{\nu'} j_{\pi'}) J' \rangle\, W(j_\nu j_\pi j_{\nu'} j_{\pi'}; J' J)$$

The residual proton-neutron interaction is usually **defined in the form:**

$$H_\delta = 4\pi\, V_\delta\, \delta(\vec{r}_\pi - \vec{r}_\nu)\, \delta(r_\pi - R_0)\, \delta(r_\nu - R_0)$$

The strength parameters of the boson-fermion interactions should be those obtained in the analysis of the neighboring nuclei. For example, the boson-fermion strength parameters for the couplings of two and four-proton configurations to the boson core in an even-even nucleus have to be the same as for coupling of one-proton configurations to the boson core in the neighboring odd-even nucleus. This is the case for spherical, transitional and γ-soft nuclei. However, approaching the rotational SU(3) limit of IBM, the boson-fermion interaction strengths are not identical for an even-even nucleus and odd-even neighbour The effective core for configurations based on broken pairs in a deformed nucleus can be somewhat different from the one obtained by a simple decrease of the boson number by one.

$$T(E2)=\frac{3}{4\pi}e^{\text{vib}}R_0^2[(d^\dagger\times\tilde{s}+s^\dagger\times\tilde{d})^{(2)}+\chi(d^\dagger\times\tilde{d})^{(2)}]$$

$$-e\frac{1}{\sqrt{5}}\sum_{j_1j_2}q_{j_1j_2}[(u_{j_1}u_{j_2}-v_{j_1}v_{j_2})(a_{j_1}^\dagger\times\tilde{a}_{j_2})^{(2)}-\frac{u_{j_1}v_{j_2}}{\sqrt{N}}[(a_{j_1}^+\times a_{j_2}^+)^{(2)}\times\tilde{s}]^{(2)}+\frac{u_{j_2}v_{j_1}}{\sqrt{N}}[(\tilde{a}_{j_1}\times\tilde{a}_{j_2})^{(2)}\times s^\dagger]^{(2)}]$$

where

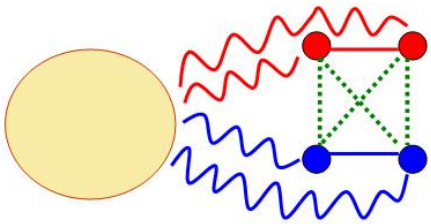
$q_{j_1j_2}=\langle j_1\|r^2Y_2\|j_2\rangle$.

We take $\langle r^2\rangle=\frac{1}{5}R_0^2$, and $R_0=0.12A^{1/3}\times10^{-12}$ cm. N is the number of bosons.

$$T(M1)=\sqrt{30/4\pi}g_R(d^\dagger\times\tilde{d})^{(1)}$$

$$-\frac{1}{\sqrt{4\pi}}\sum_{j_1j_2}[g_1\langle j_1\|\vec{j}\|j_2\rangle+(g_s-g_1)\langle j_1\|\vec{s}\|j_2\rangle]$$

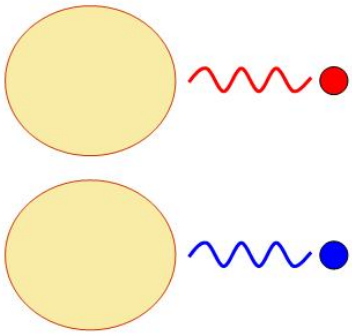
$$\times\{(u_{j_1}u_{j_2}+v_{j_1}v_{j_2})(a_{j_1}^\dagger\times\tilde{a}_{j_2})^{(1)}-\frac{u_{j_1}v_{j_2}}{\sqrt{N}}[(a_{j_1}^\dagger\times a_{j_2}^\dagger)^{(1)}\times\tilde{s}]^{(1)}+\frac{u_{j_2}v_{j_1}}{\sqrt{N}}[(\tilde{a}_{j_1}\times\tilde{a}_{j_2})^{(1)}\times s^\dagger]^{(1)}]$$



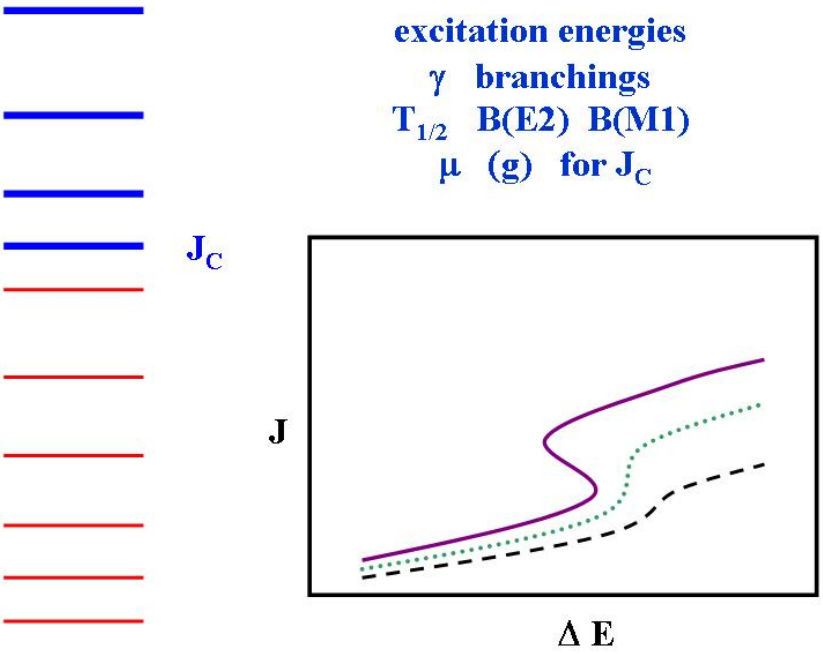
proton

neutron

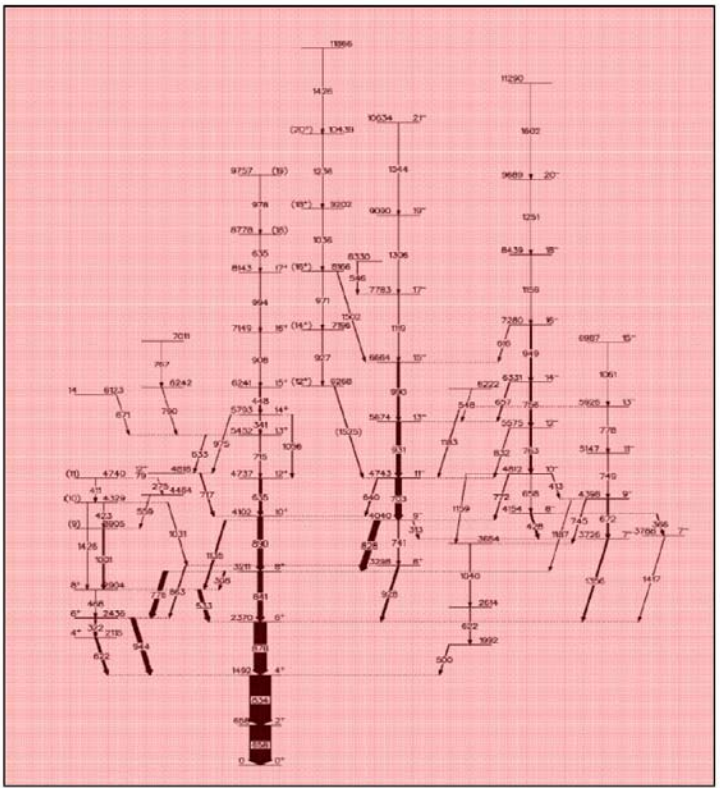
boson –fermion interactions from odd – A neighbours



Important data for high spin states



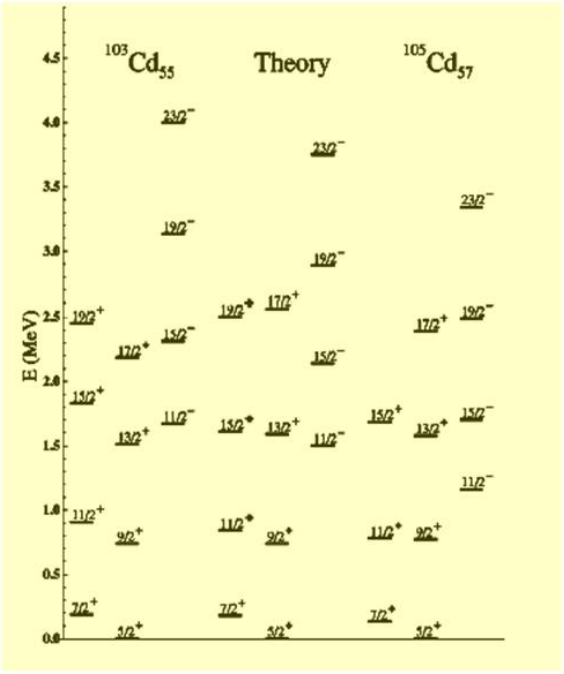
Spherical nuclei

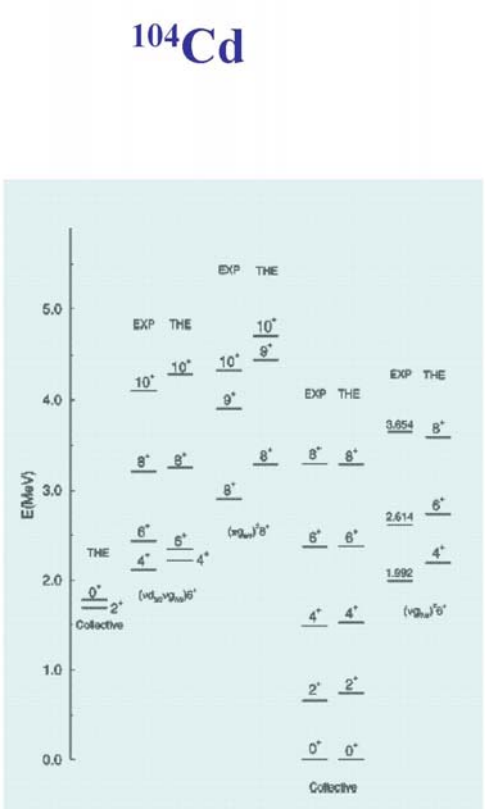


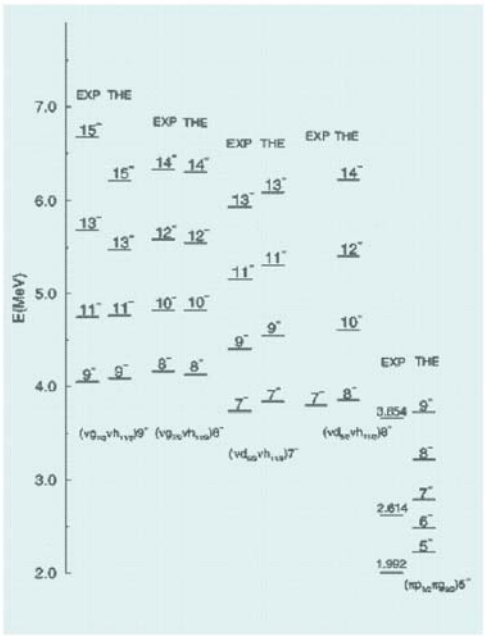
^{104}Cd

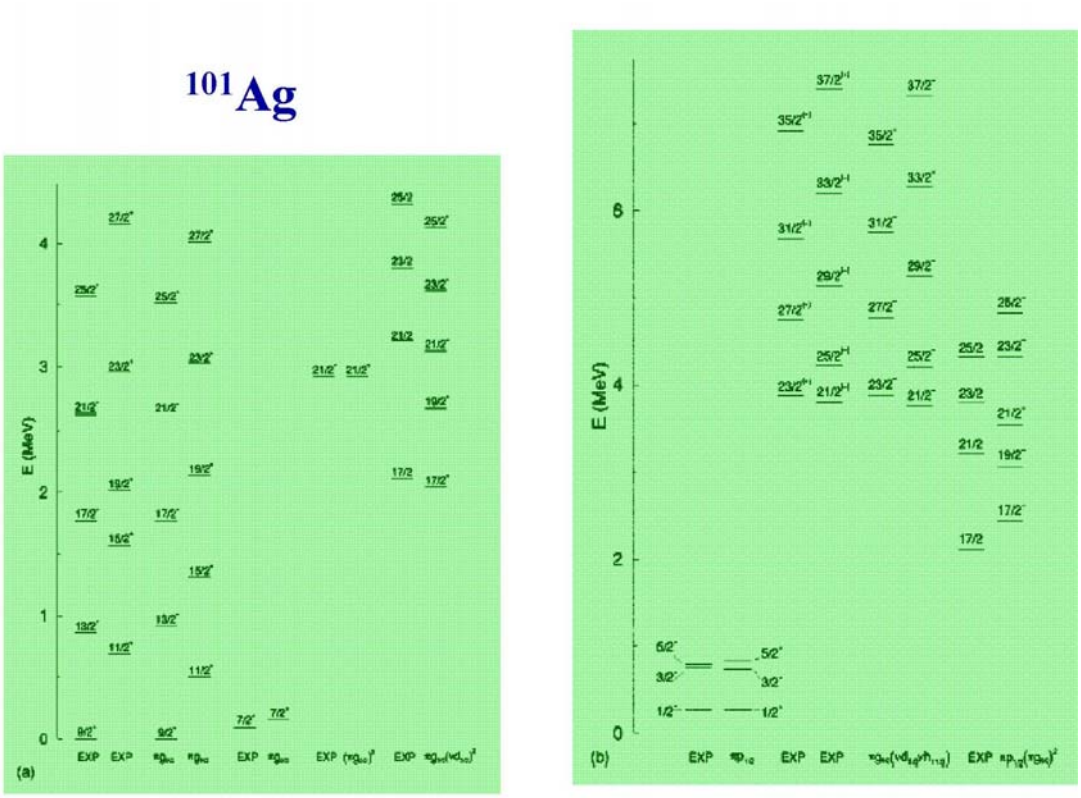
Parametrization for neutrons from even-odd Cd nuclei

Parametrization for protons in accordance with odd-even In and Ag nuclei







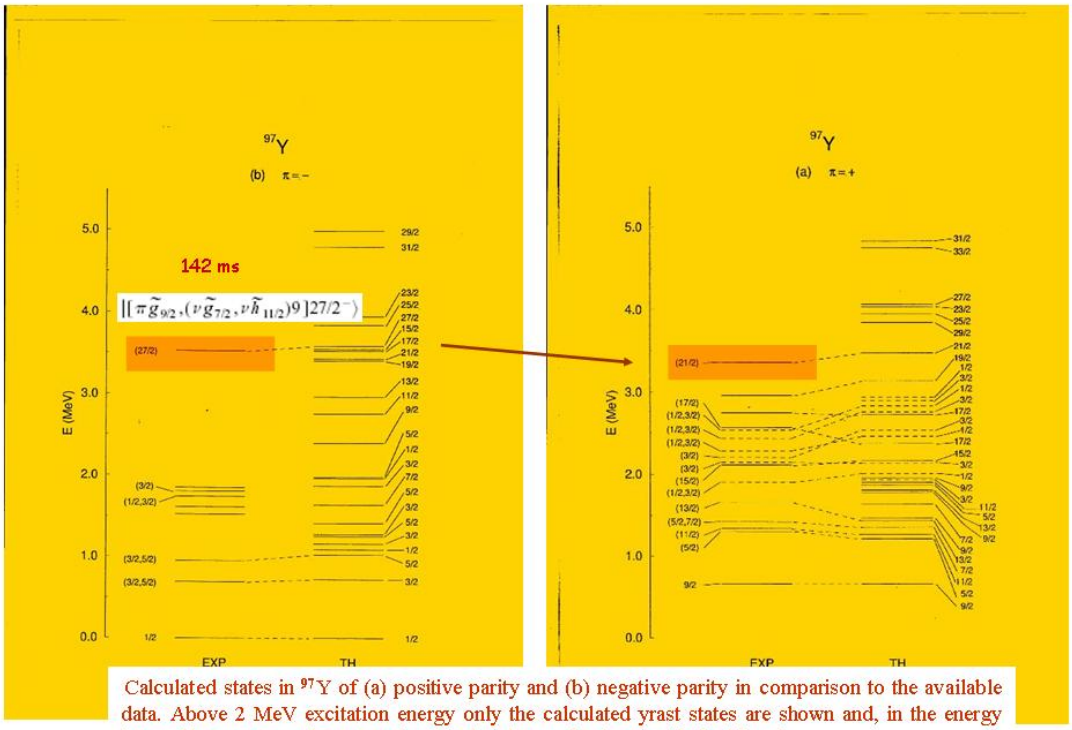


^{101}Ag

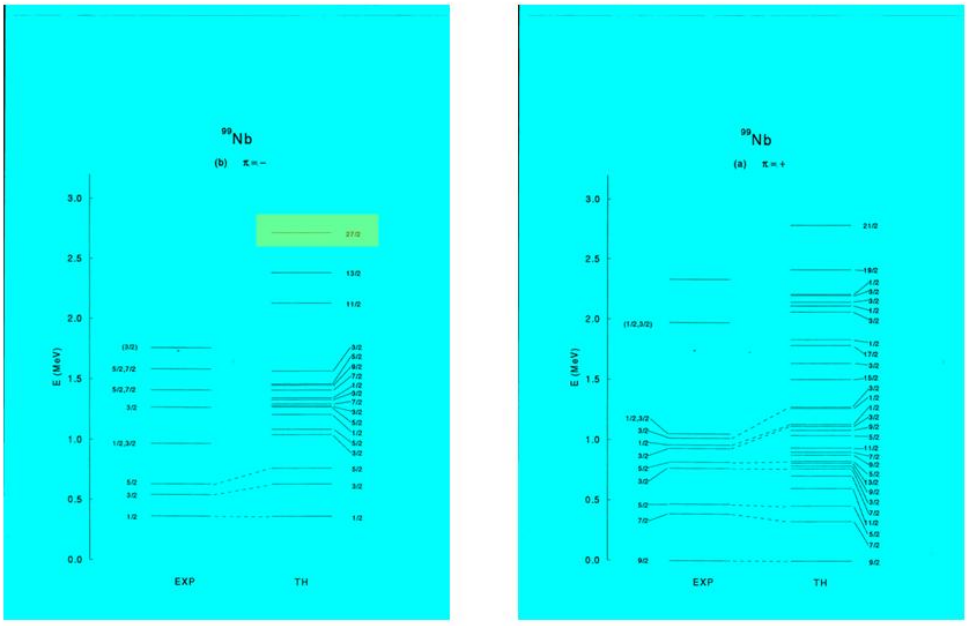
State E_x (keV)	I^π	Lifetime (ps) DDCM	RDDS	DSA/NGTB	Adopted	Theory	
Positive parity							
98	$7/2^+$					425	
687	$11/2^+$	2.7(3)			2.7(3)	2.0	
861	$13/2^+$	11.7(10)			11.7(10)	3.4	
1573	$15/2^+$	2.1(5)			2.1(5)	0.4	
1769	$17/2^+$	1.9(2)			1.9(2)	1.9	
2017	$19/2^+$	9(1)			9(1)	5.0	
2621	$21/2^+$	0.6(1)			0.6(1)	0.4	
2922	$21/2_2^+$					1700[a]	
						2.8[b]	
2956	$23/2^+$	1.8(3)			1.8(3)	0.9	
3578	$25/2^+$		<2.0		<2.0	0.4	
4159	$27/2^+$		<2.5		<2.5	0.3	
4572	$(29/2^+)$		14(1)		14(1)		
5300	$(31/2^+)$			≤1.7	≤1.7		
Negative parity							
750	$3/2^{(-)}$					10.2	
797	$5/2^{(-)}$					30.5	
3870	$23/2^{(-)}$	11.4(11)			11.4(11)	8.4	
4217	$25/2^{(-)}$	1.1(2)			1.1(2)	1.2	
4749	$27/2^{(-)}$		1.1(1)		1.1(1)	1.1	
5134	$29/2^{(-)}$			0.83(8)	0.83(8)	0.81	
5678	$31/2^{(-)}$			0.41(5)	0.41(5)	0.45	
6197	$33/2^{(-)}$			0.30(4)	0.30(4)	0.34	
6917	$35/2^{(-)}$			0.18(5)	0.18(5)	0.13	
7393	$37/2^{(-)}$			≤1.3	≤1.3	0.39	
No parity assigned						$\pi=+$	$\pi=-$
2115	17/2		199(7)		199(7)	120	
3210	21/2	1.2(1)			1.2(1)	1.0	2.9
3801	23/2					0.5	0.9
4315	25/2					0.5	0.4

[a]If wave function predominantly $\pi^3(g_{9/2})$
[b]If wave function predominantly $\pi(g_{9/2})$

Structure of isomers in spherical nuclei



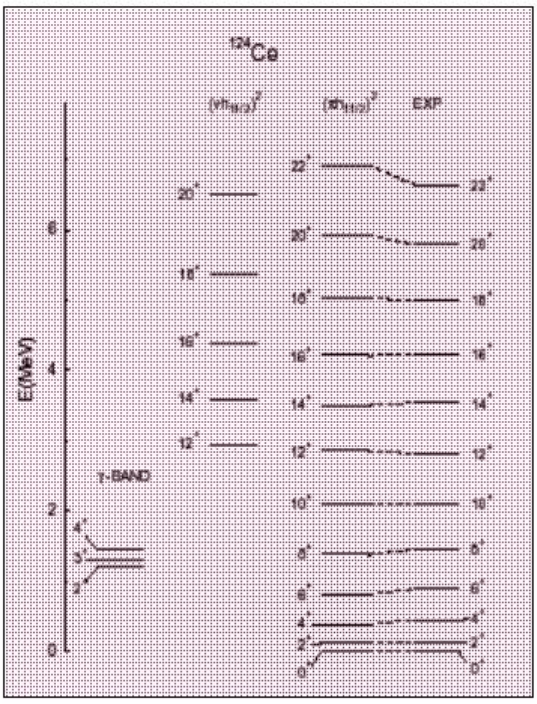
Calculated states in ^{97}Y of (a) positive parity and (b) negative parity in comparison to the available data. Above 2 MeV excitation energy only the calculated yrast states are shown and, in the energy interval between 2 and 3 MeV, the calculated ½⁻ and ½⁺ states (dashed lines).



Assuming a possible error of 200 – 300 keV for the predicted energies, a 27/2⁻ isomer with a halflife in the μs - ms range could be found in ^{99}Nb

-

Deformed nuclei



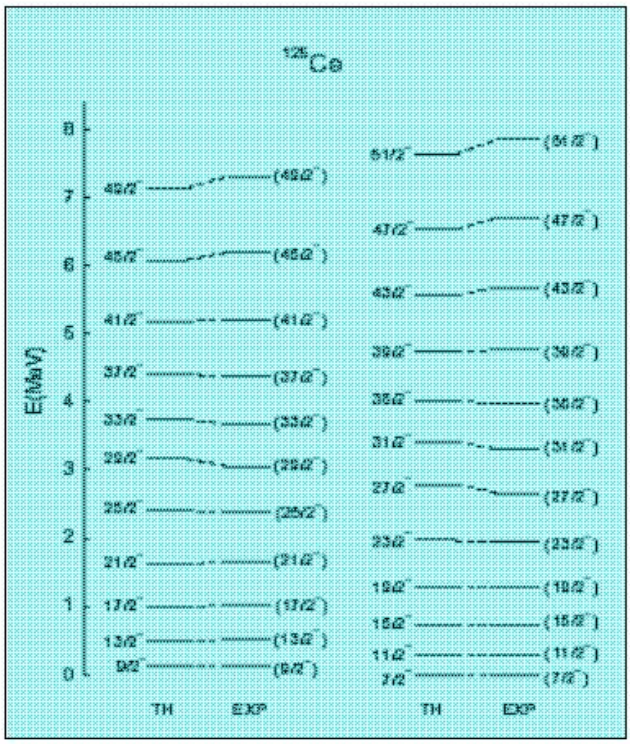
This nucleus displays a transitional structure between deformed nuclei (lighter Ce isotopes) described by the SU(3) limit of the IBM, and γ-soft nuclei (heavier Ce isotopes) which correspond to the O(6) limit of the of the IBM. The SU(3)-O(6) transition can be described by the boson Hamiltonian

$$H_{IBM} = -\frac{\alpha}{10}\, Q\cdot Q \;+\; \frac{\beta}{10}\, L\cdot L$$

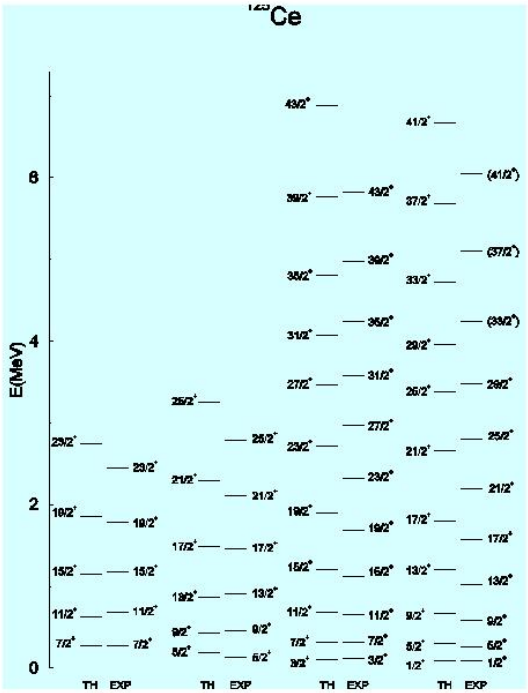
and is determined by the value of the parameter χ in the quadrupole boson operator. The limiting cases are: $\chi = 0$ corresponds to the O(6) limit of the IBM-1, and $\chi = -\frac{\sqrt{7}}{2}$ describes a prolate shape in the SU(3) dynamical symmetry limit.

Here: $\alpha = 0.19$ MeV, $\beta = 0.13$ MeV, $\chi = -1.0$ and the boson number $N = 12$.

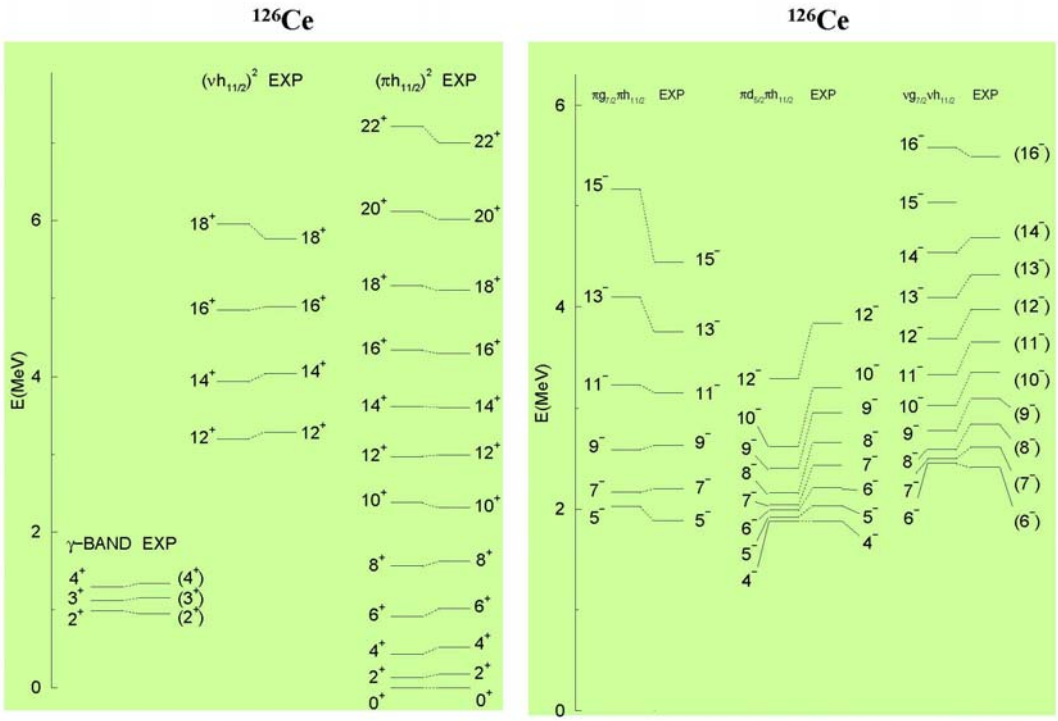
$v^2(\pi h_{11/2}) = 0.06$
$\varepsilon(\pi h_{11/2}) = 1.70$ MeV
$v^2(\nu h_{11/2}) = 0.40$
$\varepsilon(\nu h_{11/2}) = 1.32$ MeV



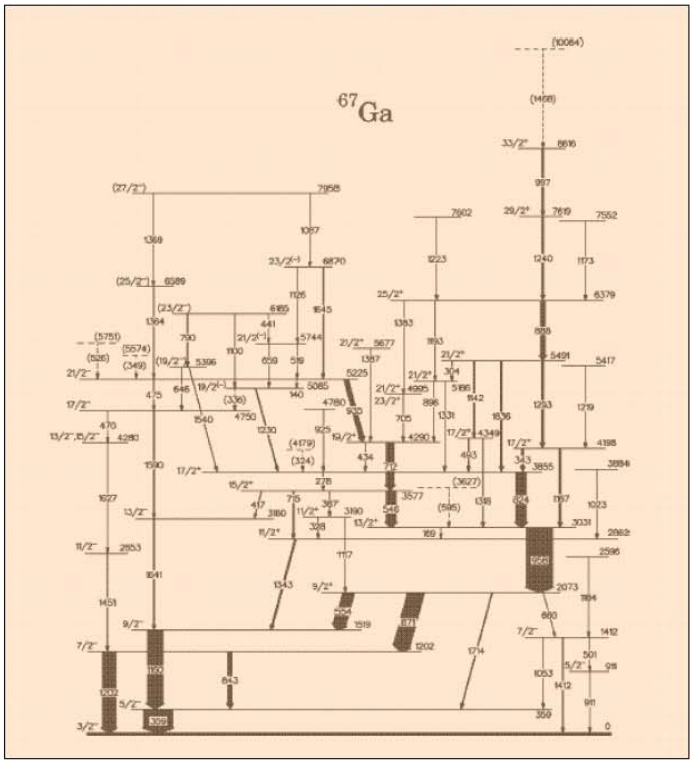
This band is based on the $\nu h_{11/2}$ orbital for the states with $I \leq 27/2^-$, and on the three-fermion configuration $\nu h_{11/2}\,(\pi h_{11/2})^2$ for $I \geq 29/2^-$. The structure of this band is very simple. The neutron $\nu h_{11/2}$ orbital couples to the yrast sequence of states in the core nucleus ^{124}Ce.



Band is based on the $\nu d_{5/2}$ and $\nu g_{7/2}$ neutron orbitals. Band 3, in addition, con- tains sizeable components based on the $\nu d_{3/2}$ and $\nu s_{1/2}$ states. While the alignment of a proton pair is not observed in band 2, the states with $I \geq 25/2^+$ of band 3 are based on the one-neutron plus $(\pi h_{11/2})^2$ configuration.



Transitional nuclei



Wave functions

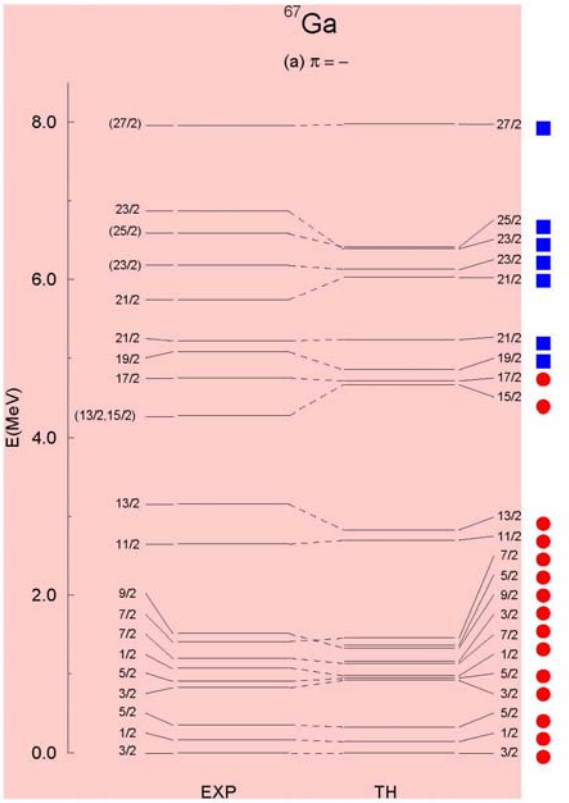
$$|I_k^{\pi}\rangle = \sum_{j n_d \upsilon R;I} \xi_{j,n_d \upsilon R;I} \; |\pi\tilde{j}, n_d \upsilon R; I\rangle$$

$$+ \sum_{jj'j''I_{\alpha\alpha}I_{\pi\alpha\alpha}n_d\upsilon R} \eta_{jj'j''I_{\alpha\alpha}I_{\pi\alpha\alpha},n_d\upsilon R;I}$$

$$\times |[\pi\tilde{j},(\alpha\tilde{j}',\alpha\tilde{j}'')I_{\alpha\alpha}]I_{\pi\alpha\alpha},n_d\upsilon R;I\rangle$$

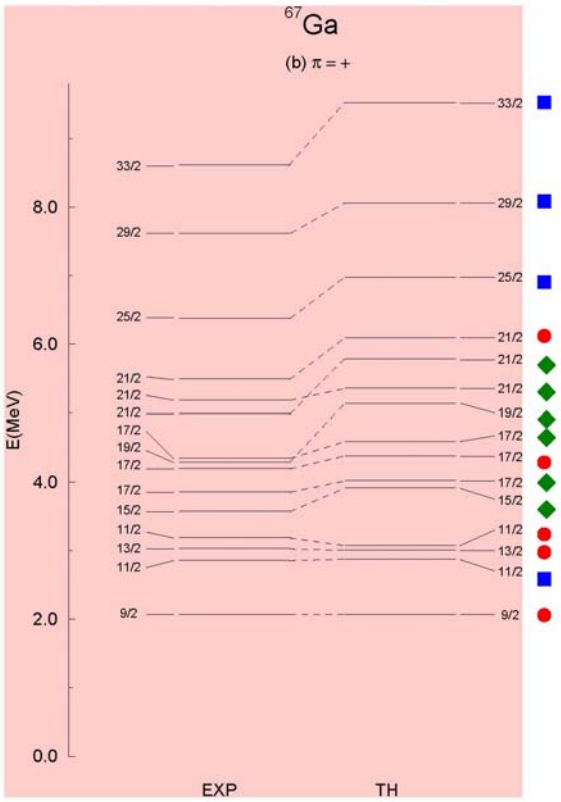
$\pi\tilde{j}$ stands for a proton quasiparticle, and $\alpha\tilde{j}', \alpha\tilde{j}''$ for neutron quasiparticles ($\alpha = \nu$), or proton quasiparticles ($\alpha = \pi$), which are coupled to the angular momentum $I_{\alpha\alpha}$. Angular momenta j and $I_{\alpha\alpha}$ are coupled to the three-quasiparticle angular momentum denoted by $I_{\pi\alpha\alpha}$. In the boson part of the wave function, the $n_d d$ bosons are coupled to the total boson angular momentum R. The additional quantum number υ is used to distinguish between the n_d-boson states having the same angular momentum R. We note that the number of s bosons associated with the boson state $|n_d \upsilon R\rangle$ is $n_s = N - n_d$, where N is the total number of bosons.

To follow the origin of states, and for the indexing of the theoretical states, we use I_{qpi} for the quasiparticle+phonon states, I_{bp_i} for proton broken pair states and I_{bn_i} for neutron broken pair states. Here the index i denotes the ith state of the denoted type. In the standard notation I_k, the index k is used as **the total label obtained** the IBFBPM calculation. The indexing I_k is pointed out only for states where $i \neq k$. Otherwise, the indexes i and k are equal.



one proton two neutron state

one proton state



three proton state

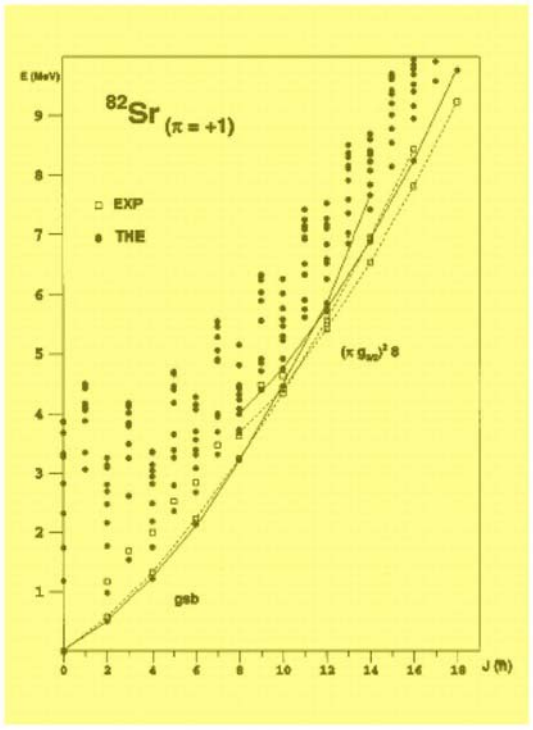
one proton two neutron state

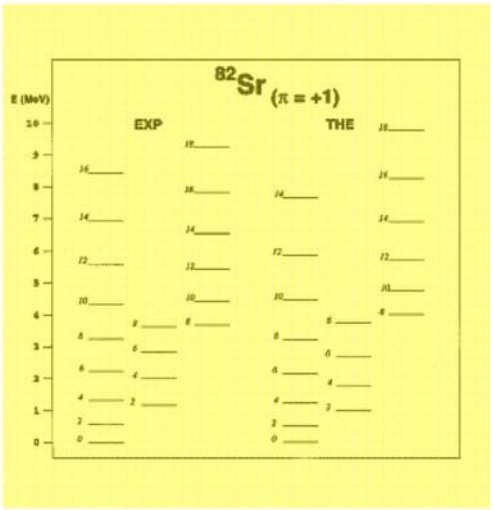
one proton state

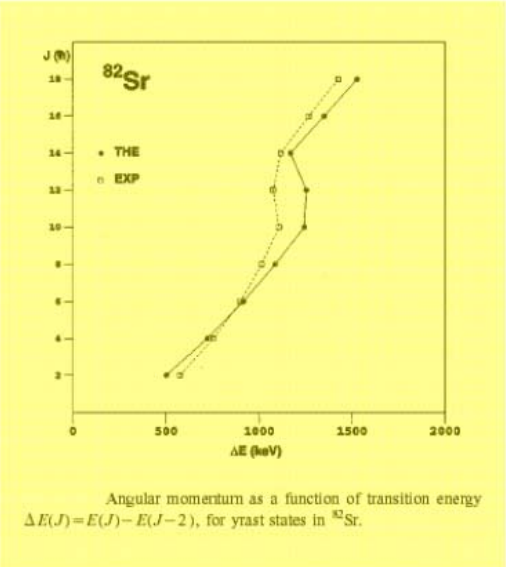
I_i^π → I_f^π ($\hbar$) ($\hbar$)	$E_i \to E_f$ Expt. Expt.	$B(E2)(e^2b^2)$ IBFBPM	$B(M1)(\mu_N^2)$ IBFBPM	I_γ Expt.	I_γ IBFBPM
$1/2^-_{\Phi_1} \to 3/2^-_{\Phi_1}$	167→0	0.013	0.058	100	100
$5/2^-_{\Phi_1} \to 1/2^-_{\Phi_1}$	359→167	0.027			1.8
$\to 3/2^-_{\Phi_1}$	→0	0.003	0.006	100	100
$3/2^-_{\Phi_2} \to 5/2^-_{\Phi_1}$	828→359	1×10^{-5}	0.013	4	6
$\to 1/2^-_{\Phi_1}$	→167	2×10^{-5}	0.022	10	27
$\to 3/2^-_{\Phi_1}$	→0	0.027	0.028	100	100
$5/2^-_{\Phi_2} \to 3/2^-_{\Phi_2}$	911→828	0.002	0.306		0.9
$\to 5/2^-_{\Phi_1}$	→359	9×10^{-5}	0.0005	2.2	0.5
$\to 1/2^-_{\Phi_1}$	→167	0.003		2.2	2.0
$\to 3/2^-_{\Phi_1}$	→0	0.029	0.010	100	100
$1/2^-_{\Phi_2} \to 5/2^-_{\Phi_2}$	1082→911	0.0004			0.0002
$\to 3/2^-_{\Phi_2}$	→828	0.0003	0.533	12	37
$\to 5/2^-_{\Phi_1}$	→359	0.003			1.7
$\to 1/2^-_{\Phi_1}$	→167		0.030	100	100
$\to 3/2^-_{\Phi_1}$	→0	0.021	0.005	33	122
$7/2^-_{\Phi_1} \to 5/2^-_{\Phi_2}$	1202→911	0.002	0.131		6
$\to 3/2^-_{\Phi_2}$	→828	0.0004			0.0004
$\to 5/2^-_{\Phi_1}$	→359	0.002	0.012	31	14
$\to 3/2^-_{\Phi_1}$	→0	0.033		100	100
$7/2^-_{\Phi_2} \to 7/2^-_{\Phi_1}$	1412→1202	0.002	0.002		0.06
$\to 5/2^-_{\Phi_2}$	→911	0.002	0.011	20	5
$\to 3/2^-_{\Phi_2}$	→828	0.001			0.2
$\to 5/2^-_{\Phi_1}$	→359	0.024	0.008	100	100
$\to 3/2^-_{\Phi_1}$	→0	3×10^{-5}		20	0.3
$9/2^-_{\Phi_2} \to 7/2^-_{\Phi_2}$	1519→1412	0.003	0.018		0.03
$\to 7/2^-_{\Phi_1}$	→1202	0.0007	0.005		0.2
$\to 5/2^-_{\Phi_2}$	→911	0.0003			0.02
$\to 5/2^-_{\Phi_1}$	→359	0.049		100	100
$11/2^-_{\Phi_1} \to 9/2^-_{\Phi_1}$	2653→1519	0.001	0.007		5
$\to 7/2^-_{\Phi_2}$	→1412	0.0004			0.4
$\to 7/2^-_{\Phi_1}$	→1202	0.051		100	100
$13/2^-_{\Phi_1} \to 11/2^-_{\Phi_1}$	3160→2653	0.0003	0.004		0.1
$\to 9/2^-_{\Phi_1}$	→1519	0.065		100	100
$15/2^-_{\Phi_1} \to 13/2^-_{\Phi_1}$	4280→3160	0.0009	0.004		1.5
$\to 11/2^-_{\Phi_1}$	→2653	0.056		100	100
$17/2^-_{\Phi_1} \to 15/2^-_{\Phi_1}$	4750→4280	8×10^{-5}	0.002	12	0.04
$\to 13/2^-_{\Phi_1}$	→3160	0.067		100	100
$21/2^-_{5p_1} \to 21/2^-_{5p_1}$	5744→5225	2×10^{-6}	0.003	100	100
$\to 19/2^-_{5p_1}$	→5085	0.0003	0.002	24	161
$23/2^-_{5p_1} \to 21/2^-_{5p_2}$	6185→5744	0.0004	0.718	30	89
$\to 21/2^-_{5p_1}$	→5225	0.0007	0.007		10
$\to 19/2^-_{5p_1}$	→5085	0.025		40	40
$25/2^-_{5p_1} \to 23/2^-_{5p_1}$	6589→6185	0.0006	0.006		0.4
$\to 21/2^-_{5p_2}$	→5744	8×10^{-6}			0.002
$\to 21/2^-_{5p_1}$	→5225	0.036		100	100
$23/2^-_{5p_2} \to 25/2^-_{5p_1}$	6870→6589	0.007	0.598		20
$\to 23/2^-_{5p_1}$	→6185	0.0002	0.0004		0.2
$\to 21/2^-_{5p_2}$	→5744	4×10^{-5}	0.003	36	6
$\to 21/2^-_{5p_1}$	→5225	0.008	0.0003	100	100
$\to 19/2^-_{5p_1}$	→5085	3×10^{-7}			0.005

^{67}Ga

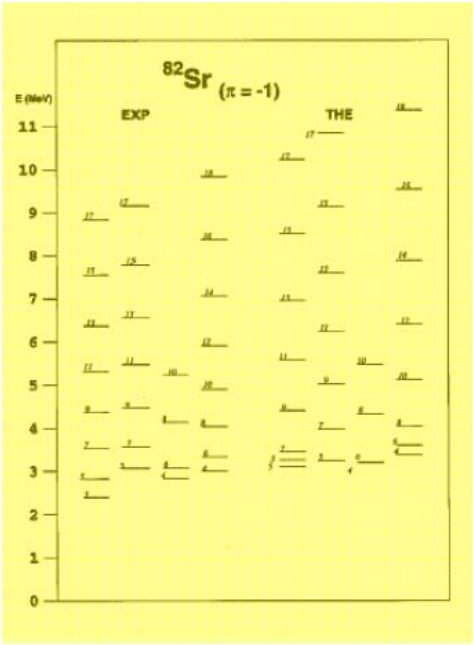
I_i^π → I_f^π ($\hbar$) ($\hbar$)	$E_i \to E_f$ Expt. Expt.	$B(E2)(e^2b^2)$ IBFBPM	$B(M1)(\mu_N^2)$ IBFBPM	I_γ Expt.	I_γ IBFBPM
$27/2^+_{5p_2} \to 23/2^+_{5p_2}$	7958→6870	0.041		50	259
$\to 25/2^+_{5p_1}$	→6589	0.005	0.0001	100	100
$\to 23/2^+_{5p_1}$	→6185	9×10^{-6}			0.6
$13/2^+_{\Phi_1} \to 9/2^+_{\Phi_1}$	3031→2073	0.037		100	100
$11/2^+_{\Phi_1} \to 13/2^+_{\Phi_1}$	3190→3031	0.001	0.119		0.4
$\to 9/2^+_{\Phi_1}$	→2073	0.041	0.058	100	100
$15/2^+_{5p_1} \to 11/2^+_{\Phi_1}$	3577→3190	0.002		3.4	33
$\to 13/2^+_{\Phi_1}$	→3031	0.0009	4×10^{-5}	100	100
$17/2^+_{5p_1} \to 15/2^+_{5p_1}$	3855→3577	0.006	0.039	1.2	22
$\to 13/2^+_{\Phi_1}$	→3031	0.015		100	100
$17/2^+_{\Phi_1} \to 17/2^+_{5p_1}$	4198→3855	6×10^{-5}	0.095	90	6
$\to 15/2^+_{5p_1}$	→3577	0.001	0.028		11
$\to 13/2^+_{\Phi_1}$	→3031	0.043		100	100
$19/2^+_{5p_1} \to 17/2^+_{\Phi_1}$	4290→4198	0.002	0.001		0.02
$\to 17/2^+_{5p_1}$	→3855	0.004	9×10^{-5}	1.6	1.2
$\to 15/2^+_{5p_1}$	→3577	0.029		100	100
$17/2^+_{5p_2} \to 19/2^+_{5p_1}$	4349→4290	6×10^{-5}	0.004		0.02
$\to 17/2^+_{5p_1}$	→4198	3×10^{-5}	0.008		0.8
$\to 17/2^+_{5p_1}$	→3855	0.0004	0.001	52	5
$\to 15/2^+_{5p_1}$	→3577	0.0001	0.012	<10	146
$\to 13/2^+_{5p_1}$	→3031	0.0014		100	100
$21/2^+_{5p_2} \to 17/2^+_{5p_2}$	4995→4349	0.035			24
$\to 19/2^+_{5p_1}$	→4290	2×10^{-5}	0.033	100	100
$\to 17/2^+_{5p_1}$	→4198	0.009			17
$\to 17/2^+_{5p_1}$	→3855	0.0002			2.7
$21/2^+_{5p_1} \to 21/2^+_{5p_2}$	5186→4995	0.0002	0.005		0.03
$\to 17/2^+_{5p_2}$	→4349	0.0002			0.04
$\to 19/2^+_{5p_1}$	→4290	0.003	0.106	31	67
$\to 17/2^+_{5p_1}$	→4198	0.0003			0.2
$\to 17/2^+_{5p_1}$	→3855	0.040		100	100
$21/2^+_{5p_1} \to 21/2^+_{5p_1}$	5491→5186	0.0002	0.029	2.1	0.7
$\to 21/2^+_{5p_2}$	→4995	1×10^{-5}	0.001		0.1
$\to 17/2^+_{5p_2}$	→4349	0.008		27	9
$\to 19/2^+_{5p_1}$	→4290	0.0004	0.004		7
$\to 17/2^+_{5p_1}$	→4198	0.048		100	100
$\to 17/2^+_{5p_1}$	→3855	0.002		67	14





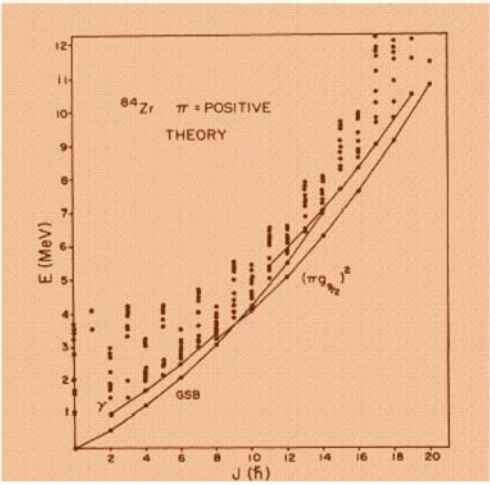


Angular momentum as a function of transition energy $\Delta E(J) = E(J) - E(J-2)$, for yrast states in ^{82}Sr.

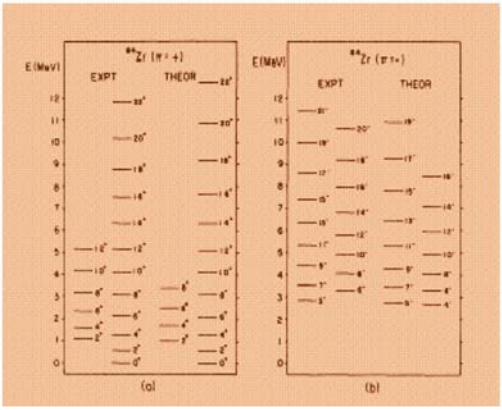


Interactions ?

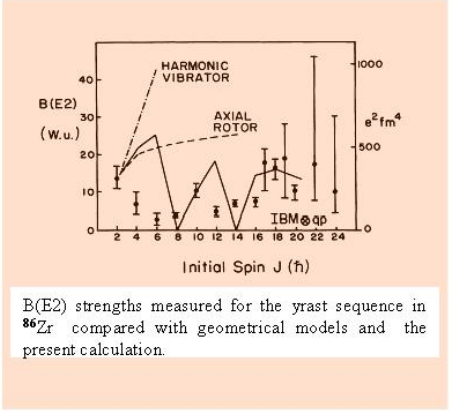
The strength of the exchange interaction is adjusted to reproduce the energy spacings of negative-parity states in ^{82}Sr, differing considerably from that used for odd-even isotopes. In order to understand the origin of this anomaly, one may consider the coupling of unpaired protons to proton bosons in the ^{82}Sr. To create multiproton states in the even-even nucleus we destroy proton bosons and the effective coupling of the exchange interaction is reduced. In the IBM-2, this reduction would be implicit and no adjustment of strength parameters should be needed. However, in our model based on IBM-1, we couple to all the core bosons, irrespective of their nature, and the suppression of coupling is greatly diminished – thus, the need to empirically reduce the strength of the coupling parameter. This effect should be especially pronounced near closed shells, and in our case the reduction of the exchange interaction might be due to the subshell closure at $Z = 40$.



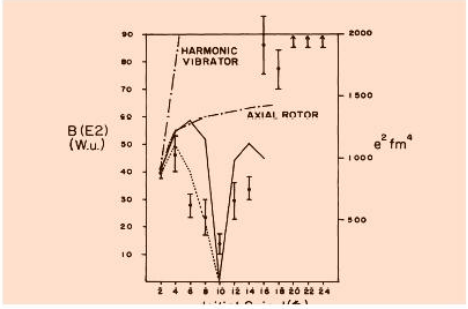
Some of the positive-parity states calculated for ^{84}Zr. The first ten states of each spin are shown for configurations involving core vibrations coupled to quasiproton states.



A detailed comparison of states calculated for ^{84}Zr (a) in the positive-parity sequence (b) in the negative-parity sequence



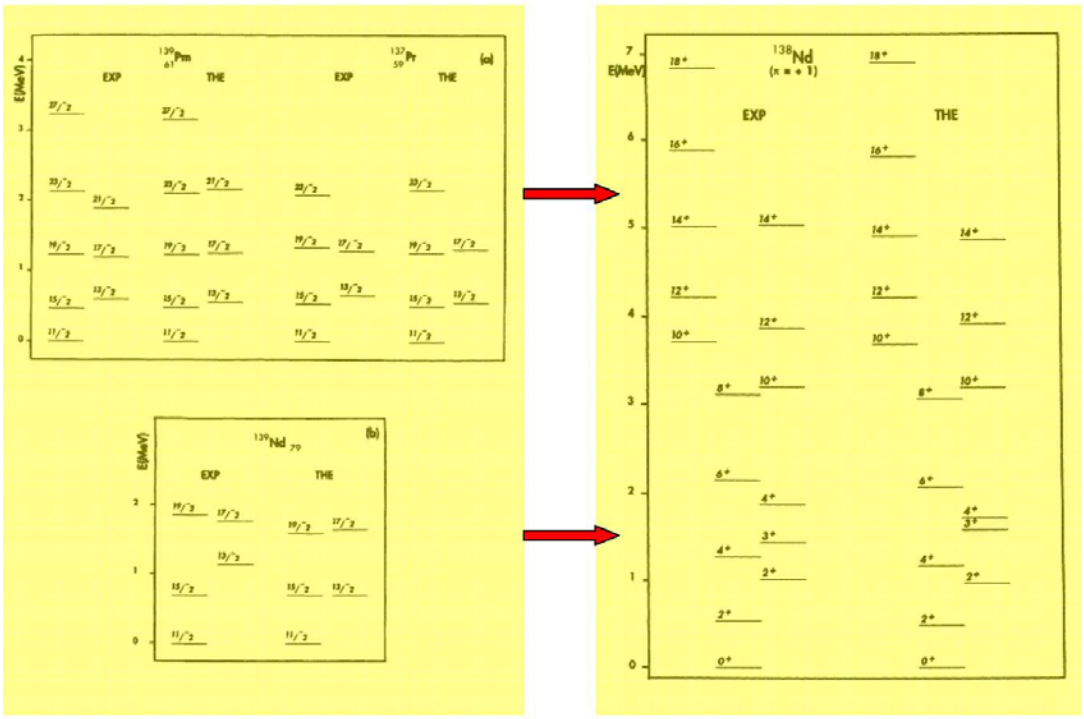
B(E2) strengths measured for the yrast sequence in ^{86}Zr compared with geometrical models and the present calculation.

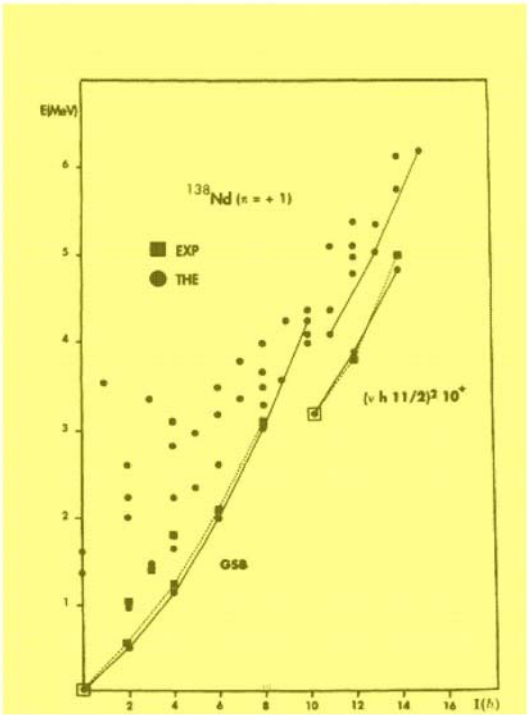


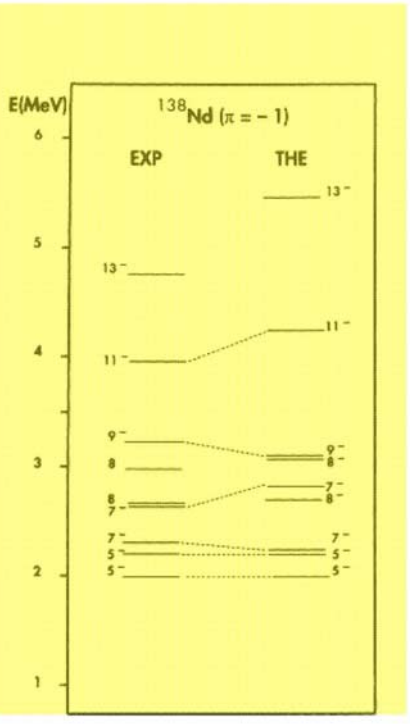
A comparison of experimental B(E2) for ^{86}Zr along the ground-state sequence compared with geometrical models (-.-.-.), our calculations in the full 28-50 shell model space (----), and our calculations in a space truncated by the Z = 38 sub-shell closure (. . . .).

The pair breaking interaction V^{mix}, which mixes with different number of fermions and conserves only the total number of valence nucleons does not normally induce sufficient mixing as can be deduced, for example, from observed transition strengths – lowest order contributions to a pair-breaking interaction. The interaction contains only fermion operators of rank 0 and 2, and cannot connect in first order the ground state band with two-fermion states of higher fermion angular momenta. In order to enhance the mixing, interactions that contain fermion operators of higher rank could be included in the model Hamiltonian. However, such an interaction would also require higher order boson operators, with parameters that cannot be determined from available experimental data, or from the intrinsic structure of the model.

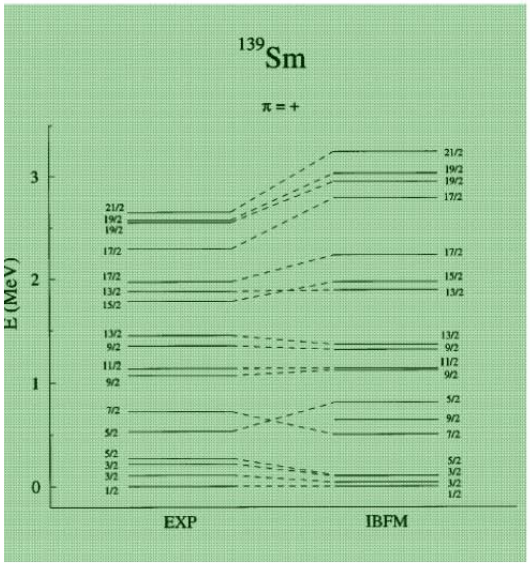
^{138}Nd

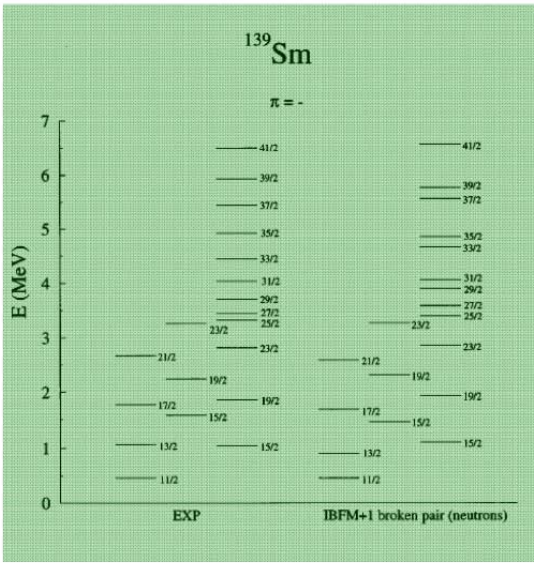


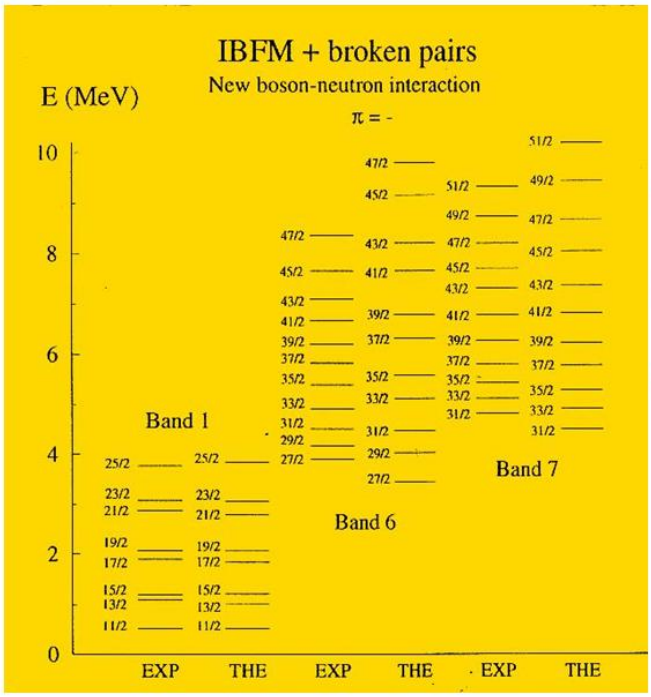




h11/2 d3/2 neutron pair





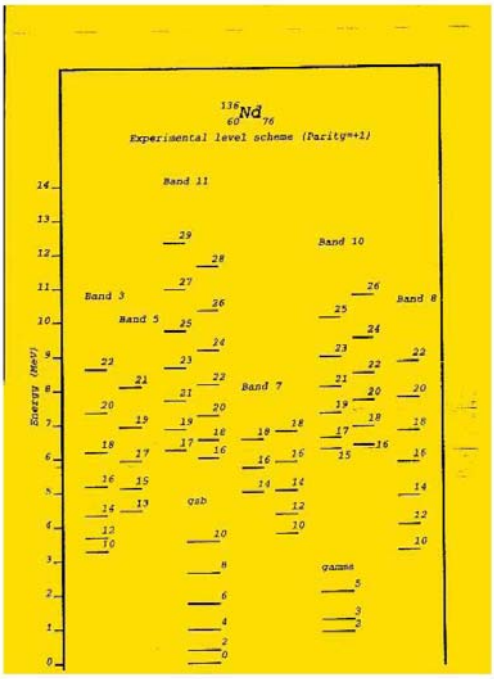


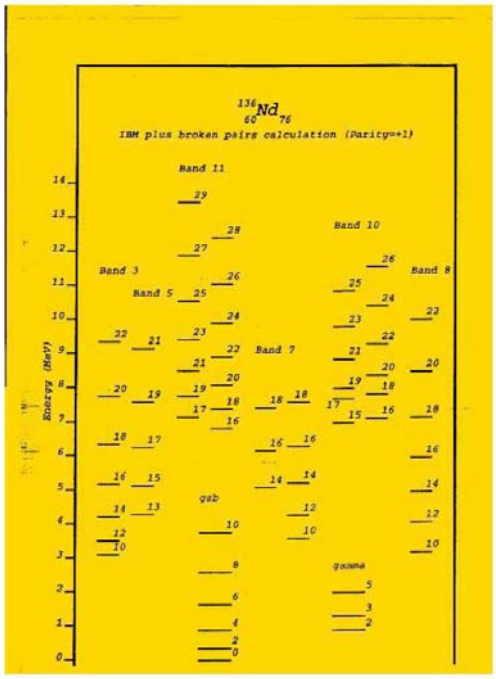
$^{137}Nd_{77}$

Band 1 (ν h11/2)

Band 6 (ν h11/2)³

Band 7 (ν h11/2) (π h11/2)²

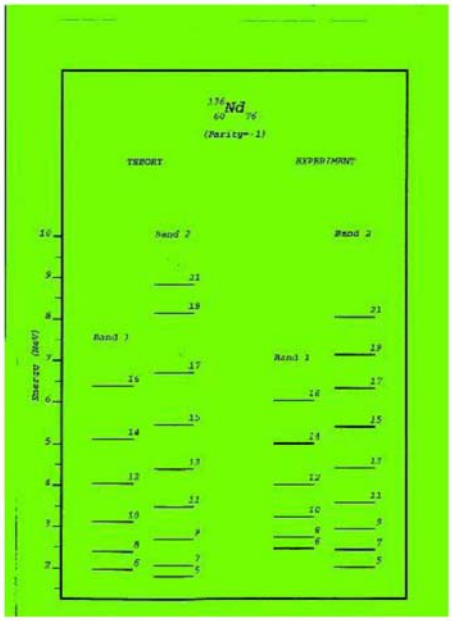


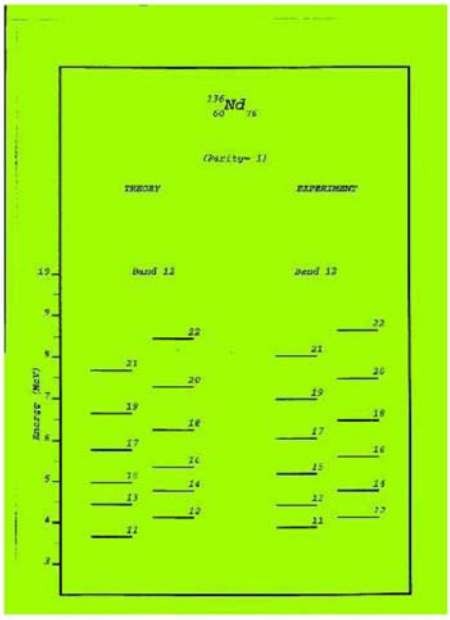


Bands 3, 5, 7 $(\pi\ h11/2)^2$

Band 8 $(\nu\ h11/2)^2$

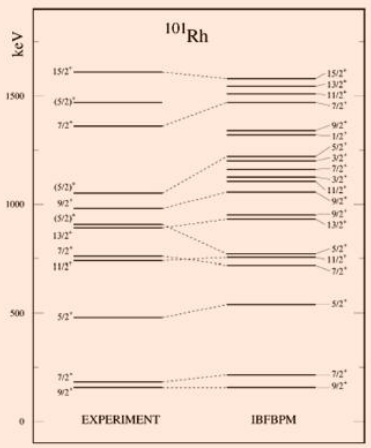
Bands 10, 11 $(\pi\ h11/2)^2\ (\nu\ h11/2)^2$!!!



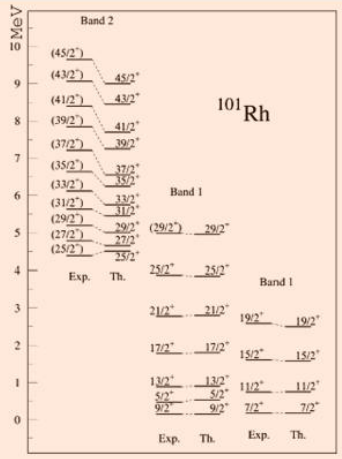


Bands 1, 2 $(\nu\ d3/2\ \ \nu\ h11/2)$

Band 12 $(\nu\ d3/2\ \ (\nu\ h11/2)^3)$



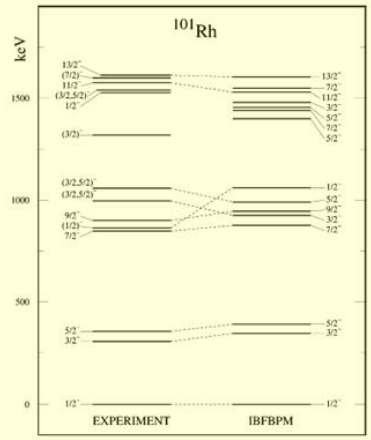
Comparison of positive parity levels in the 0 – 1.6 MeV range observed in experiments and calculated using the IBFBPM model. All the calculated levels are shown for a given spin.



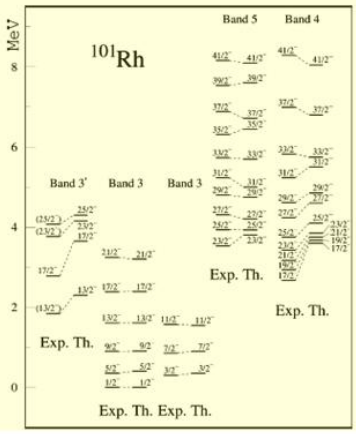
Comparison of positive parity levels in bands 1 and 2 observed in the present experiment (Exp.) and calculated using the IBFBPM model (Th.) up to spin $I = 45/2$.

Band 1 π g9/2

Band 2 π g9/2 (ν h11/2)^2



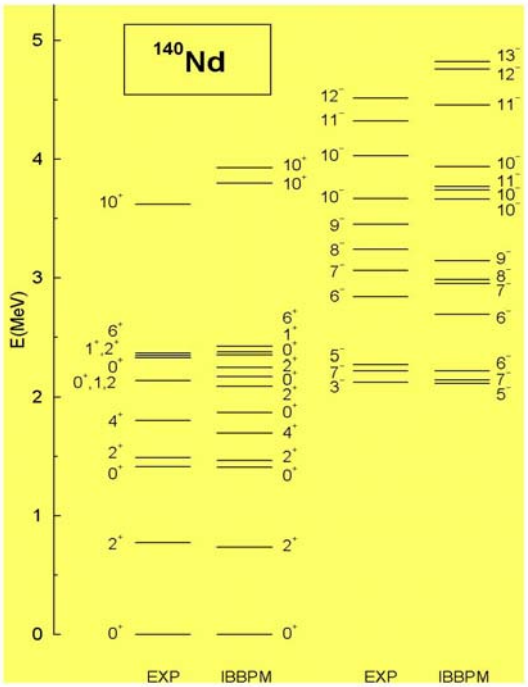
Comparison of negative–parity levels in the 0 – 1.5 MeV range observed in experiments and calculated using IBFBPM model. All the calculated levels are shown for a given spin,.

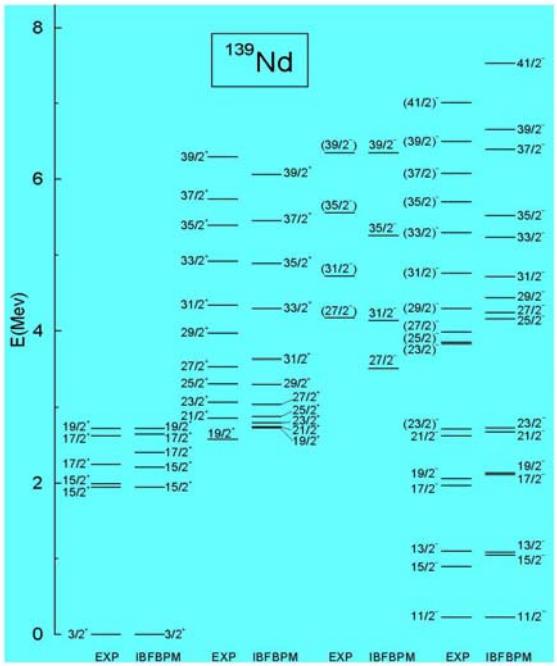


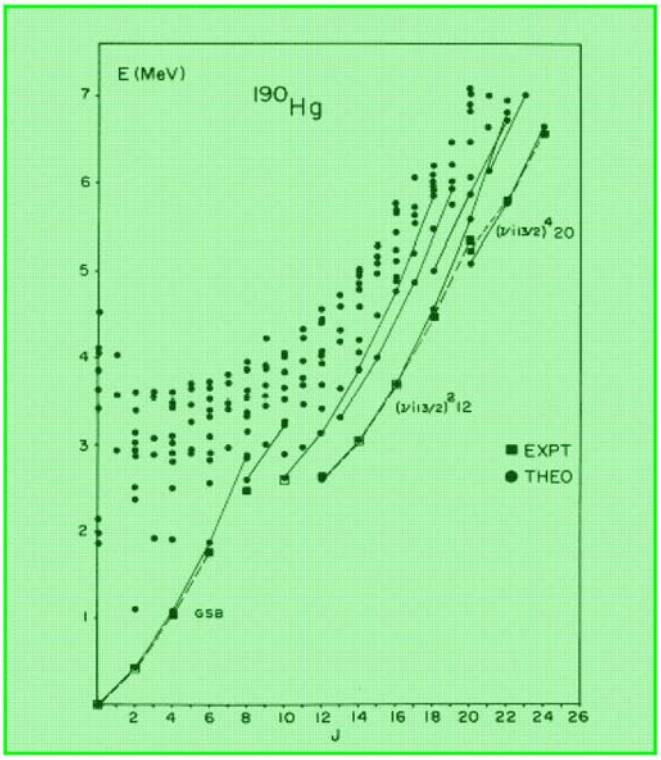
Comparison of negative–parity levels in Bands 3, 4, 5 observed in the present experiment (EXP.) and calculated using IBFBPM model (Th) up to spin $I = 41/2$.

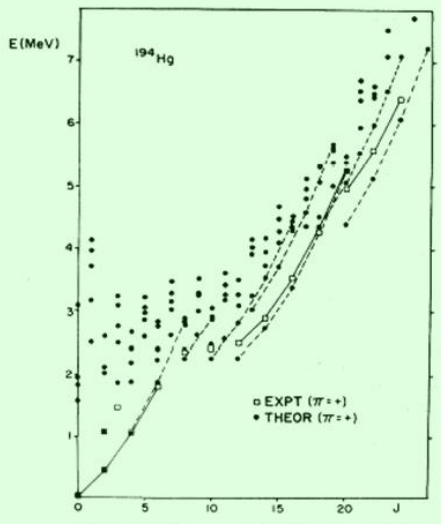
Band 3 π p1/2

Bands 4, 5 (π g9/2) (ν d5/2 ν h11/2) or (π g9/2) (ν g7/2 ν h11/2)

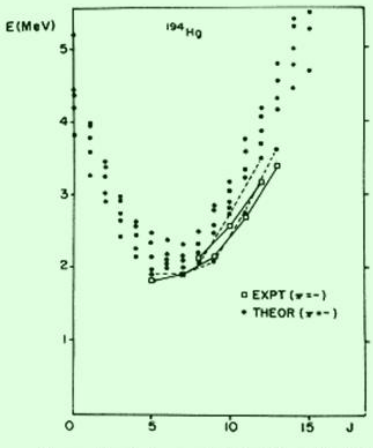

140Nd
E(MeV)
EXP
IBBPM
EXP
IBBPM


139Nd
E(Mev)
EXP
IBFBPM
EXP
IBFBPM
EXP
IBFBPM
EXP
IBFBPM

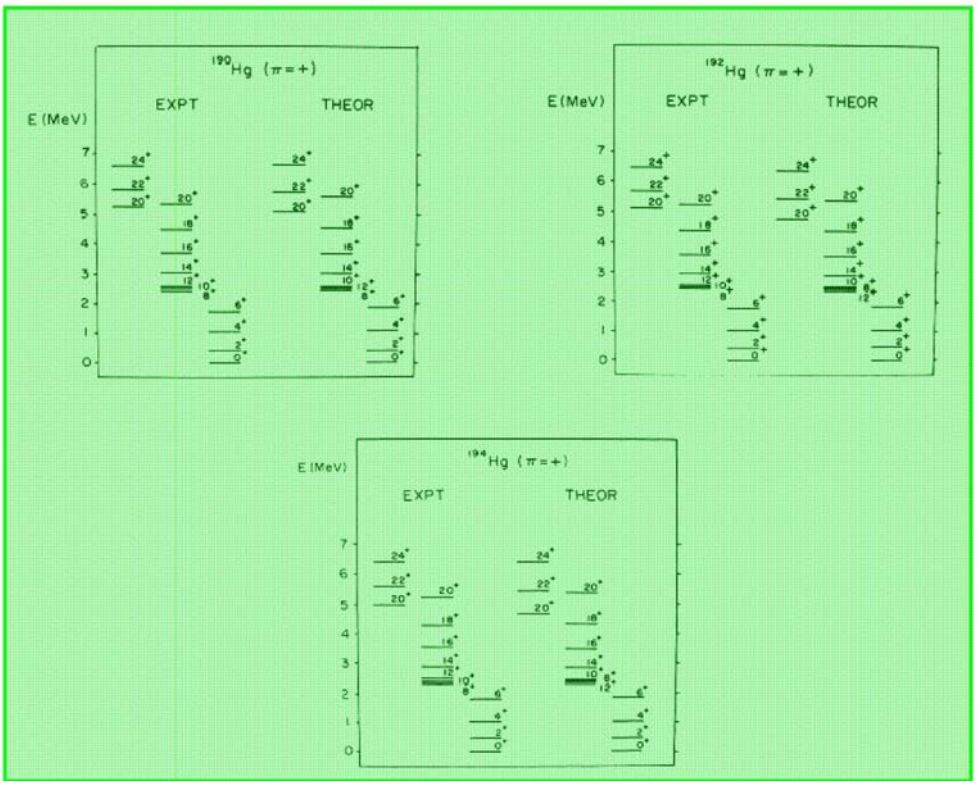


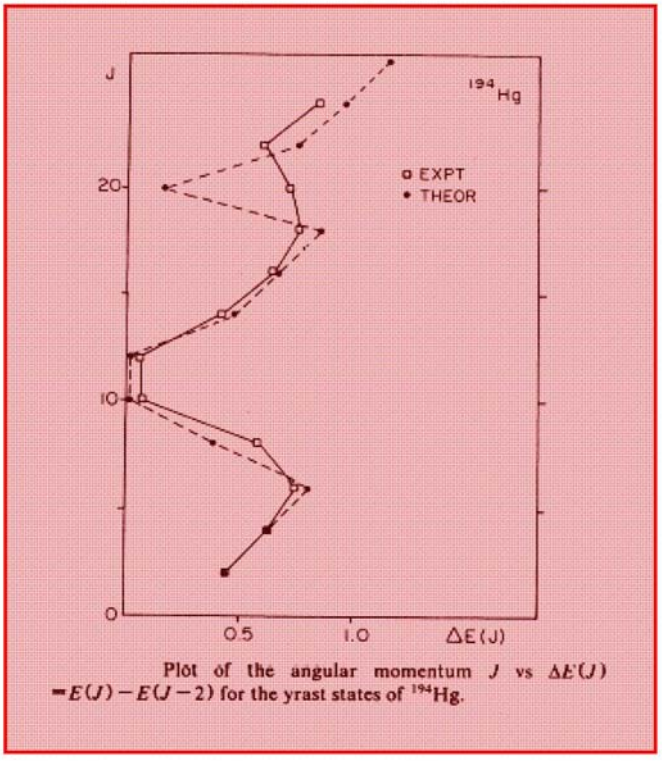


Comparison between calculated (0, 2, and 4qp) (circles) and experimental (squares) positive-parity states in ^{194}Hg. Only the first five calculated levels of each angular momentum J are shown. Sets of states with similar structure (bands) are joined together: dashed lines (calculated bands), solid lines (experimental bands).



Comparison between calculated (0 and 2qp) (circles) and experimental (squares) negative-parity states in ^{194}Hg. Only the first five calculated levels of each angular momentum J are shown. Sets of states with similar structure (bands) are joined together





Plot of the angular momentum J vs $\Delta E(J)$ $= E(J) - E(J-2)$ for the yrast states of ^{194}Hg.

Nuclear Theory:
Structure of the Odd-Odd Nuclei in the Interacting Boson Fermion-Fermion Model

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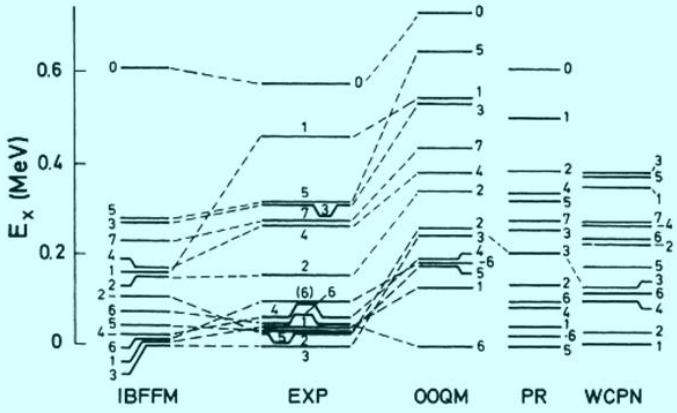
3.

Structure of odd-odd nuclei in the interacting boson fermion-fermion model

The IBFFM is able to give an accurate description of the structure of odd-odd nuclei. Odd-odd nuclei constitute a very stringent test of the model:

- A detailed knowledge of even-even cores and odd-mass neighbours is required
- Odd-odd nuclei do not provide the same sort of smoothly varying systematics as do other types of nuclei

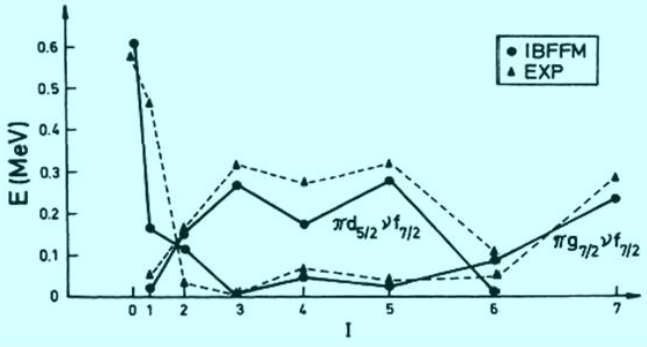
IBFFM vs other models ?



IBFFM negative-parity energy spectrum of ^{140}La compared with the experimentally known energy spectrum and three previous calculations performed using the odd-odd quasiparticle model (OOQM), the parabolic rule (PR), and the weak-coupling shell model in the proton-neutron formalism (WCPN).

IBFFM is successful in describing and predicting

- Level energies
- Electromagnetic properties
- Transfer properties
- Isomers

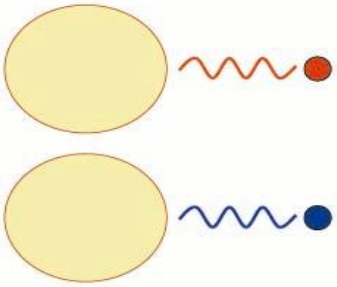


Classification of the IBFFM levels into multiplets on the basis of largest components in the wave functions. The experimental levels of ^{140}La are compared with theoretical spectra on the basis of level energies, electromagnetic de-excitation, and transfer properties. IBFFM and experimental levels are presented by solid circles and triangles respectively.

proton

neutron

boson –fermion interactions from odd – A neighbours



Important data

excitation energies

γ branchings

B(E2)

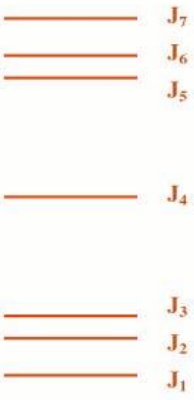
B(M1)

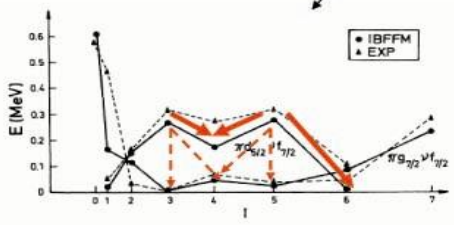
Q

μ

B(M1) for spherical soft transitional

Odd – Odd nucleus





The IBFFM Hamiltonian for an odd-odd nucleus is:

$$H = H_B + H_{\nu F} + H_{\pi F} + V_{\nu BF} + V_{\pi BF} + V_{\pi\nu}$$

H_B is the boson Hamiltonian of IBM-1 describing a system of N interacting bosons (correlated S and D pairs) that approximate the valence nucleon pairs:

$$\begin{aligned} H_B &= \varepsilon\, \hat{N} + \frac{1}{2}\, v_0 \left([d^\dagger \times d^\dagger]_{(0)} \times [\tilde{s} \times \tilde{s}]_{(0)} + h.c. \right)_{(0)} \\ &+ \frac{1}{\sqrt{2}}\, v_2 \left([d^\dagger \times d^\dagger]_{(2)} \times [\tilde{d} \times \tilde{s}]_{(2)} + h.c. \right)_{(0)} \\ &+ \sum_{L=0,2,4} \frac{1}{2}\, C_L \sqrt{2L+1} \left([d^\dagger \times d^\dagger]_{(L)} \times [\tilde{d} \times \tilde{d}]_{(L)} \right)_{(0)} \end{aligned}$$

$$n_s = N - n_d$$

$H_{\pi F}$ and $H_{\nu F}$ are the fermion Hamiltonians containing quasiparticle energies of protons and neutrons, respectively. The quasiparticle energies and occupation probabilities contained in the fermion Hamiltonian, and other terms, are obtained in a BCS calculation with some standard set of single fermion energies. For protons ($\alpha = \pi$) and for neutrons ($\alpha = \nu$).

$$H_{\alpha F} = \sum_i \varepsilon_{\alpha_i}\, a^\dagger_{\alpha_i} \tilde{a}_{\alpha_i}$$

$V_{\nu BF}$ and $V_{\pi BF}$ are the IBFM-1 boson-fermion interactions containing the dynamical, exchange and monopole interactions. For protons ($\alpha = \pi$) and for neutrons ($\alpha = \nu$).

$$V_{\alpha BF} = V_{\alpha DYN} + V_{\alpha EXC} + V_{\alpha MON}$$

$$V_{\alpha DYN} = \Gamma_0 \sum_{\alpha j_1 \alpha j_2} \sqrt{5}\, (u_{\alpha j_1} u_{\alpha j_2} - v_{\alpha j_1} v_{\alpha j_2})\, \langle \alpha j_1 \parallel Y_2 \parallel \alpha j_2 \rangle \left([a^\dagger_{\alpha j_1} \times \tilde{a}_{\alpha j_2}]^{(2)} \times Q_B^{(2)} \right)^{(0)}$$

$Q_B^{(2)}$ is the standard boson quadrupole operator

$$Q_B^{(2)} = [s^\dagger \times \tilde{d} + d^\dagger \times \tilde{s}]^{(2)} + \chi [d^\dagger \times \tilde{d}]^{(2)}$$

$$V_{\alpha EXC} = A_0 \sum_{\alpha j_1 \alpha j_2 \alpha j_3} (-2) \sqrt{\frac{5}{2\ \alpha j_3 + 1}} \ (u_{\alpha j_1} v_{\alpha j_3} + v_{\alpha j_1} u_{\alpha j_3}) \ \ (u_{\alpha j_2} v_{\alpha j_3} + v_{\alpha j_2} u_{\alpha j_3})$$
$$\langle \alpha j_3 \parallel Y_2 \parallel \alpha j_1 \rangle \ \langle \alpha j_3 \parallel Y_2 \parallel \alpha j_2 \rangle \ : \left([a^\dagger_{\alpha j_1} \times \tilde{d}\ ]_{\alpha j_3} \times [\tilde{a}_{\alpha j_2} \times d^\dagger\ ]_{\alpha j_3} \right)^{(0)} :$$

$$V_{\alpha MON} = A_0 \sum_{\alpha j} \sqrt{5}\ (2\alpha j + 1)\ \left([a^\dagger_{\alpha j} \times \tilde{a}_{\alpha j}]^{(0)} \times [d^\dagger \times \tilde{d}]^{(0)} \right)^{(0)}$$

$V_{\pi\nu}$ is the residual proton-neutron interaction taken in the form of spin-spin, surface-delta, spin-spin-delta, tensor or multipole-multipole interaction.

$$H_{\sigma\sigma} = -\sqrt{3}\ V_{\sigma\sigma}\ [\vec{\sigma}_\pi \cdot \vec{\sigma}_\nu]$$

$$H_\delta = 4\pi\ V_\delta\ \delta(\vec{r}_\pi - \vec{r}_\nu)\ \delta(r_\pi - R_0)\ \delta(r_\nu - R_0)$$

$$H_{\sigma\sigma\delta} = 4\pi\ V_{\sigma\sigma\delta}\ [\vec{\sigma}_\pi \cdot \vec{\sigma}_\nu]\ \delta(\vec{r}_\pi - \vec{r}_\nu)\ \delta(r_\pi - R_0)\ \delta(r_\nu - R_0)$$

$$H_T = V_T \left(3\ \frac{[\vec{\sigma}_\pi \cdot \vec{r}_{\pi\nu}]\ [\vec{\sigma}_\nu \cdot \vec{r}_{\pi\nu}]}{r^2_{\pi\nu}} - [\vec{\sigma}_\pi \cdot \vec{\sigma}_\nu] \right)$$

$$H_{MM} = 4\pi\ \frac{\delta(r_\pi - r_\nu)}{r_\pi r_\nu} \sum_{\kappa\mu} V_\kappa\ Y^*_{\kappa\mu}(\pi)\ Y_{\kappa\mu}(\nu)$$

$$\vec{r}_{\pi\nu} = \vec{r}_\pi - \vec{r}_\nu \qquad R_0 = 1.2\ A^{\frac{1}{3}}\ \ fm$$

The electromagnetic operators have the form (for protons ($\alpha = \pi$) and for neutrons ($\alpha = \nu$)):

$$M(E2) = M_B(E2) + M_\pi(E2) + M_\nu(E2)$$

$$M_B(E2) = \frac{3}{4\pi} R_0^2 \, e^{eff} \left([s^\dagger \times \tilde{d} + d^\dagger \times \tilde{s}]^{(2)} + \chi [d^\dagger \times \tilde{d}]^{(2)} \right)$$

$$R_0^2 = 0.0144 \, A^{\frac{2}{3}} \quad barn$$

$$M_\alpha(E2) = \frac{3}{5} R_0^2 \, e_\alpha \, Y_2(\alpha)$$

$$\vec{M}(M1) = \vec{M}_B(M1) + \vec{M}_\pi(M1) + \vec{M}_\nu(M1)$$

$$\vec{M}_B(M1) = \sqrt{\frac{3}{4\pi}} \sqrt{10} \, g_R \, [d^\dagger \times \tilde{d}]^{(1)}$$

$$\vec{M}_\alpha(M1) = \sqrt{\frac{3}{4\pi}} \, [\, g_l(\alpha) \, \vec{l}(\alpha) + g_s(\alpha) \, \vec{s}(\alpha) + g_T(\alpha) \, (Y_2(\alpha) \times \vec{s}(\alpha))_1 \,]$$

Spherical nuclei

Parabolic rule for proton-neutron multiplets in the particle-vibration model

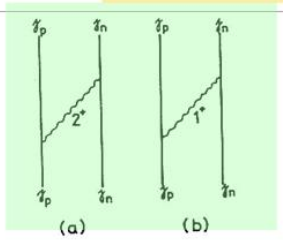
Exchange of the quadrupole phonon

The particle-quadrupole vibration interaction is

$$H_2 = \sqrt{20\pi}a_2|Y_2(b_2^\dagger + b_2)|_0$$

$$a_2 = \tfrac{1}{3}(4\pi)^{\frac{1}{2}}\frac{1}{ZR_0^2}\langle k\rangle[B(\mathrm{E2};2_1^+ \to 0_1^+)_{\mathrm{vib}}]^{\frac{1}{2}}$$

For the quasiparticle, we also include the usual blocking factors U and V in interaction strength a_2. The symbol $b_2^\dagger$ denotes the creation operator of the quadrupole phonon.



Second order diagrams for the exchange of the quadrupole (Fig. a) and spin-vibrational phonons (Fig. b).

The contribution to the splitting of the multiplet $|(j_p, j_n)I = |j_p - j_n|, \ldots, j_p + j_n\rangle$ coming from the exchange of quadrupole phonons **(Fig. a) is**

$$\delta E_2 = -\alpha_2 \nu \cdot \frac{[I(I+1) - j_n(j_n+1) - j_p(j_p+1)]^2 + [I(I+1) - j_n(j_n+1) - j_p(j_p+1)]}{2j_n(2j_n+2)2j_p(2j_p+2)} + \frac{\alpha_2 \nu}{12},$$

$$\alpha_2 = 15a_2^2/\hbar\omega_2$$

$\hbar\omega_2$ is the energy of the quadrupole phonon. We assume the coupling strength a_2 to be equal both for protons and for neutrons.

We rewrite the I-dependent terms

$$\delta E_2(I) = A[I(I+1)]^2 + BI(I+1)$$

where A and B stand for the factors which multiply $[I(I+1)]^2$ and $I(I+1)$ respectively.

The quantity ν is the occupation number defined as $\nu = 1$ if $|j_n\rangle$ and $|j_n\rangle$ are **both particle-like or both hole-like: $\nu = -1$ if $|j_n\rangle$ is particle-like and $|j_n\rangle$ is hole-like, or vice versa.**

Inclusion of the spin-vibrational 1^+ phonon

The particle-spin-vibration interaction is given by the equation:

$$H_1 = \sqrt{3}a_1[\sigma_1 \times (b_1^\dagger + b_1)]_0$$

a_1 is the coupling strength defined as $a_1 = \kappa_1(\hbar\omega_1/2c_1)^{\frac{1}{2}}$, σ_1 is the spin operator and $b_1^\dagger$ the creation operator of the $\lambda = 1^+$ spin vibration

We derive the expression for the contribution to the energy shift of the $|(j_p j_n)I\rangle$ states due to the exchange of the 1^+ phonon

$$\delta E_1(I) = B_1 I(I+1) + \alpha_1 \frac{j_n(j_n+1)+j_p(j_p+1)}{(2j_n+2)(2j_p+2)}$$

$$B_1 = -\alpha_1 \frac{\xi}{(2j_p+2)(2j_n+2)} \qquad \alpha_1 = 4\frac{a_1^2}{\hbar\omega_1}$$

$$\xi = \begin{cases} 1 & \text{if } \mathcal{N} = -1, \quad \dfrac{(2j_p+2)(2j_n+2)}{2j_p 2j_n} \quad \text{if } \mathcal{N} = 1, \\ -\dfrac{2j_p+2}{2j_p} & \text{if } \mathcal{N} = 0^-, \quad -\dfrac{2j_n+2}{2j_n} \quad \text{if } \mathcal{N} = 0^+. \end{cases}$$

$\mathcal{N}$ is the Nordheim number defined as

$$\mathcal{N} = j_p - l_p + j_n - l_n$$

For $\mathcal{N} = 0$, we use the labels $-$ and $+$. The symbols $\mathcal{N} = 0^-$ and $\mathcal{N} = 0^+$ denote the situations $j_n - l_n = -\frac{1}{2}$, $j_p - l_p = \frac{1}{2}$ and $j_n - l_n = \frac{1}{2}$, $j_p - l_p = -\frac{1}{2}$, respectively.

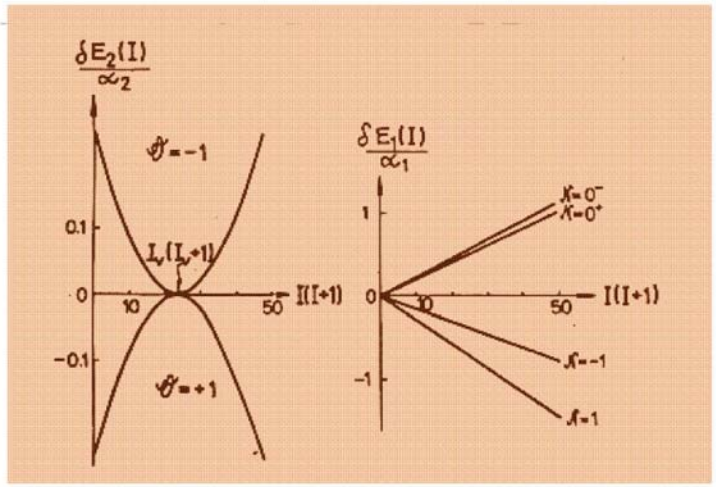
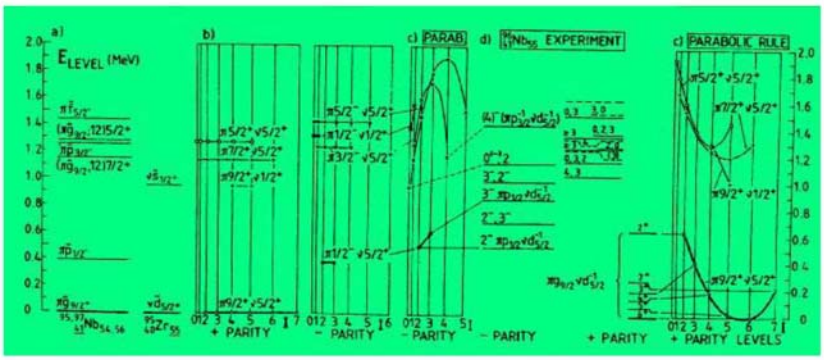
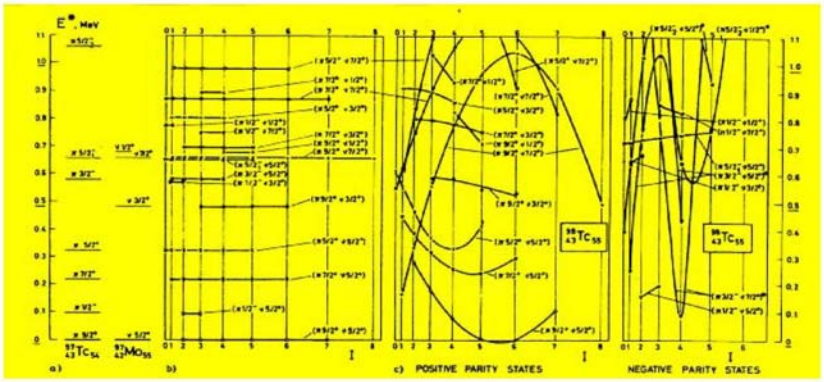
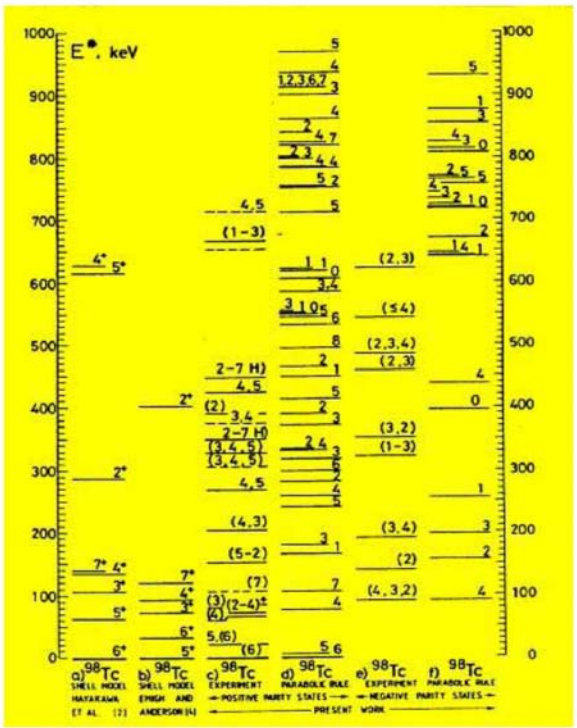


Illustration of energy contributions coming from the exchange of the quadrupole phonon (a) and the spin-vibrational phonon (b) for the multiplet ($j_p = \frac{5}{2}$, $j_n = \frac{7}{2}$), for four possible combinations of the pair ($\mathcal{N}$, $\mathcal{N}$).

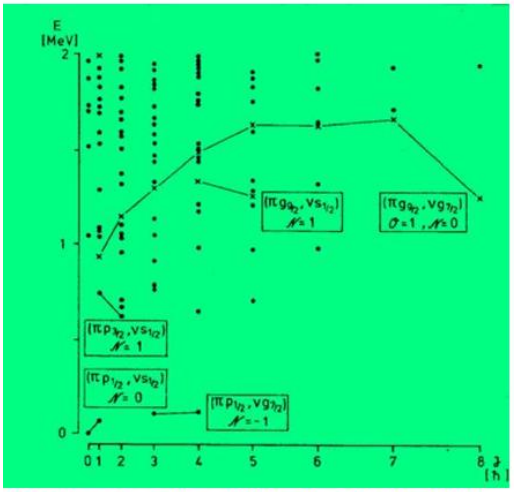

a)
E LEVEL (MeV)
b)
c) PARAB
d) EXPERIMENT
c) PARABOLIC RULE
+ PARITY
− PARITY
+ PARITY LEVELS


E*, MeV
I
c) POSITIVE PARITY STATES
NEGATIVE PARITY STATES

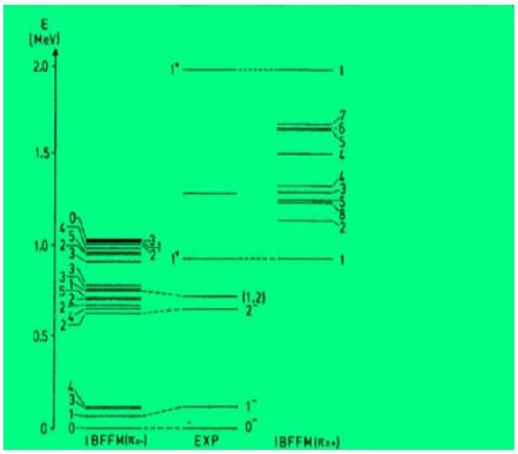

E*, keV
a) 98Tc SHELL MODEL HAYAKAWA ET AL. [2]
b) 98Tc SHELL MODEL EMISH AND ANDERSON [4]
c) 98Tc EXPERIMENT
d) 98Tc PARABOLE RULE
e) 98Tc EXPERIMENT
f) 98Tc PARABOLE RULE
POSITIVE PARITY STATES
NEGATIVE PARITY STATES
PRESENT WORK

For spherical nuclei, with only the dynamical interaction and $\chi = 0$ → $\Gamma_0 = a\sqrt{\frac{4\pi}{5N}}$

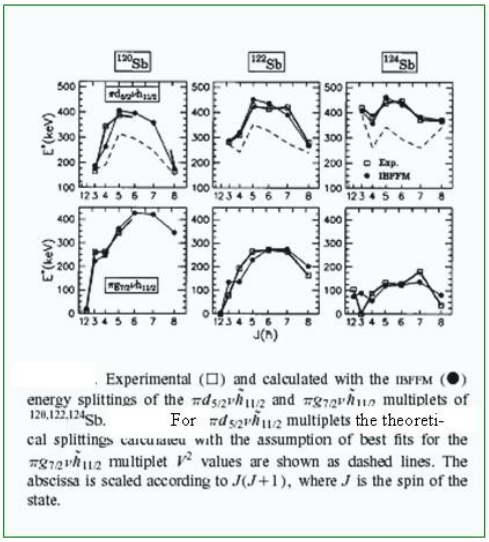
^{96}Y



Negative and positive parity levels of ^{96}Y calculated in IBFFM. Negative parity levels are denoted by full circles and positive parity by crosses. The states classified in the same multiplet on the basis of largest components in the wave function, are connected by the full line.



IBFFM positive- and negative-parity energy spectrum of ^{96}Y in comparison to available experimental data. The excitation energy of the 8* level is not known, but should amount to ≥ 1 MeV,



Experimental (□) and calculated with the IBFFM (●) energy splittings of the $\pi d_{5/2}\nu\tilde{h}_{11/2}$ and $\pi g_{7/2}\nu\tilde{h}_{11/2}$ multiplets of ^{120,122,124}Sb. For $\pi d_{5/2}\nu\tilde{h}_{11/2}$ multiplets the theoretical splittings calculated with the assumption of best fits for the $\pi g_{7/2}\nu\tilde{h}_{11/2}$ multiplet V^2 values are shown as dashed lines. The abscissa is scaled according to $J(J+1)$, where J is the spin of the state.

For the whole sequence of nuclei the following are the same:

Cores

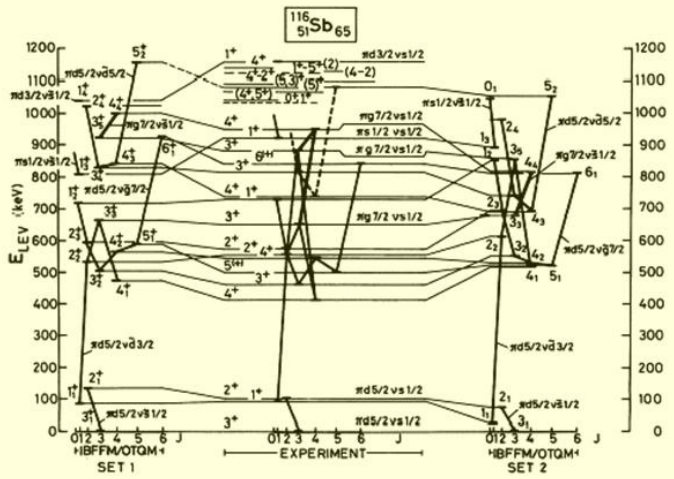
Dynamical, exchange and monopole interactions for protons

Dynamical, exchange and monopole interactions for neutrons

Occupation probabilities for protons

Residual proton-neutron delta interaction

Occupation probabilities for neutrons depend on the isotope → Parabolic like structures are present in spherical nuclei even in cases when other interactions (not the dynamical) dominate.



IBFFM energy spectrum of ^{116}Sb in comparison with experimental data. The solid lines connect the members of the given multiplets. The leading proton-neutron configurations for several multiplets were identified on the basis of the (^{3}He, d) proton transfer results.

Comparison of measured and calculated in IBFFM spectroscopic factors for the ^{121}Sb(p, d)^{120}Sb one neutron transfer reaction. The first two columns contain the energy, spin and parity of the final states involved in the reaction.

Energy (keV)	J^π	ℓ_n	$S_{(p,d)}$ [a]	S_{IBFFM} [b]
0	1^+	2	0.11	0.15
78	3^+	0	0.19	0.12
149	3^+	0	0.05	0.03
166	3^-	5	0.63	0.44
193	2^+	0	0.11	0.08
		2	0.07	0.05
233	2^+	0	0.06	0.03
		2	0.12	0.05
334	$4^{(+)}$	2	0.10	0.19
343	$4^{(-)}$	5	0.54	0.39
387	$(3-5)$	5	0.44	0.61
390	$(2,3)^+$	2	0.06	0.07
438	(2)	0	0.01	0.02
		2	0.02	0.13

a Reference [9]
b $S(2j_{target}+1)$

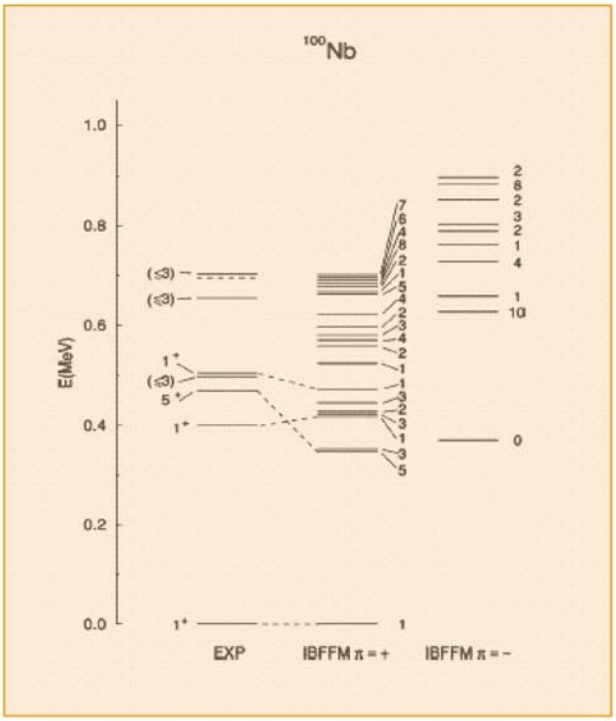
Comparison of measured and calculated in IBFFM spectroscopic factors for the one neutron transfer reaction ^{122}Sb. The first two columns contain the energy, spin and parity of the final states involved in the reaction.

Energy (keV)	J^π	ℓ_n	$S_{(p,d)}$ [a]	ℓ_n	$S_{(d,t)}$ [b]	S_{IBFFM} [d]	ℓ_n	$S_{(d,p)}$ [c]	S_{IBFFM}
0	2^-	5	0.20		0.46	0.46			
61	3^+	0	0.23	(0)	0.45	0.13	(2)	0.05	0.00
78	3^-	5	0.46			0.52			
121	1^+						(2)	0.30	0.47
137	5^+	2	0.38	(2)	0.37	0.20			
164	8^-	5	0.50			0.53			
167	2^+	2	0.10			0.14	(2)	0.09	0.09
193	4^-	5	0.41			0.58			
210	4^+	0	0.30	(0)	0.34	0.11			
255	3^+						0	0.34	0.44
264	5^-					0.66			
265	7^-	5	0.62			0.57			
272	6^-					0.68			
283	3^-						(5)	2.40	0.40
311	4^-						(5)	0.80	0.43
323	2^+						0	0.30	0.40
334	3^+	2	0.07		0.09	0.22	2	0.16	0.01
394	4^+						2	0.45	0.46
397	2^+	2	0.03		0.10		2	0.45	0.38
414	6^-								0.55
≈ 420	7^-	5	0.03			0.16	(5)	1.70	0.43
425	5^-								0.49
481	4^+	2	0.19	(2)	0.30	0.22			
484	3^+						2	0.51	0.60

a Reference [9]
b Reference [7]
c Reference [13]
d $S(2j_{target}+1)$

Magnetic dipole (μ in μN) and electric quadrupole (Q in c b) moments of some $^{120\text{-}124}$Sb states.

Nucleus	E^*	J^π	μ_{expt} [a]	μ_{IBFFM}	Q_{expt} [a]	Q_{IBFFM}
^{120}Sb	0 keV	1^+	±2.34(22)	+2.25		−0.10
	78 keV	3^+	+2.584(6)	+2.67	±0.41(4)	−0.47
		8^-	±2.34(4)	+2.45		−0.51
^{122}Sb	0 keV	2^-	−1.905(20)	−2.33	+0.85(11)	−0.08
	61 keV	3^+	+2.983(12)	+3.07	±0.41(4)	−0.48
	137 keV	5^+	+3.05(10)	+3.07		−0.62
^{124}Sb	0 keV	3^-	±1.20(2)	−1.23	+1.87(38)	+0.35
	41 keV	3^+	+2.970(33)	+3.01		−0.46
	125 keV	6^-	+0.384(12)	+0.36		+0.16



1^+ π g9/2 ν g7/2

5^+ π g9/2 ν s1/2

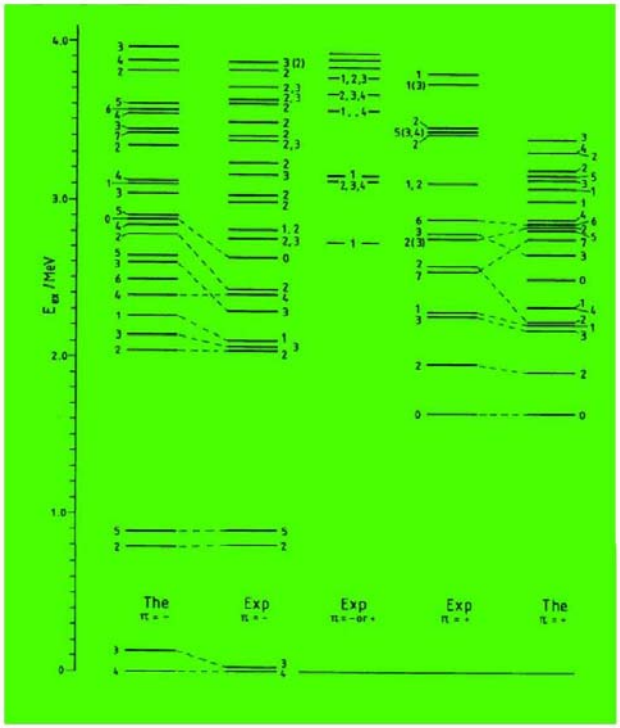
8^+ π g9/2 ν g7/2

10^- π g9/2 ν h11/2

5^+ 1.5 s isomer

10^- possibly 100 – 150 keV higher

10^- or 8^+ candidates for the 12 μs isomer

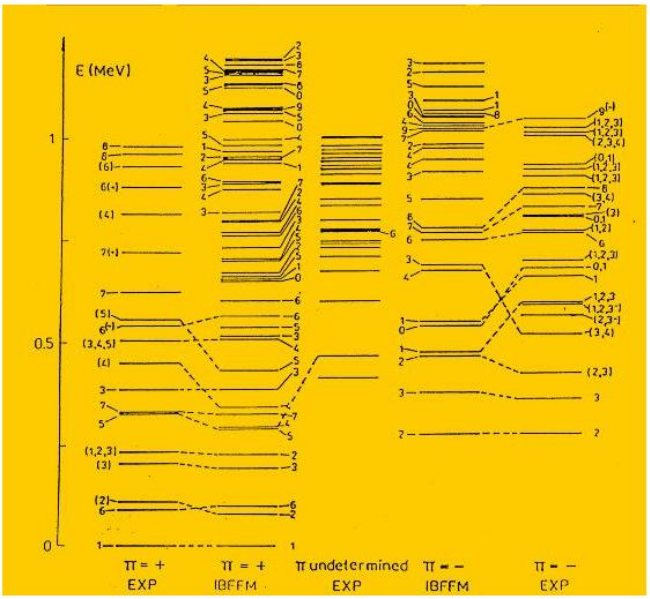


^{40}K

State (keV)	$T_{1/2}$	
	Exp	The
3_1^- (30)	4.24(8) ns	5.2 ns
2_1^- (800)	0.28(4) ps	0.23 ps
5_1^- (891)	0.87(14) ps	0.6 ps
2_2^- (2047)	0.34(4) ps	0.3 ps
3_2^- (2070)	0.47(10) ps	0.1 ps
1_1^- (2104)	0.52(10) ps	0.14 ps
4_2^- (2397)	0.035(14) ps	0.03 ps
0_1^- (2626)	0.21(4) ps	0.2 ps
1_1^+ (2290)	0.083(14) ps	0.25 ps
3_2^+ (2787)	<0.04 ps	0.07 ps
6_1^+ (2879)	0.27(10) ps	0.6 ps

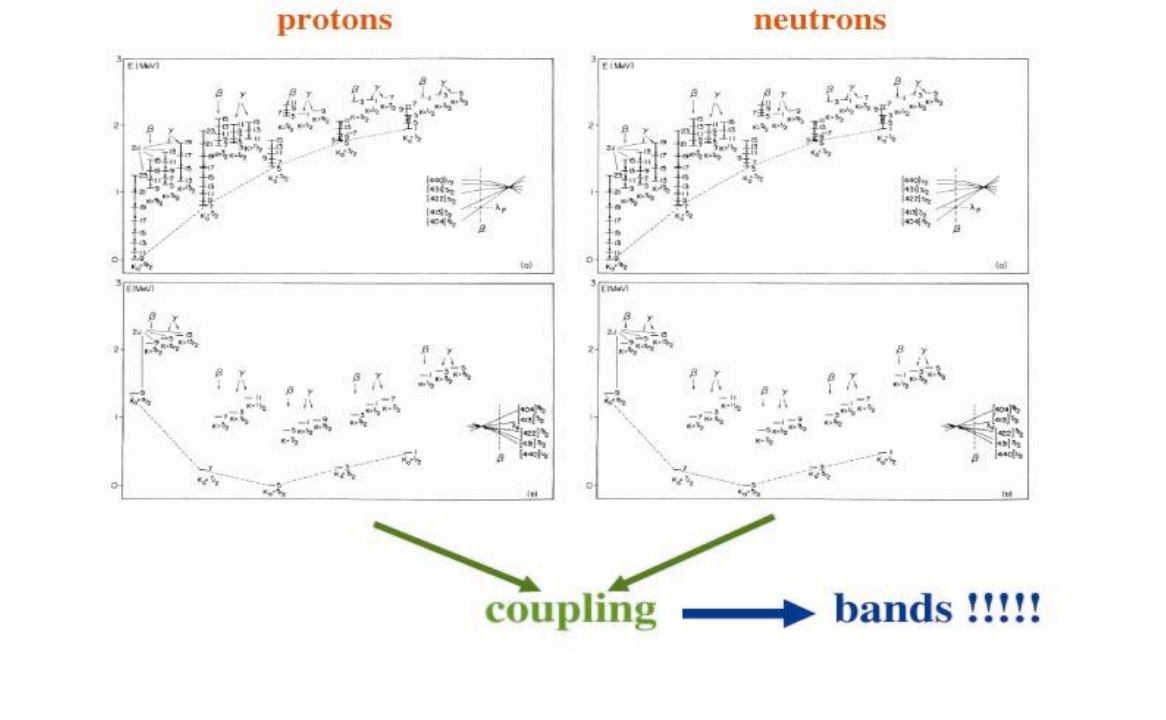
^{40}K

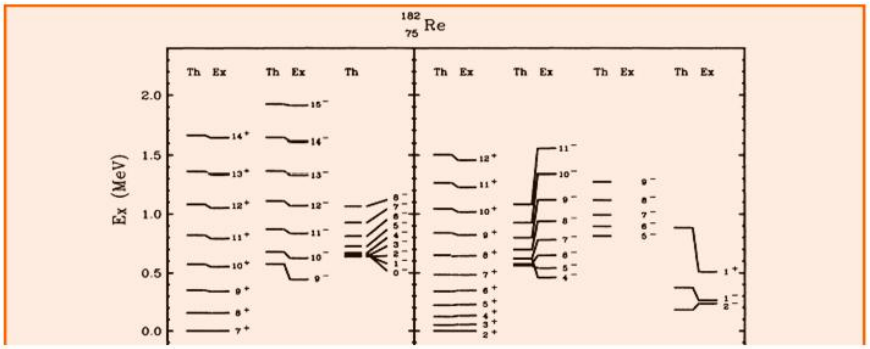
Transition[a]		E_{tr}/keV	Gamma-branching	
			Exp[b]	The[c]
2_1^- (800)	$\rightarrow 4_1^-$ (0)	800	0.15	0.17
	$\rightarrow 3_1^-$ (30)	770	100	100
5_1^- (891)	$\rightarrow 4_1^-$ (0)	891	99	99
	$\rightarrow 3_1^-$ (30)	862	1	0.1
2_2^- (2047)	$\rightarrow 4_1^-$ (0)	2047	29	128
	$\rightarrow 3_1^-$ (30)	2018	29	100
	$\rightarrow 2_1^-$ (800)	1247	41	41
3_2^- (2070)	$\rightarrow 4_1^-$ (0)	2070	36	56
	$\rightarrow 3_1^-$ (30)	2040	49	49
	$\rightarrow 2_1^-$ (800)	1270	9	6
	$\rightarrow 5_1^-$ (891)	1178	7	3
1_1^- (2104)	$\rightarrow 3_1^-$ (30)	2074	70	70
	$\rightarrow 2_1^-$ (800)	1304	29	96
	$\rightarrow 2_2^-$ (2047)	57	—	0.1
	$\rightarrow 3_2^-$ (2070)	34	—	0.0
4_2^- (2397)	$\rightarrow 4_1^-$ (0)	2397	26	7
	$\rightarrow 3_1^-$ (30)	2367	67	67
	$\rightarrow 2_1^-$ (800)	1597	—	0.4
	$\rightarrow 5_1^-$ (891)	1506	—	0.1
	$\rightarrow 2_2^-$ (2047)	350	—	0.0
	$\rightarrow 3_2^-$ (2070)	327	7	1
	$\rightarrow 3_3^-$ (2291)	106	—	0.01
0_1^- (2626)	$\rightarrow 2_1^-$ (800)	1826	30	41
	$\rightarrow 2_2^-$ (2047)	579	—	0.001
	$\rightarrow 1_1^-$ (2104)	522	70	70
	$\rightarrow 2_3^-$ (2419)	207	—	0.0
1_1^+ (2290)	$\rightarrow 0_1^+$ (1644)	646	56	56
	$\rightarrow 2_1^+$ (1959)	331	9	10
	$\rightarrow 3_1^+$ (2260)	30	—	0.0
3_2^+ (2787)	$\rightarrow 2_1^+$ (1959)	828	17.4	17.4
	$\rightarrow 3_1^+$ (2260)	527	—	0.5
	$\rightarrow 1_1^+$ (2290)	497	—	0.0
	$\rightarrow 2_2^+$ (2576)	211	—	0.0
	$\rightarrow 2_3^+$ (2757)	30	—	0.0



The structure of ^{106}Ag is very complex. Ground states of odd-mass Ag nuclei are $7/2^+$ states based on the proton g9/2 configuration. The IBFFM is successful in the description even of such nuclei.

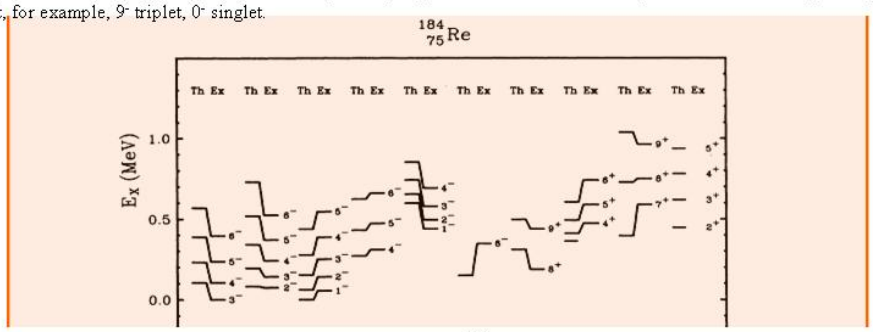
Deformed nuclei





I IBFFA-calculated excitation energies for states in odd-odd ^{182}Re compared with experimental data. Because the experimental separation b between the 7^+ triplet and the 2^- singlet couplings is not known, the figure is divided into two parts, using each coupling as the reference point. Otherwise the triplet coupling is shown on the left of a pair of bands, the singlet coupling on the right, for example, 9^- triplet, 0^- singlet.

Scholten PRC 37



IBFFA-calculated excitation energies for states in odd-odd ^{184}Re compared with experimental data. The bands are plotted in pairs, with the triplet coupling on the left, the singlet coupling on the right of each pair.

Quadrupole moments for odd-odd Re isotopes.

Isotope	J^π	Q_{IBA} (e b)	Q_{exp} (e b)
^{180}Re	6^-	6.50	
	1^-	6.45	
^{182}Re	7^+	5.66	<6.4
	2^+	5.40	>6.6
^{184}Re	3^-	5.06	7.9 ± 0.7
	8^+	4.83	

Magnetic moments for odd-odd Re isotopes.

Isotope	J^π	μ_{IBA} (μ_{N})	μ_{exp} (μ_{N})
^{180}Re	6^-	2.41	
	1^-	2.35	
^{182}Re	7^+	2.33	2.76 ± 0.07
	2^+	3.28	3.07 ± 0.24
^{184}Re	3^-	3.19	2.50 ± 0.19
	8^+	2.09	2.89 ± 0.13

The investigations of odd-A nuclei have revealed the following decoupled–strongly coupled rule:

(i) The strongly coupled band pattern arises if the odd fermion is a particle coupled to an oblate core, or a hole coupled to a prolate core.

(ii) The decoupled band pattern arises if the odd particle is coupled to a prolate core or a hole to the oblate core.

This rule was extended to odd-odd nuclei in the case of coupling two quasiparticles to the asymmetric rotor.

Rules (i) and (ii) can be expressed in terms of quadrupole moments of the odd particle and the core Taking into account the signs of quadrupole moments $Q(j)<0$, $Q(j^{-1})>0$, $Q(2_1^{\mathrm{prolate}})<0$, and $Q(2_1^{\mathrm{oblate}})>0$, the rule reads

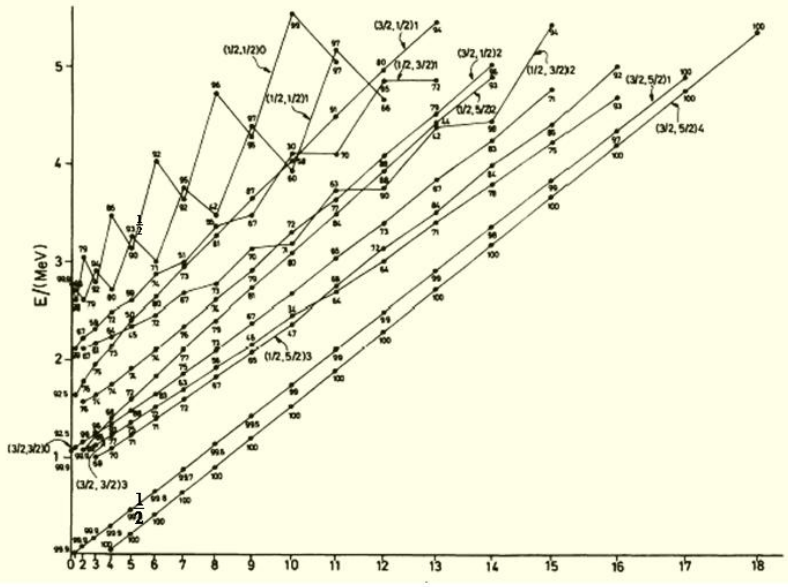
$$\text{if } Q(\bar{j})\cdot Q(2_1^{\mathrm{core}}) \begin{cases} <0, & \text{the band is strongly coupled} \\ >0, & \text{the band is decoupled} , \end{cases}$$

where $\bar{j}$ denotes the odd quasiparticle coupled to the core.

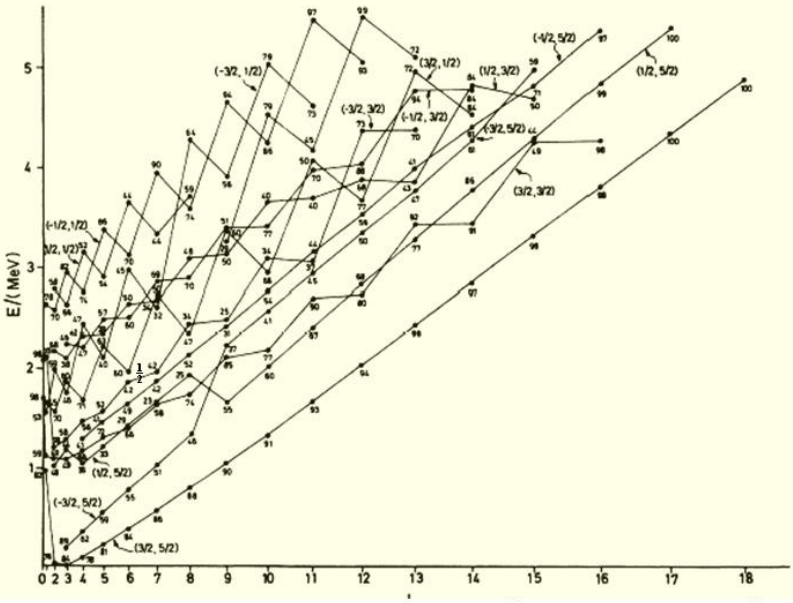
This rule is of more general character, independent of the particular nature of the core. It applies as well to the IBFM and IBFFM.

We note that the case of two particles or holes coupled to the core, referred to as the "peaceful" case in the particle–plus–asymmetric rotor model, corresponds to the inverted parabola of the parabolic rule for odd-odd nuclei;[2] this yields the bandheads with angular momenta $J=j_p+j_n$ and $J=|j_p-j_n|$ as the lowest states on two branches of the parabola.

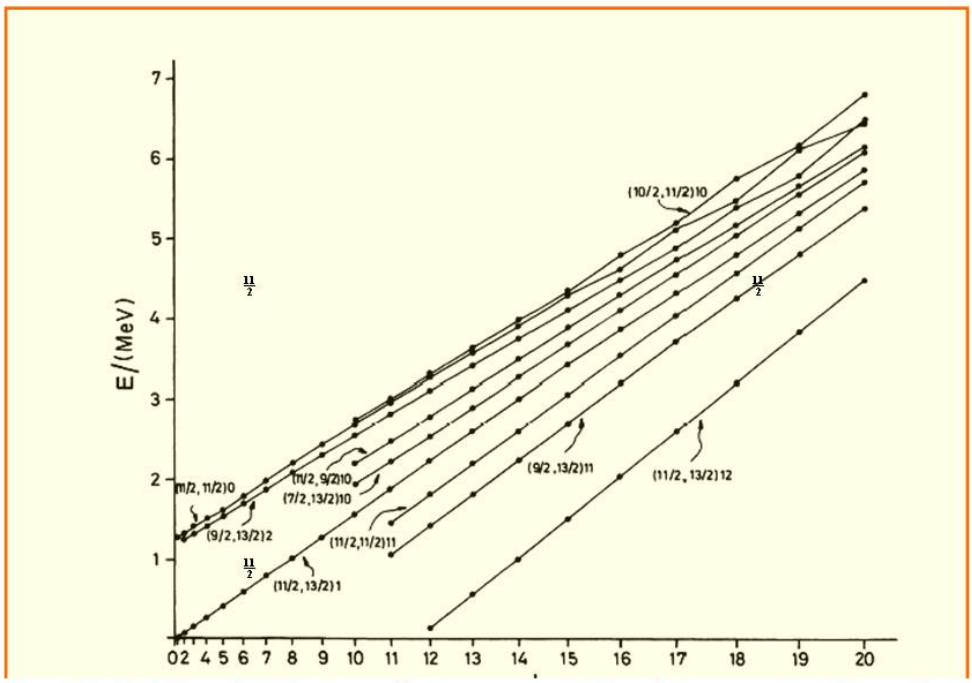
By coupling the proton particle j_1 and the neutron particle j_2 to the SU(3) boson core, there arise $2(j_1+\frac{1}{2})(j_2+\frac{1}{2})$ bands, based on the states of angular momenta $J=J_1\pm J_2$, with $J_1=j_1, j_1-1, \ldots, \frac{1}{2}$ and $J_2=j_2, j_2-1, \ldots, \frac{1}{2}$. For the particular interaction strengths Γ_1^{SUSY} and Γ_2^{SUSY} the band based on the lowest $J=j_1+j_2$ state exhibits an exact $J(J+1)$ energy rule, with the same moment of inertia as for the ground-state band of the boson core. Furthermore, the states of this band are characterized by the exact quantum numbers $(K_1=j_1, K_2=j_2)K=j_1+j_2$, defined according to the IBFFM relation: The other IBFFM bands in the odd-odd system deviate from the $J(J+1)$ energy rule, in general, more so with increasing energy (decrease of K_1, K_2). Simultaneously, the IBFFM wave functions expressed in the KR basis are a mixture of different K values. However, in each state a particular KR basis state dominates. In this way we can attribute approximate quantum numbers $(K_1, K_2)K$ to each state.



Twelve ground state bands calculated in the IBFFM for the odd-odd system with $j_1 = \frac{1}{2}$ proton hole and $j_2 = \frac{5}{2}$ neutron hole coupled to the SU(3) prolate boson core. The $J(J+1)$ scale is employed for the angular momentum axis.

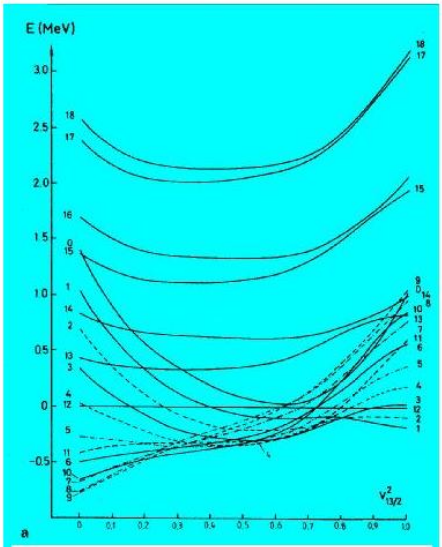


The IBFFM ground state bands for the odd-odd system with $j_1 = \frac{1}{2}$ proton particle and $j_2 = \frac{5}{2}$ neutron hole coupled to the SU(3) prolate boson core.

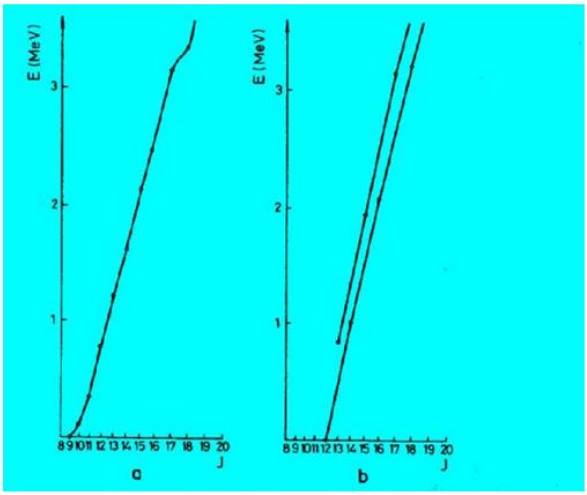


Lowest bands in the odd-odd system with $j_1 = \frac{11}{2}$ proton hole and $j_2 = \frac{11}{2}$ neutron hole coupled to the SU(3) prolate boson core.

Realistic case: Dynamical and exchange interactions different from zero and not limited by supersymmetry constraints

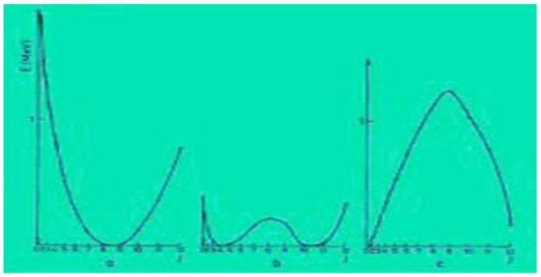


Calculated IBFFM yrast states (0_1, 1_1, …, 20_1) for $_{\pi}$ = , ν=$_{13/2}$ coupled to an O(6) core, as a function of $_{3/2}$.



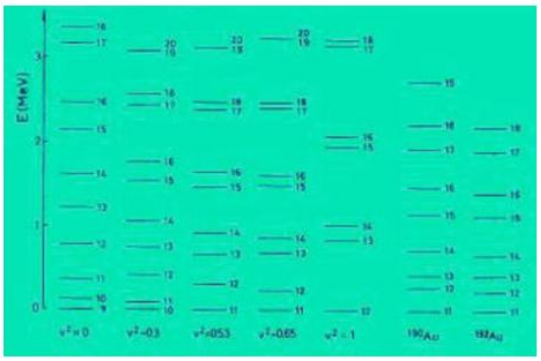
E/J plots for the lowest-lying high-spin bands for $\nu_{3/2} = 0$ (Fig. a), and $\nu_{3/2} = 1$ (Fig. b).

E/J plots for the levels 1, 2, …., 12, for $\nu_{3/2}$=0 (Fig. a), $\nu_{3/2}$=0.5 (Fig. b) and $\nu_{3/2}$=1 (Fig.c). The scale on the abscissa is given by $J(J+1)$; points for levels are connected by curves to guide the eye.



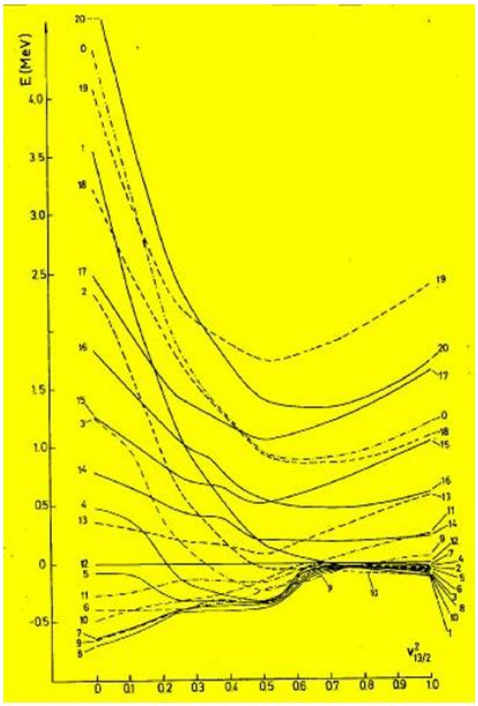
The head of the lowest high-spin band is

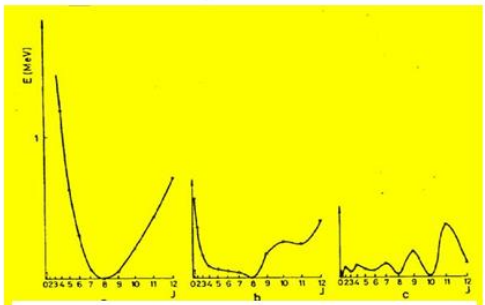
$J = j_\pi + j_\nu - 3 = 9$ for $\nu_{3/2} \sim 0.2$,
$J = j_\pi + j_\nu - 2 = 10$ for $0.2\nu_{3/2} \sim 0.2$,
$J = j_\pi + j_\nu - 1 = 11$ for $0.5\nu_{3/2} \sim 0.8$
and
$J = j_\pi + j_\nu = 12$ for $0.8\nu_{3/2} \sim$.
A pronounced feature is a rather broad region with $J = J_\pi + J_\nu - 1 = 11$ level as the lowest high-spin state. This resembles the $J = j - 1$ anomaly for a rather broad region around $\nu^2 = 0.5$ in odd-even nuclei.



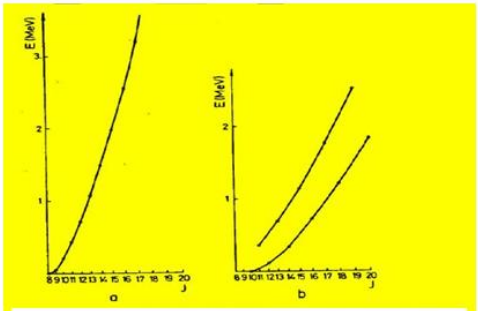
Characteristic lowest high-spin band patterns associated with O(6) limit for several values of $\nu_{3/2}$ in the illustrative IBFFM calculation. Examples with all possible high-spin band heads are presented. For comparison the experimental bands ^{190,192}Au are presented to the right. We note that the Au-region is approximately associated with an O(6) symmetry, but the present calculation is not fitted to Au isotopes

Calculated IBFFM yrast states (0_1, 1_1, …., 20_1) for $j_\pi = h_{11/2}^{-1}$, $j_\nu = f_{13/2}$ coupled to an SU(3) core, as a function of $\nu_{3/2}$





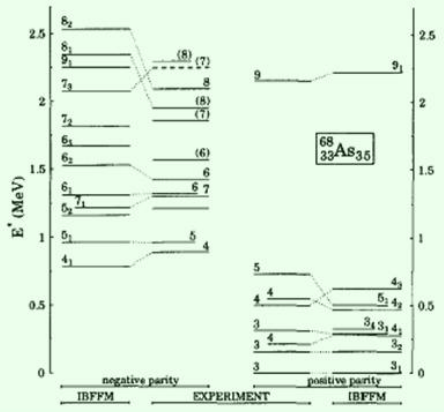
E/J plots for the levels 1_1, 2_1, …., 12_1, $\nu_{3/2}$=0 a, $\nu_{3/2}$= 0.5 b and $\nu_{3/2}$= 1 c.



E/J plots for the lowest-lying high-spin bands for $\nu_{3/2}$= 0 (Fig. a), and $\nu_{3/2}$= 0.5 (Fig. b).

Transitional nuclei

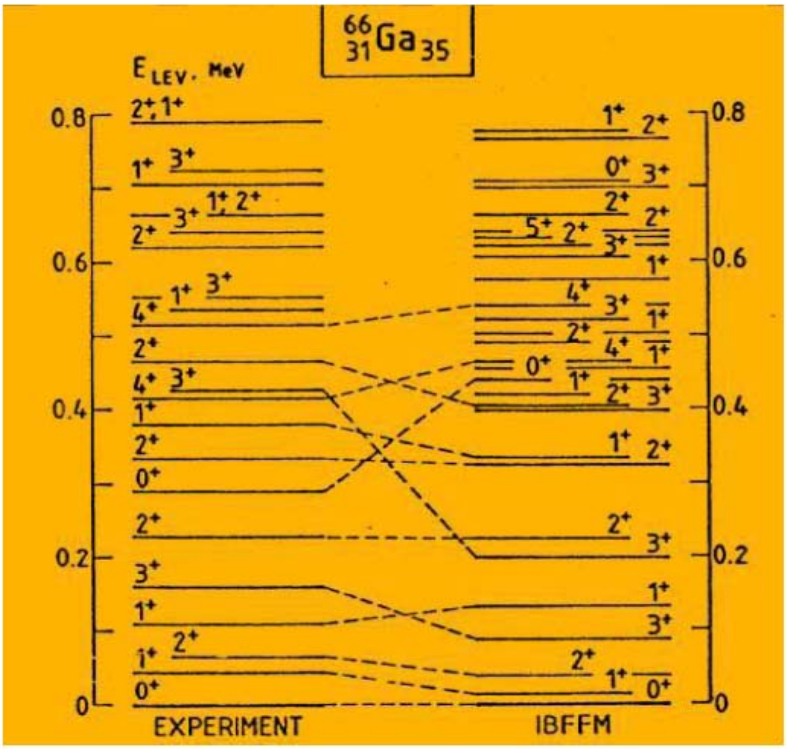
^{68}As

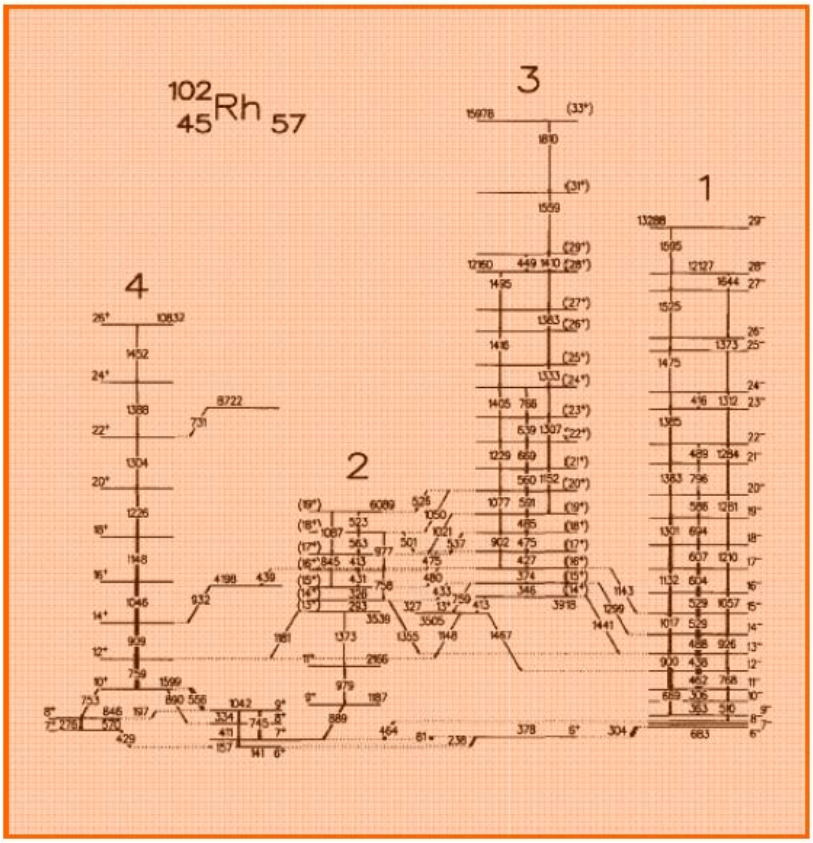


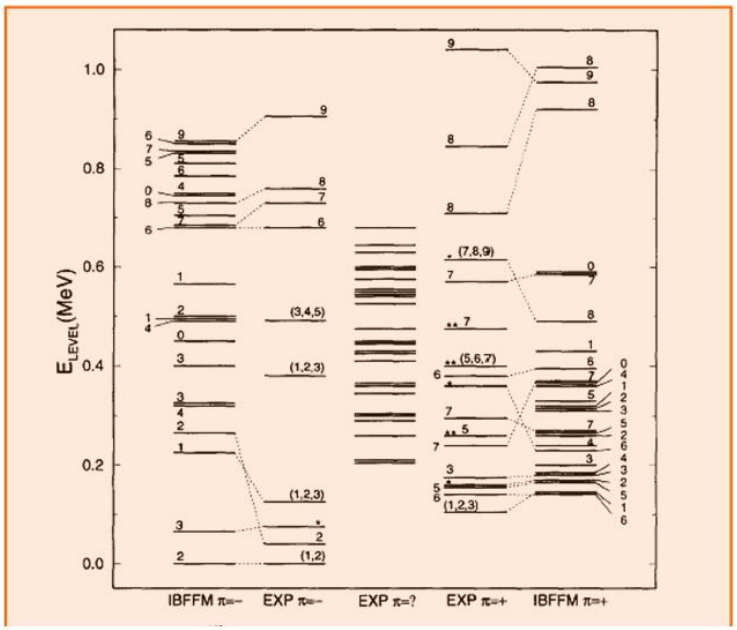
Experimental and theoretical IBFFM energy spectra of the low lying states in ^{68}As. Up to 0.6 MeV, the positive parity levels 3^+, 4^+, 5^+ are shown, along with the high spin isomer 9 is shown. For negative parity the calculated states with J^π = 4, 5, 5, 6, 6, 6, 7, 7, 7, 8, 8, 9 are shown.

IBFFM calculated branching ratio for ^{68}As compared with the experimental data

E^{π}_{exp} (MeV)	J^{π}_{exp} ($\hbar$)	$J^{\pi}_i \rightarrow J^{\pi}_f$ (theor.)	I_γ Exp.	I_γ Theor.
0.158	3^+	$3^+_2 \rightarrow 3^+_1$	100(6)	100
0.214	4^+	$4^+_1 \rightarrow 3^+_2$	6(2)	5
		$\rightarrow 3^+_1$	100(14)	100
0.313	3^+	$3^+_3 \rightarrow 4^+_1$	<2	4
		$\rightarrow 3^+_2$	16(2)	86
		$\rightarrow 3^+_1$	100(2)	100
0.500	4^+	$4^+_3 \rightarrow 3^+_3$	5(1)	12
		$\rightarrow 4^+_1$	5(1)	5
		$\rightarrow 3^+_1$	100(2)	100
0.550	4^+	$4^+_2 \rightarrow 3^+_3$	9(1)	100
		$\rightarrow 4^+_1$	36(2)	16
		$\rightarrow 3^+_2$	100(4)	9
		$\rightarrow 3^+_1$	48(2)	10
0.733	5^+	$5^+_1 \rightarrow 4^+_2$	17(2)	3
		$\rightarrow 4^+_3$	<6	26
		$\rightarrow 4^+_1$	100(5)	100
3.183	$11^{(+)}$	$11^+_1 \rightarrow 9^+_1$	100(3)	100
0.965	$5^{(-)}$	$5^-_1 \rightarrow 4^-_1$	100(3)	100
1.304	$7^{(-)}$	$7^-_1 \rightarrow 5^-_1$	100(3)	100
1.323	$6^{(-)}$	$6^-_1 \rightarrow 5^-_1$	100(4)	100
		$\rightarrow 4^-_1$	<3	4
1.427	$6^{(-)}$	$6^-_2 \rightarrow 5^-_2$	8(2)	2
		$\rightarrow 5^-_1$	100(5)	100
1.956	(8^-)	$8^-_1 \rightarrow 6^-_1$	100(8)	100
		$\rightarrow 7^-_1$	23(6)	16
2.094	$8^{(-)}$	$8^-_2 \rightarrow 7^-_1$	100(3)	100
2.251	(7^-)	$7^-_3 \rightarrow 6^-_2$	<55	75
		$\rightarrow 6^-_1$	100(15)	100
		$\rightarrow 5^-_2$	<40	45





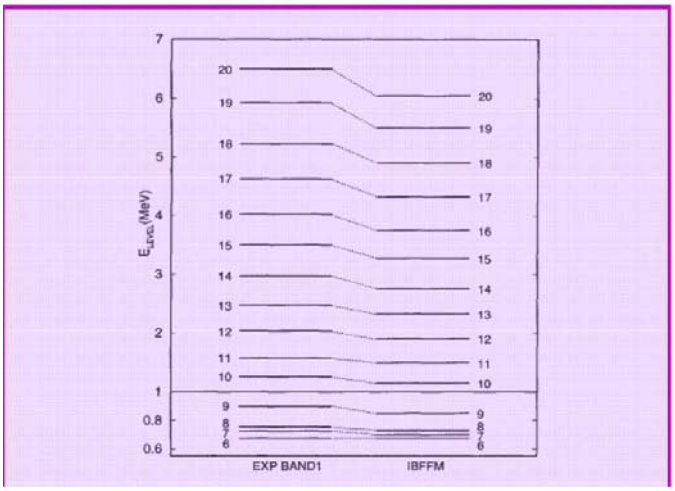


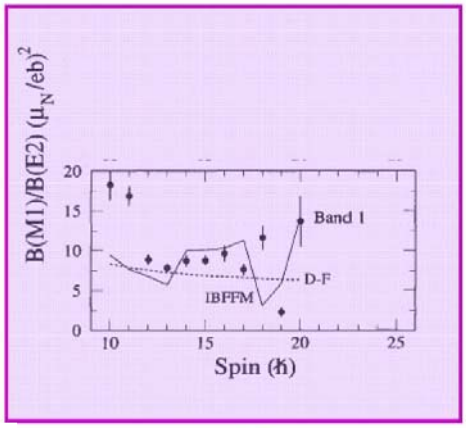
Low-lying yields in ^{102}Rh calculated with the IBFFM model and compared with experimental data. For clarity, only the three lowest calculated levels for a given spin are shown. The left- hand and right-hand sides of the figure are for the negative- and positive-parity states, respectively. Levels with unidentified parity are shown in the central column. Experimental states of uncertain parity are denoted by *; states interpreted as intruders are denoted by **.

^{102}Rh

Transition $I_i^\pi \to I_f^\pi$	$E_i \to E_f$	$B(E2)(e^2b^2)$ Exp.	$B(E2)(e^2b^2)$ IBFFM	$B(M1)(\mu_N^2)$ Exp.	$B(M1)(\mu_N^2)$ IBFFM	I_γ Exp.	I_γ IBFFM
$2_2^- \to 2_1^+$	42 → 0		0.0089	0.0054(18)	0.0033	100	100
$3_1^- \to 2_2^-$	76 → 42		0.0206		0.0731		68
$\to 2_1^+$	→ 0		0.0065		0.0097		100
$1_1^- \to 3_1^-$	124 → 76		0.0092				0.0
$\to 2_2^-$	→ 42		0.0068	0.0072(54)	0.0169	12.9	3.4
$\to 2_1^+$	→ 0		0.0307	0.034(18)	0.1436	100	100
$5_1^+ \to 6_1^+$	155 → 141		0.0003		0.0515	100	100
$2_3^+ \to 1_1^+$	157 → 105		0.0246		1.1948	100	100
$3_1^+ \to 2_1^+$	179 → 157		0.0109		1.2919	82[a]	43[a]
$\to 1_1^+$	→ 105		0.0232				0.1[a]
$7_2^+ \to 5_1^+$	242 → 155		0.0033				0.0
$\to 6_1^+$	→ 141		0.0342		0.1286	100	100
$7_1^+ \to 7_2^+$	297 → 242		0.0057		0.0019		8
$\to 5_1^+$	→ 155		0.0178				20
$\to 6_1^+$	→ 141	≥0.039[b]	0.0164	≥ 0.093[b]	0.0007	100	100
$6_2^+ \to 7_1^+$	360 → 297		0.0322		0.2138		100
$\to 7_2^+$	→ 242		0.0181		0.0287		90
$6_3^+ \to 6_2^+$	378 → 360		0.0099		0.0002		0.0
$\to 7_1^+$	→ 297		0.0009	0.045[b]	0.5392	92	69
$\to 7_2^+$	→ 242		0.0023	0.016[b]	0.0046	58	3
$\to 5_1^+$	→ 155	0.0063[b]	0.0006		0.0375	83	100
$\to 6_1^+$	→ 141	0.0044[b]	0.0038	0.0018[b]	0.0309	100	100
$7_3^+ \to 6_3^+$	570 → 378		0.0343		0.1572		19
$\to 6_2^+$	→ 360		0.0000		0.0088		1.4
$\to 7_1^+$	→ 297		0.0018		0.0000	5	0.1
$\to 7_2^+$	→ 242		0.0000		0.0035		2.1
$\to 5_1^+$	→ 155		0.0076		0.0000		1.1
$\to 6_1^+$	→ 141		0.0016		0.0728	100	100
$8_1^+ \to 7_3^+$	616 → 570		0.0080		0.2705		0.3
$\to 6_3^+$	→ 378		0.0009				0.0
$\to 6_2^+$	→ 360		0.0228				0.2
$\to 7_1^+$	→ 297		0.0374		0.2572	100	100
$\to 7_2^+$	→ 242		0.0022		0.0006		0.5
$\to 6_1^+$	→ 141		0.0020				0.4

^{102}Rh





IBFFM energy spectrum of the $\pi g_{9/2} \nu h_{11/2}$ configuration in ^{102}Rh compared to experimental band 1. Because of the concentration of the lowest states, the bottom of the band is shown with a different scale.

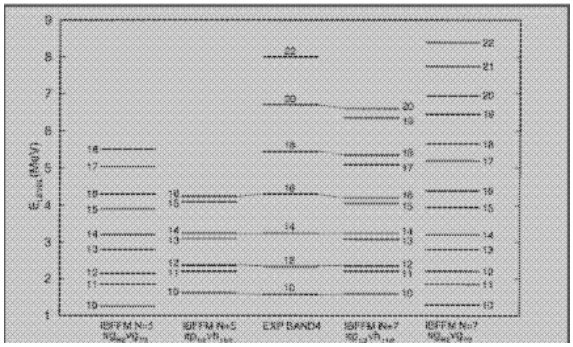
π g9/2 ν h11/2 Full line IBFFM

Dashed line Donau-Frauendorf model

The ΔI=2 positive-parity band 4

In the present IBFFM calculation we obtain two positive-parity high-spin bands, based on $\pi p_{1/2}\nu h_{11/2}$ and $\pi g_{9/2}\nu g_{7/2}$ two-quasiparticle configurations, respectively These bands are clearly formed above the 10^+ state, while for lower spins there is a stronger configuration mixing. The two lowest 10^+ states are based on the $(\pi p_{1/2}\nu h_{11/2})6, 2\ 4; 10$ (50%) and $(\pi g_{9/2}\nu g_{7/2})8, 1\ 2; 10$ (59%) configurations

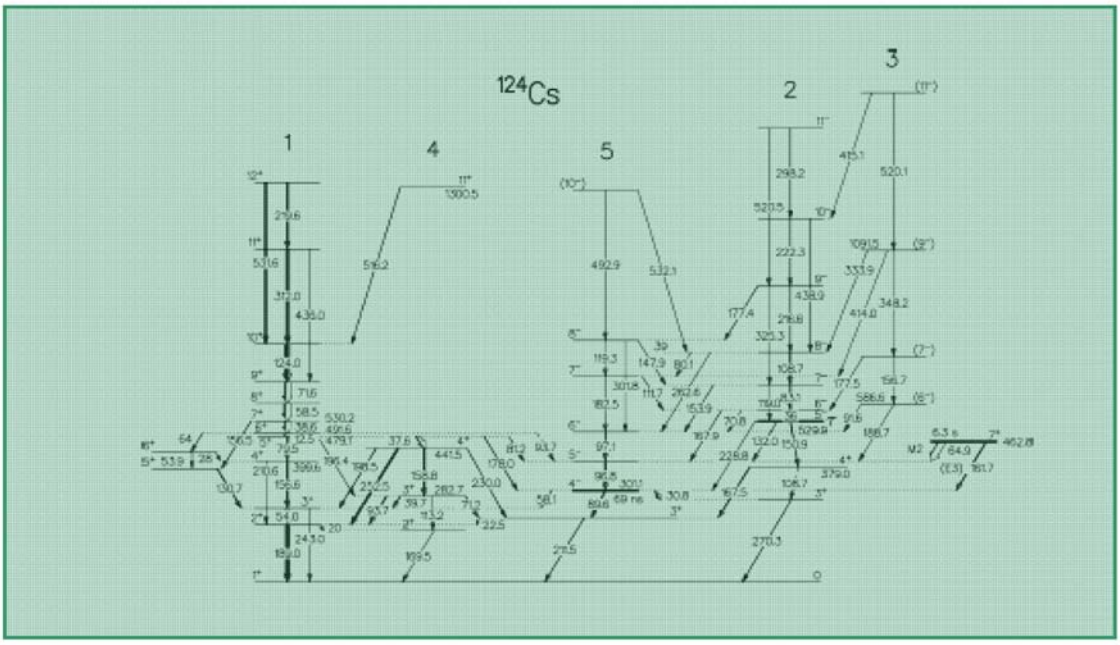
These two calculated bands appear close lying and they cross at angular momentum $I \approx 15\hbar$. Contrary to the experimental band 4 which is of $\Delta I = 2$ type with signature $\alpha = 0$, the calculated bands show doublet-type structures. The $\pi p_{1/2}\nu h_{11/2}$ configuration is associated with a much larger signature splitting than the $\pi g_{9/2}\nu g_{7/2}$ configuration and exhibit a pronounced tendency towards decoupled band On this basis we attribute the $\pi p_{1/2}\nu h_{11/2}$ configuration to band 4.

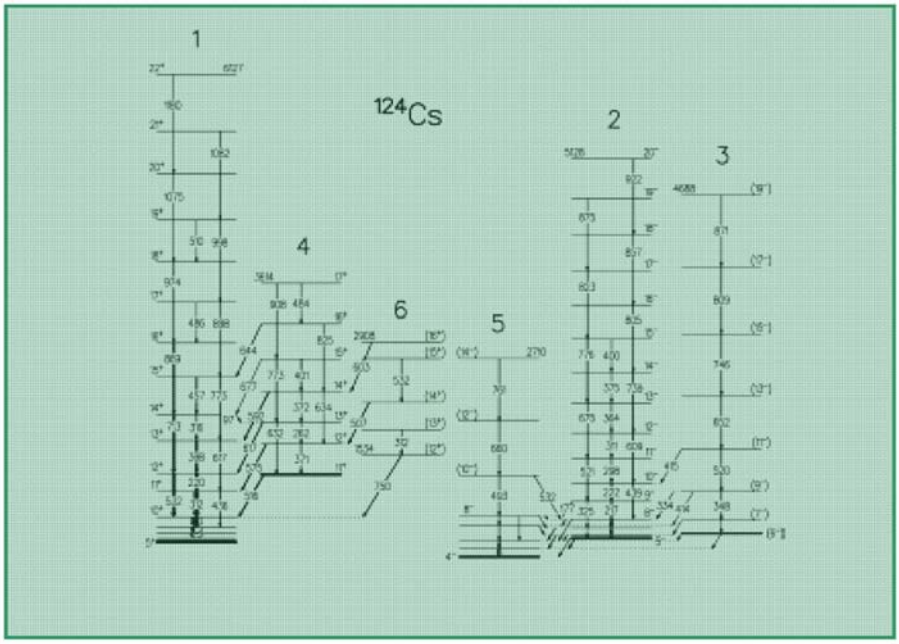


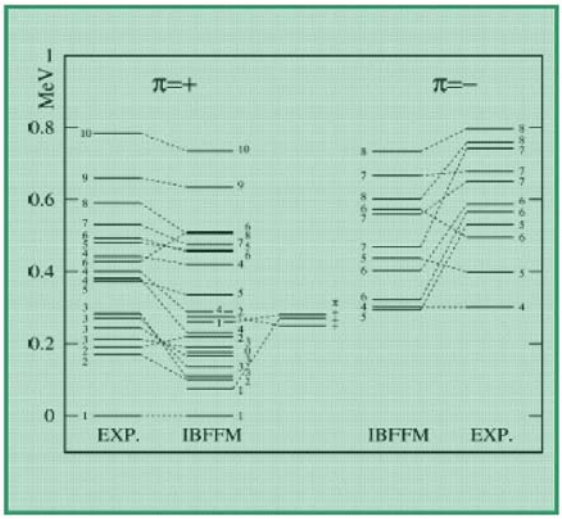
B(E2) and B(M1) reduced transition probabilities calculated between states of the $\pi p_{1/2}\nu h_{11/2}$ configuration with $N = 7$ in ^{102}Rh and comparison of the intensities of γ-rays observed in band 4 with those calculated for the above configuration

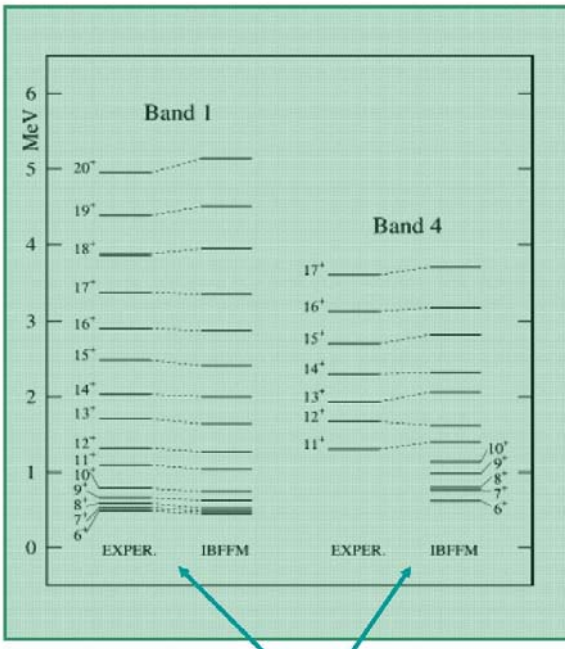
Transition	B(E2)(e^2b^2)	B(M1)(μ_N^2)	I_γ	
	IBFFM	IBFFM	Exp.	IBFFM
$12^+ \rightarrow 11^+$	0.0016	0.0073		0.0
$12^+ \rightarrow 10^+$	0.4295		100	100
$14^+ \rightarrow 13^+$	0.0021	0.0001		0.0
$14^+ \rightarrow 12^+$	0.1003		100	100
$16^+ \rightarrow 15^+$	0.0005	0.0049		0.1
$16^+ \rightarrow 14^+$	0.0418		100	100
$18^+ \rightarrow 17^+$	0.0010	0.0019		0.0
$18^+ \rightarrow 16^+$	0.1076		100	100
$20^+ \rightarrow 19^+$	0.0011	0.0061		0.1
$20^+ \rightarrow 18^+$	0.0634		100	100

The two remaining experimental bands (bands 2 and 3) are expected to be based on four-quasiparticle states involving broken neutron pairs, in particular the ½ broken pair, so that four-quasiparticle states should be coupled to the boson core. The model including boson pairs of fermions has not been applied yet to odd-odd nuclei, and therefore the corresponding theoretical states are missing in the present IBFFM calculations.


124Cs
1
2
3
4
5

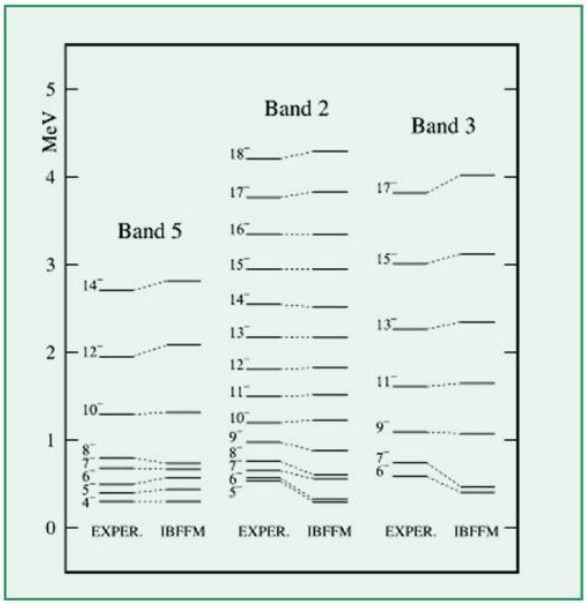

124Cs
1
2
3
4
5
6





^{124}Cs

π h11/2 ν h11/2



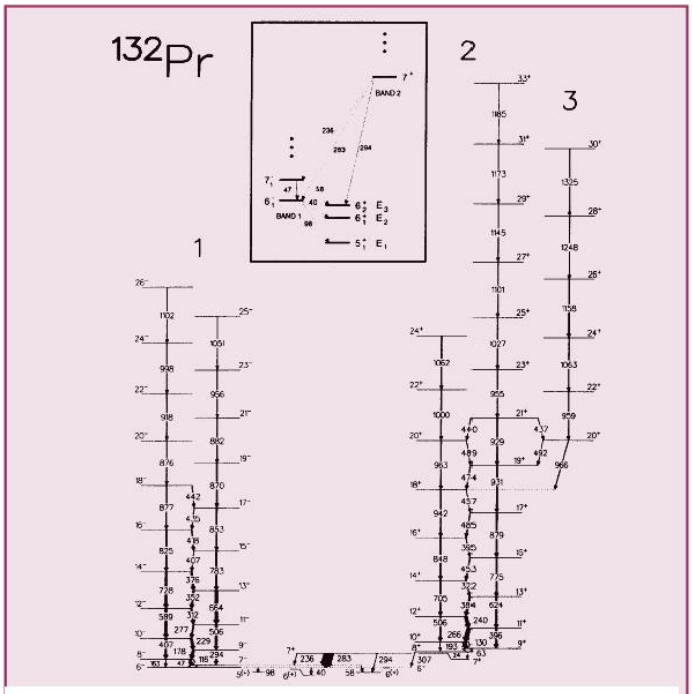
^{124}Cs

Wave functions are very complex !!!!

There is strong configuration mixing

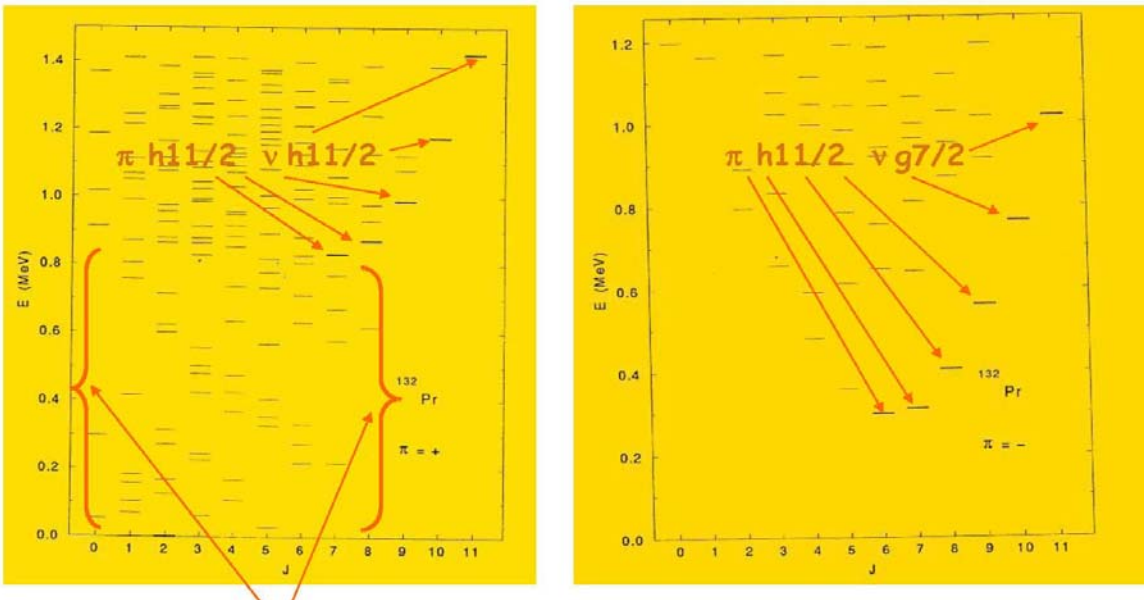
IBFFM is able to predict properly the structure of high spin states in a multi-j case

On the basis of the IBFFM analysis, we propose that the negative-parity bands presented have a $\pi(d_{5/2g7/2})\nu h_{11/2}$ configuration in their low-spin part and, starting from $I \approx 12$, are almost pure $\pi h_{11/2\nu g7/2}$, with band 2 being the yrast structure and bands 3 and 5 the yrare structures. Thus the collective band structures start at spin $I \approx 12$.



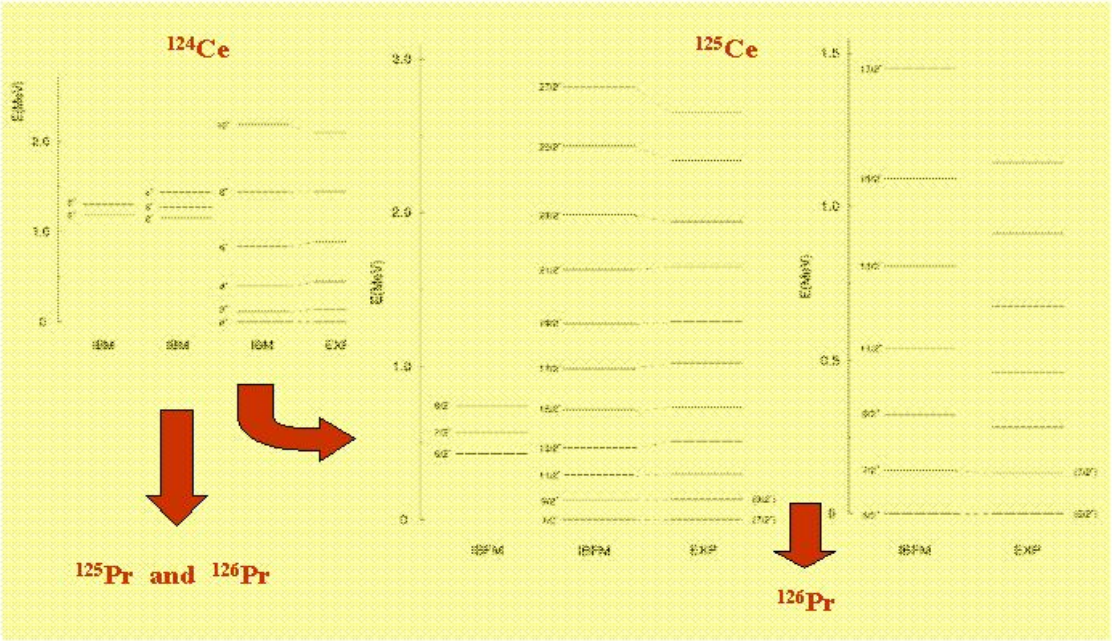
Level scheme of ^{132}Pr deduced from the present work. Transition intensities are proportional to the width of the arrows. The inset shows the IBFFM identification of levels populated in the decays of bands 1 and 2.

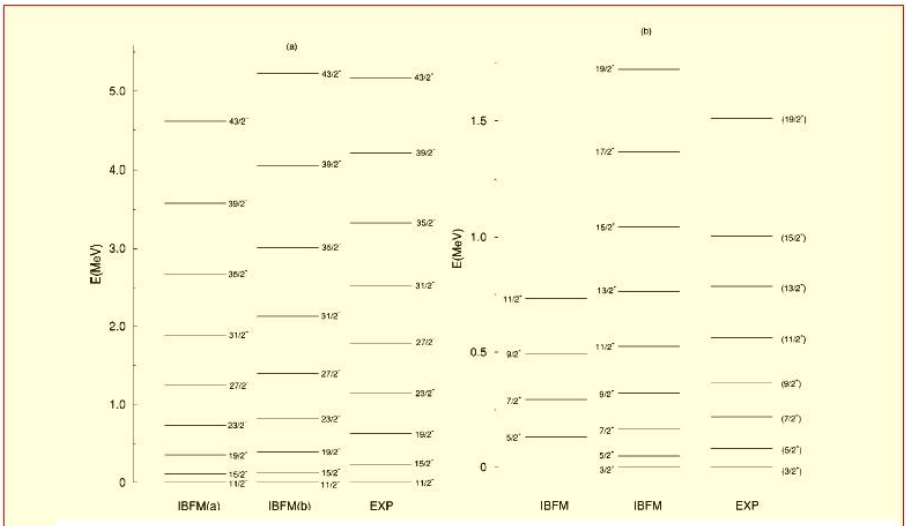
Mixing of configurations with different parity
both for protons and for neutrons (high with low spin states)



Positive parity proton and positive
parity neutron configurations

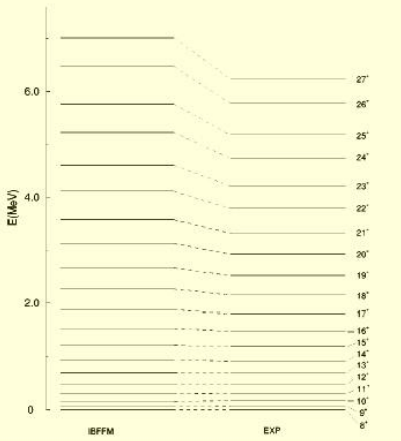
Transitional SU(3) – O(6) ^{126}Pr nucleus



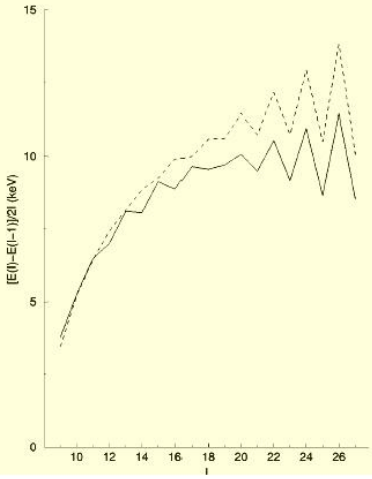


The negative parity (a) and positive parity (b) yrast states in the Z-nucleus ^{125}Pr are compared with the experimental states of ^{127}Pr.

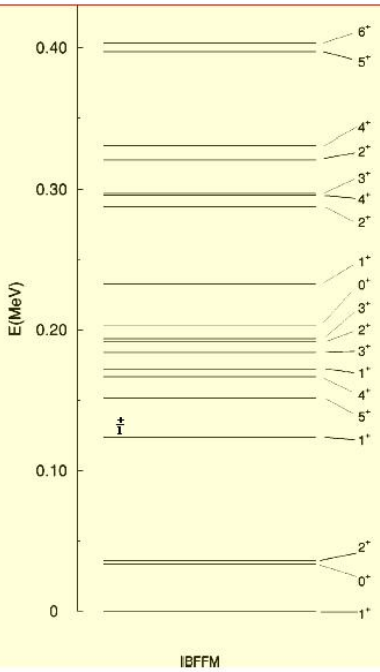
^{126}Pr



The yrast sequence of high angular momentum positive parity states based on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration is compared with experimental counterpart in ^{126}Pr. The assignment for the band is head 8^+ (i.e., the lowest observed state).



IBFFM (dashed line) and experimental (solid line) $[E(I) - (E(I-1)]/2I$ vs I plots for the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast band in ^{126}Pr. The state 8+ is assigned to the band head.

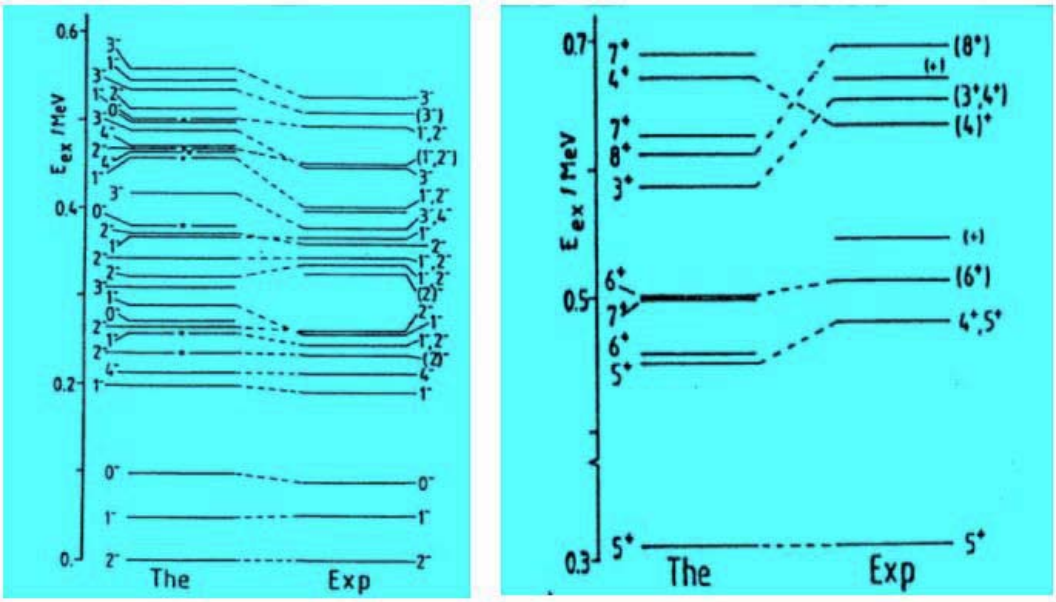


The IBM prediction for low angular momentum states in ^{126}Pr. These states are based on positive parity proton and neutron configurations.

The IBFFM analysis predicts the existence of another isomer in ^{126}Pr 5^+ at ≈ 150 keV excitation energy - isomeric character depends strongly on the choice of the proton-neutron interaction. In the present calculation 5^+_1 is below 4^+_1, and therefore is an isomer with a possible γ decay to 2. This transition is slow enough to allow for a β decay that has been reported.

^{198}Au

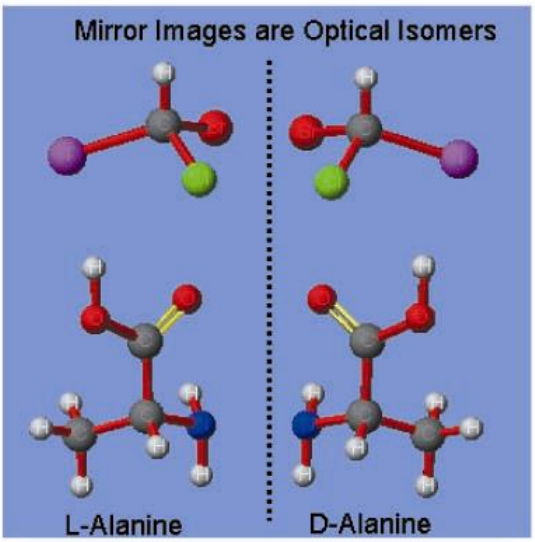
The first odd-odd nucleus calculated in IBFFM



Chirality in nuclei

I call any geometrical figure, or group of points, chiral, and say it has chirality, if its image in a plane mirror, ideally realized, cannot be brought to coincide with itself.

Lord Kelvin, 1904.



Numerous examples :

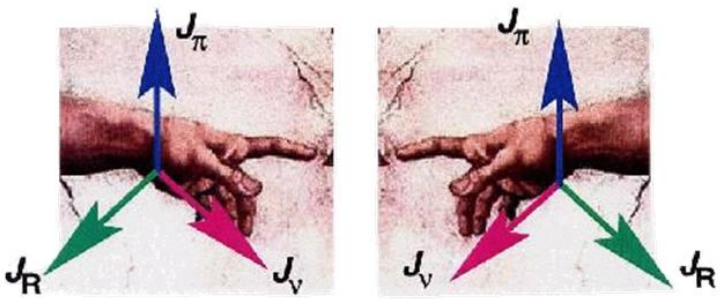
- Chemistry
- Biology
- Pharmacy
- Particle physics

Atomic nuclei ?

- Chirality in molecules is static
- Chirality in nuclei has dynamical origin (?)

relates to the orientation of angular momenta with respect to some well defined axes

! The three angular momenta can be arranged to form a left-handed and a right-handed system



Candidates ?

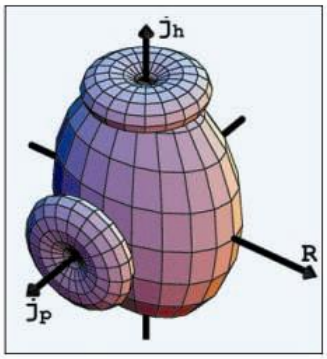
Three angular momenta → odd-odd nuclei
(rotational core + proton + neutron)

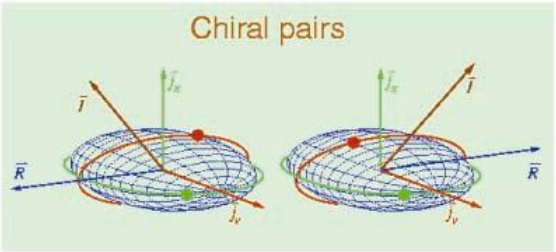
Three axes → rotational core has to be triaxial
(angular momentum aligned along the intermediate axis)

Angular momentum of one fermion aligned along the short axis
The fermion has to be of particle type (BCS occupation < 0.5)

Angular momentum of the other fermion aligned along the long axis
The fermion has to be of hole type (BCS occupation > 0.5)

The angular momenta of both fermions have to be big enough





The system is chiral if it is not symmetric to mirror-reflection S in any plane. For nuclear rotation, instead of S, the operator R^T (the product of time reversal and rotation through 180^0) has to be used (angular momentum is an axial pseudo-vector).

For a given spin, the two states of the doublet in the laboratory system are $|+\rangle$ and $|-\rangle$, while the left-handed and right-handed states in the body-fixed system are $|L\rangle$ and $|R\rangle$.

$$|+\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right) \qquad |-\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle - |R\rangle\right)$$

$$R^T|L\rangle = |R\rangle \qquad R^T|R\rangle = |L\rangle$$

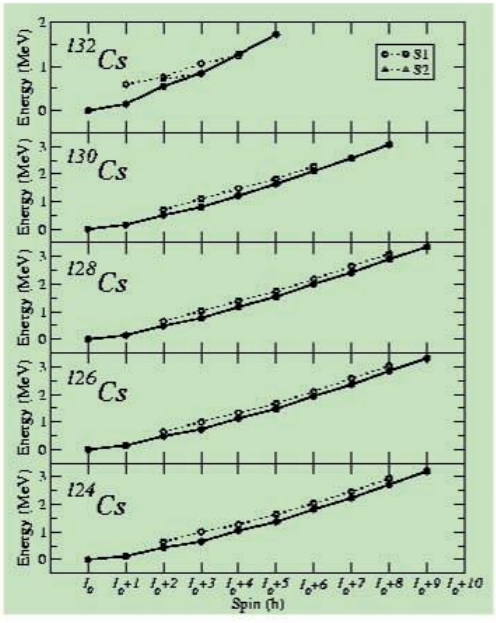
$$R^T|+\rangle = |+\rangle \qquad R^T|-\rangle = |-\rangle$$

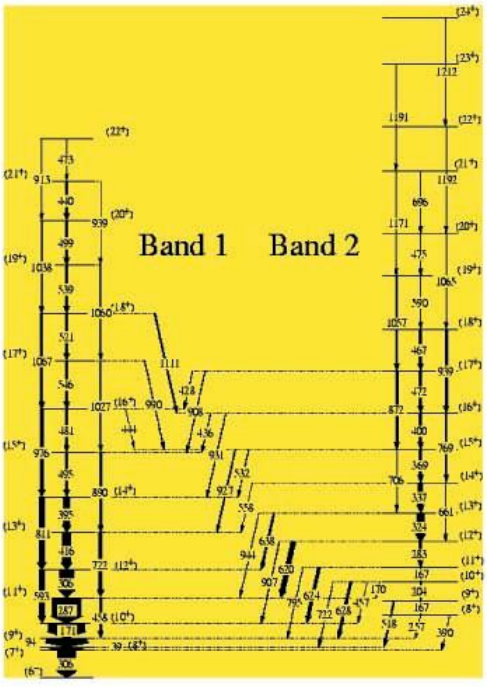
The Hamiltonian H is invariant under R^T

$$\langle L|H|L\rangle = \langle R|H|R\rangle = E$$

$$|\langle L|H|R\rangle| = \Delta \neq 0$$

$$\langle +|H|+\rangle = E + \Delta \qquad \langle -|H|-\rangle = E - \Delta$$



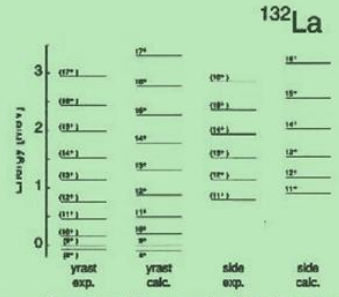


134 Pr

Models

- Tilted axis cranking model
- Particle-core coupling model
- Two quasiparticle + triaxial rotor model
- Interacting boson fermion fermion model

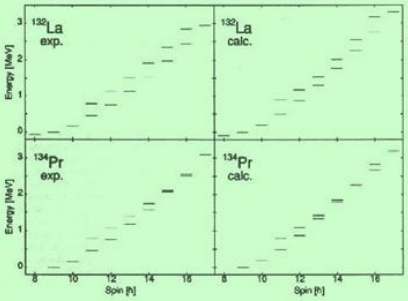
K. STAROSTA *et al.*



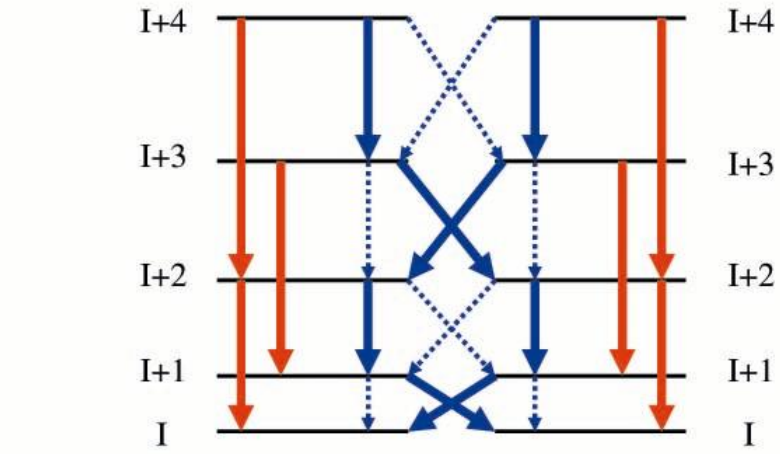
Comparison between energies of excited states in the partner band in ^{132}La with those calculated for $\pi h_{11/2}\nu^{-1}h_{11/2}$ particle-hole coupling with a rigid triaxial rotor

Theoretical states are shown only when the corresponding experimental states are known.

Comparison between energies of excited states in the partner band of ^{132}La with those calculated for $\boldsymbol{\pi h_{11/2}\otimes\nu^{-1}h_{11/2}}$ particle-hole coupling based on a rigid triaxial rotor. Theoretical states are shown only when the corresponding experimental states are known.



Comparison between energies of observed $\boldsymbol{\pi h_{11/2}\otimes\nu^{-1}h_{11/2}}$ states in ^{132}La (top) and ^{134}Pr (bottom) with those calculated for $\boldsymbol{\pi h_{11/2}\otimes\nu^{-1}h_{11/2}}$ particle-hole coupling based on a rigid triaxial rotor.



B(E2) de-exciting analogue states in both bands EQUAL

B(M1) de-exciting analogue states in both bands show the odd-even "staggering"

PROBLEM !!!!!!!!!

All odd-nuclei in which chiral (?) bands have been observed are in regions of masses:

A ~ 105
A ~ 130
A ~ 190 (?)

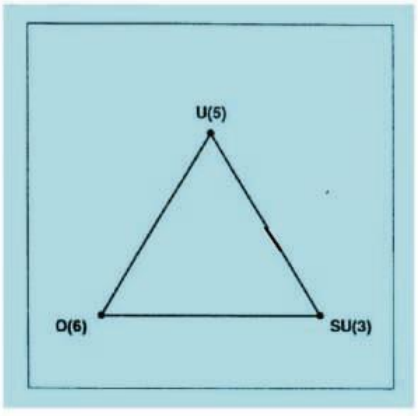
where even-even nuclei are γ–soft and NOT rigid triaxial

The Interacting boson fermion fermion model IBFFM1 (based on one type of boson) cannot describe stable triaxial nuclei, especially not rigid triaxial rotors !!!

BUT !!!!

INTERACTING BOSON MODEL

$U(6)$	$\supset$	$U(5) \supset O(5) \supset O(3) \supset O(2)$	*vibrational limit*
$U(6)$	$\supset$	$SU(3) \supset O(3) \supset O(2)$	*rotational limit*
$U(6)$	$\supset$	$O(6) \supset O(5) \supset O(3) \supset O(2)$	$\gamma - soft$ *limit*

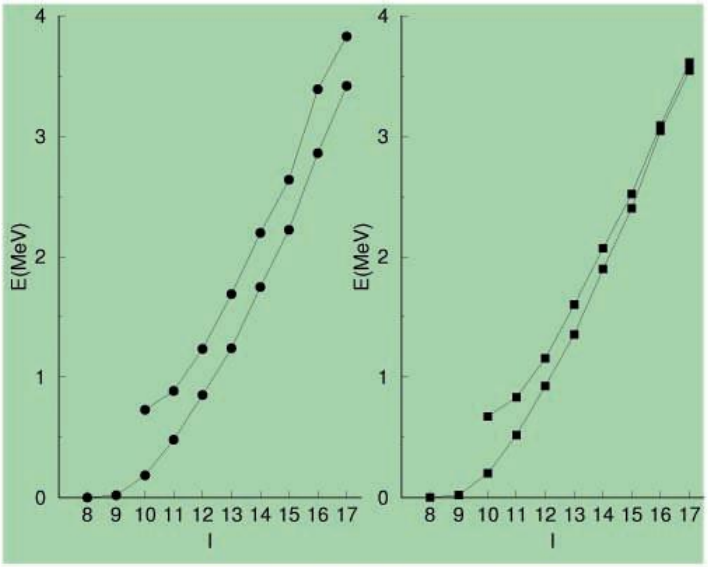


$$H_{IBM} = \epsilon_d\, \hat{n}_d + p\; P \cdot P + k'\; L \cdot L + k\; Q \cdot Q + \Theta_3 \left[(d^\dagger\; d^\dagger)_2\; d^\dagger \right]_3 \cdot \left[(\tilde{d}\; \tilde{d})_2\; \tilde{d} \right]_3$$

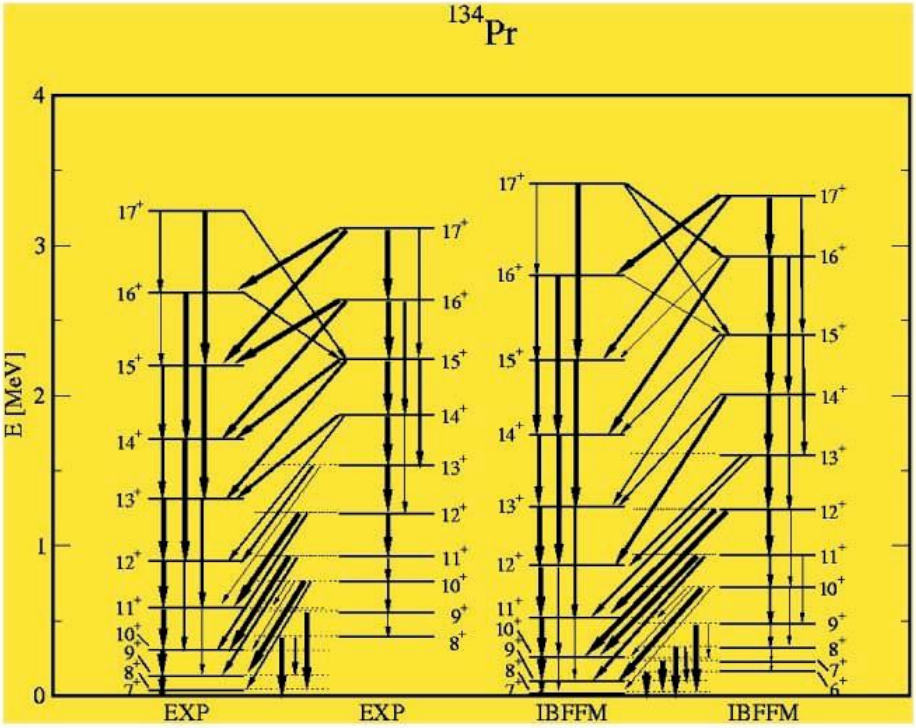
The first four terms represent the standard Hamiltonian of the Interacting Boson Model (IBM-1). The cubic interaction in the last term, with the strength parameter Θ_3, introduces a degree of triaxiality.

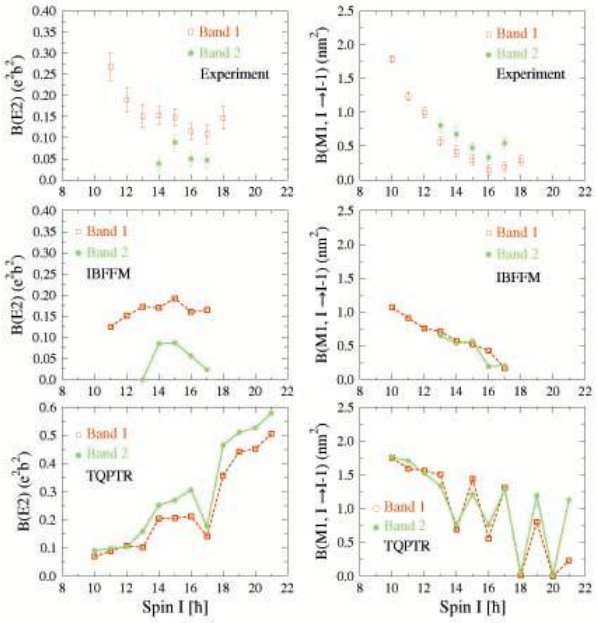
With the inclusion of the three-body term in the boson Hamiltonian, the boson quadrupole operator appearing in the dynamical boson-fermion interaction and in the E2 operator should also be extended to higher order. The standard boson quadrupole operator is modified by including the additional term

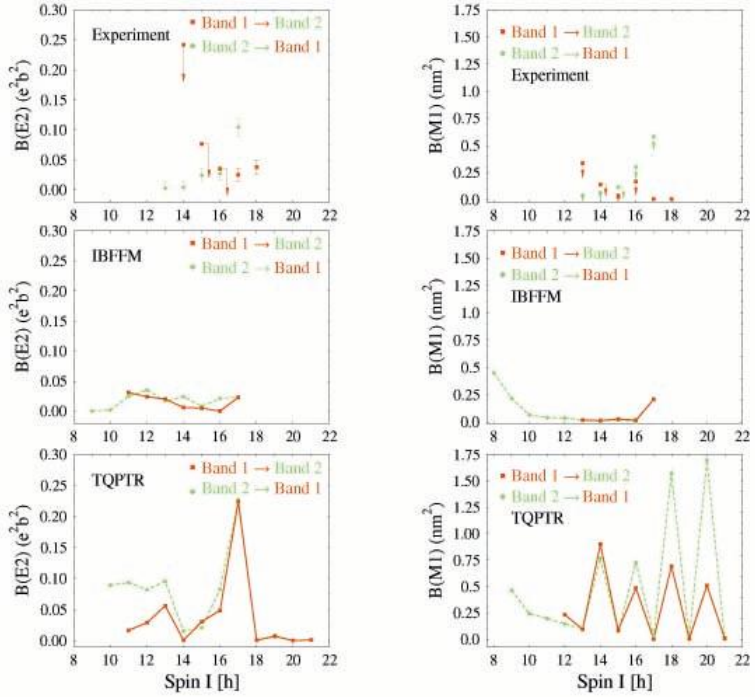
$$\eta \left[(d^\dagger\; \tilde{d})_3\; (d^\dagger\; \tilde{d})_3 \right]_2$$

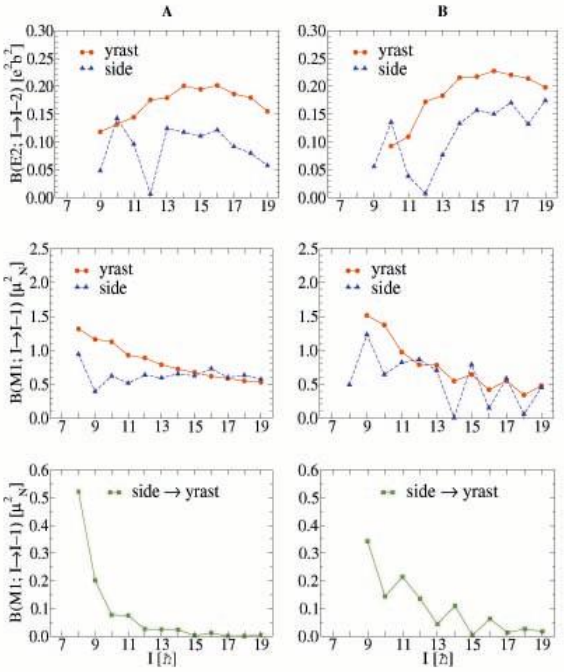


The yrast and yrare $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in ^{134}Pr calculated in the IBFFM for the ^{134}Ce core without triaxiality (left panel, $\Theta_3 = 0$), and with stable triaxial deformation (right panel, $\Theta_3 = 0.03$ MeV).


134Pr
E [MeV]
EXP
EXP
IBFFM
IBFFM


Band 1
Band 2
Experiment
IBFFM
TQPTR
B(E2) (e²b²)
B(M1, I →I-1) (nm²)
Spin I [ħ]

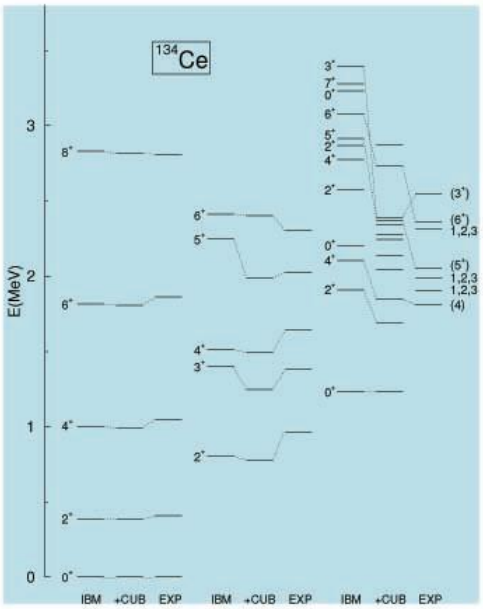




The difference is in shape fluctations

↓

More pronounced in A than in B



Coupling to:

Rigid ground state band
"Static chirality"
(Realized ???)

Soft ground state and γ band
Full dynamic chirality

Soft ground state and γ band and higher lying core structures
Weak dynamic chirality

Nuclear Theory:
β Decay in the Interacting Boson-Fermion Model

S. Brant

University of Zagreb, Croatia

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4.

β decay in the interacting boson-fermion model

OBJECTIVES

- To test the nuclear model by analyzing experimental data

  Wave functions (two odd-even and one even-even nucleus are involved)

  Transition operators

- To provide reliable information for astrophysical applications

The process is very sensitive to configuration mixing both in the initial and final states. A detailed knowledge of the wavefunctions is required. Beta decay properties can be calculated by using:

- Shell model (in light nuclei and in medium-mass and heavy nuclei in the neighborhood of doubly magic nuclei)
- Other models for medium-mass and heavy nuclei.

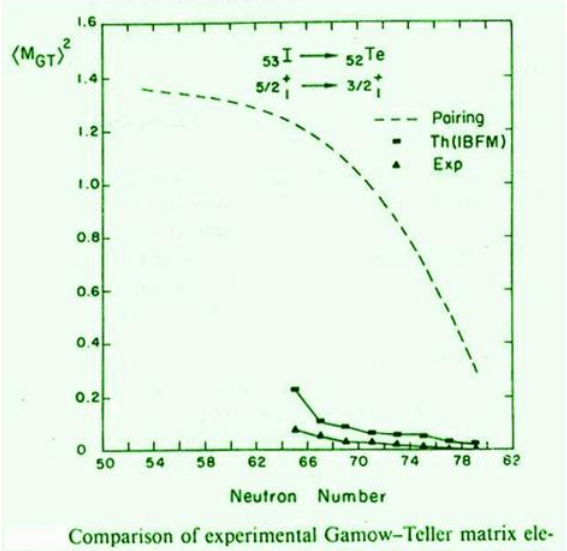
Example: Simple pairing theory

Overestimates the Gamow-Teller strengths by a large factor (up to a factor 70 !!!!!)

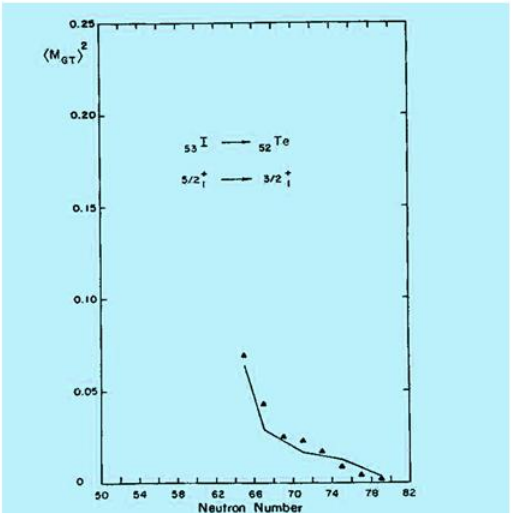
How to account for the large hindrance:

Nuclear deformation
Mixing with 2p-2h states
Mesonic degrees of freedom

In the IBFM there is NO quenching factor (once the wave functions have been calculated, the calculation of beta decay properties is parameter free), or the quenching factor is SMALL.



Comparison of experimental Gamow–Teller matrix elements with pairing theory and results of the calculation using the interacting boson–fermion model (IBFM).



Comparison between experimental Gamow – Teller matrix elements (triangles) and those obtained using IBFM renormalized by a factor 3.5 (continuous line).

PROCEDURE

IBM2 calculations of the structure of even-even core nuclei:

Energy levels and wave functions

↓

Electromagnetic properties (electric quadrupole and magnetic dipole moments, B(E2) and B(M1) values, branching ratios).

↓

Wave functions

IBFM2 calculations of the structure of odd-even parent and daughter nuclei:

Energy levels and wave functions

↓

Electromagnetic properties (electric quadrupole and magnetic dipole moments, B(E2) and B(M1) values, branching ratios).

↓

Wave functions

Beta decay calculations:

Matrix elements, logft values

Cs → Xe

A = 125, 127, 129

Soft nuclei close to the O(6) limit → complex wave functions

→ Sensitive test of the model

IBFM2 Hamiltonian → $H = H^{\mathrm{B}} + H^{\mathrm{F}} + V^{\mathrm{BF}}$

IBM2 Hamiltonian (core nuclei) :

$$
\begin{aligned}
H^{\mathrm{B}} \;=\; & \epsilon_d\,(n_{d_\nu} + n_{d_\pi}) + \kappa\,(Q_\nu^{\mathrm{B}} \cdot Q_\pi^{\mathrm{B}}) \\
& + \frac{1}{2}\xi_2\,((d_\nu^\dagger s_\pi^\dagger - d_\pi^\dagger s_\nu^\dagger)\cdot(\tilde{d}_\nu s_\pi - \tilde{d}_\pi s_\nu)) + \sum_{K=1,3}\xi_K\,([d_\nu^\dagger d_\pi^\dagger]^{(K)}\cdot[\tilde{d}_\pi \tilde{d}_\nu]^{(K)}) \\
& + \frac{1}{2}\sum_{L=0,2,4} c_L^\nu\,([d_\nu^\dagger d_\nu^\dagger]^{(k)}\cdot[\tilde{d}_\nu \tilde{d}_\nu]^{(k)}) + \frac{1}{2}\sum_{L=0,2,4} c_L^\pi\,([d_\pi^\dagger d_\pi^\dagger]^{(k)}\cdot[\tilde{d}_\pi \tilde{d}_\pi]^{(k)})
\end{aligned}
$$

$$H^{\mathrm{F}} = \sum_i \epsilon_i \, n_i$$ Hamiltonian of the odd fermion

BCS → ϵ_i is the quasi-particle energy of the ith orbital
n_i is the number operator of this ith orbital

Interaction between bosons and the odd fermion :

$$\begin{aligned} V^{\mathrm{BF}} &= \sum_{i,j} \Gamma_{ij} \left([a_i^\dagger \tilde{a}_j]^{(2)} \cdot Q_\rho^{\mathrm{B}} \right) \\ &+ \sum_{i,j} \Gamma'_{ij} \left([a_i^\dagger \tilde{a}_j]^{(2)} \cdot Q_{\rho'}^{\mathrm{B}} \right) \\ &+ \sum A_i \, n_i n_{d_\rho} + \sum A'_i \, n_i n_{d_{\rho'}} \\ &+ \sum_{i,j} \Lambda^j_{ki} \left\{ : \left[\left[d_\rho^\dagger \tilde{a}_j \right]^{(k)} a_i^\dagger s_\rho \right]^{(2)} : \cdot \left[s_{\rho'}^\dagger \tilde{d}_{\rho'} \right]^{(2)} \right. \\ &+ \left. H.c. \right\} \\ &+ B \, J \cdot L_\rho + B' \, J \cdot L_{\rho'}. \end{aligned}$$

ρ and ρ' denote π (ν) and ν (π) if the odd fermion is a proton (a neutron).

Orbital dependence of the interaction strengths

$$\begin{aligned} \Gamma_{i,j} &= (u_i u_j - v_i v_j) \, Q_{i,j} \, \Gamma \\ \Lambda^j_{k,i} &= -\beta_{k,i} \beta_{j,k} \left(\frac{10}{N_\rho (2j_k + 1)} \right)^{1/2} \Lambda \\ \beta_{i,j} &= (u_i v_j + v_i u_j) \, Q_{i,j} \\ Q_{i,j} &= < l_i, \frac{1}{2}, j_i || Y^{(2)} || l_j, \frac{1}{2}, j_j > \end{aligned}$$

← uj and vj from BCS

Electromagnetic transition operators

$$T^{(\mathrm{E2})} = e_\pi^{\mathrm{B}} \, Q_\pi^{\mathrm{B}} + e_\nu^{\mathrm{B}} \, Q_\nu^{\mathrm{B}} + \sum_{i,j} e'_{i,j} \, [a_i^\dagger \tilde{a}_j]^{(2)}$$

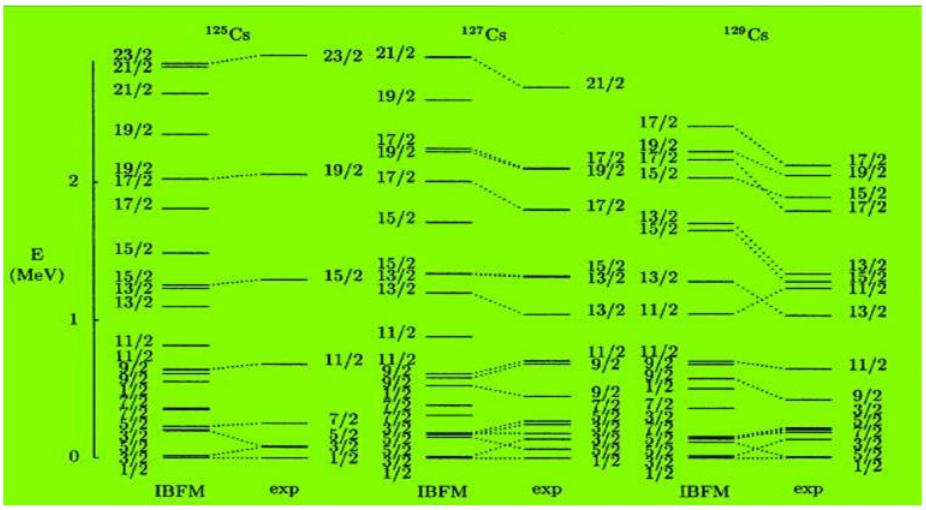
$$e'_{i,j} = -\frac{e_\rho^{\mathrm{F}}}{\sqrt{5}} (u_i u_j - v_i v_j) < i || r^2 Y^{(2)} || j >$$

u_j and v_j from BCS →

$$T^{(\mathrm{M1})} = \sqrt{\frac{3}{4\pi}} \left(g_\pi^{\mathrm{B}} \, L_\pi^{\mathrm{B}} + g_\nu^{\mathrm{B}} \, L_\nu^{\mathrm{B}} + \sum_{i,j} e^{(1)}_{i,j} \, [a_i^\dagger \tilde{a}_j]^{(1)} \right)$$

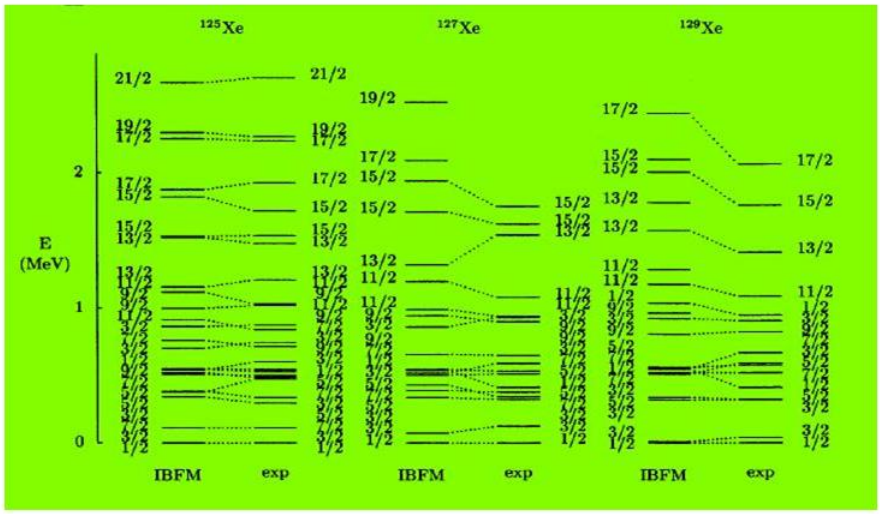
$$e^{(1)}_{i,j} = -\frac{1}{\sqrt{3}} (u_i u_j + v_i v_j) < i || g_l \mathbf{l} + g_s \mathbf{s} || j >$$

Cs isotopes (odd proton)



Positive parity levels

Xe isotopes (odd neutron)



Positive parity levels

The Fermi $\sum_k t^{\pm}(k)$ and the Gamow-Teller $\sum_k t^{\pm}(k)\sigma(k)$ transition operators can be expressed in the framework of IBFM2. They can be constructed from the transfer operators.

$$A_m^{\dagger(j)} = \zeta_j a_{jm}^{\dagger} + \sum_{j'} \zeta_{jj'} s^{\dagger} [\tilde{d} a_{j'}^{\dagger}]_m^{(j)} \qquad (\Delta n_j = 1,\ \Delta N = 0)$$

$$B_m^{\dagger(j)} = \theta_j s^{\dagger} \tilde{a}_{jm} + \sum_{j'} \theta_{jj'} [d^{\dagger} \tilde{a}_{j'}]_m^{(j)} \qquad (\Delta n_j = -1,\ \Delta N = 1)$$

The former creates a fermion, while the latter annihilates a fermion simultaneously creating a boson. Either operator increases the quantity $n_j + 2N$ by one unit. The conjugate operators are:

$$\tilde{A}_m^{(j)} = (-1)^{j-m} \left\{ A_{-m}^{\dagger(j)} \right\}^{\dagger} = \zeta_j^* \tilde{a}_{jm} + \sum_{j'} \zeta_{jj'}^* s [d^{\dagger} \tilde{a}_{j'}]_m^{(j)} \qquad (\Delta n_j = -1,\ \Delta N = 0)$$

$$\tilde{B}_m^{(j)} = (-1)^{j-m} \left\{ B_{-m}^{\dagger(j)} \right\}^{\dagger} = -\theta_j^* s a_{jm}^{\dagger} - \sum_{j'} \theta_{jj'}^* [\tilde{d} a_{j'}^{\dagger}]_m^{(j)} \qquad (\Delta n_j = 1,\ \Delta N = -1)$$

The asterisks mean complex conjugate. These operators decrease the quantity $n_j + 2N$ by one unit.

The IBFM image of the Fermi $\sum_k \mathbf{t}^{\pm}(k)$ and the Gamow-Teller transition operator $\sum_k t^{\pm}(k)\sigma(k)$

$$O^{\mathsf{F}} = \sum_j -\sqrt{2j+1} \left[P_{\nu}^{(j)} P_{\pi}^{(j)} \right]^{(0)}$$

$$O^{\mathsf{GT}} = \sum_{j'j} \eta_{j'j} \left[P_{\nu}^{(j')} P_{\pi}^{(j)} \right]^{(1)}$$

$$\eta_{j'j} = -\frac{1}{\sqrt{3}} < l' \frac{1}{2}; j' || \sigma || l \frac{1}{2}; j >$$

The transfer operators $P_\rho^{(j)}$ depend on nuclei.
In the present case

$$\begin{aligned} P_\pi^{(j)} &= \tilde{A}_\pi^{(j)} \\ P_\nu^{(j)} &= \tilde{B}_\nu^{(j)} \end{aligned}$$

$$\begin{aligned} < M_{\mathrm{F}} >^2 &= \frac{1}{2I_i+1} | < I_f || O^{\mathrm{F}} || I_i > |^2 \\ < M_{\mathrm{GT}} >^2 &= \frac{1}{2I_i+1} | < I_f || O^{\mathrm{GT}} || I_i > |^2 \end{aligned}$$

$$ft = \frac{6163}{< M_{\mathrm{F}} >^2 + (G_{\mathrm{A}}/G_{\mathrm{V}})^2 < M_{\mathrm{GT}} >^2}$$

in units of seconds where $(G_A/G_V)^2 = 1.59$

The coefficients η_j, $\eta_{jj'}$, θ_j, $\theta_{jj'}$ appearing in transfer operators

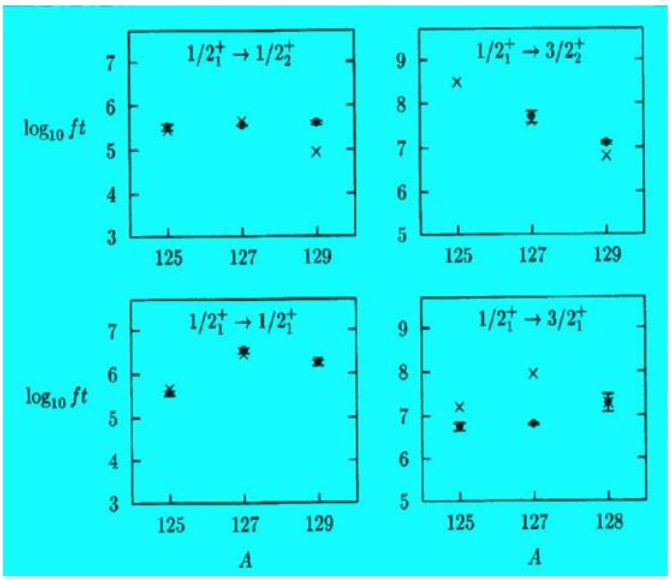
$$\begin{aligned} \zeta_j &= u_j \frac{1}{K'_j} \\ \zeta_{jj'} &= -v_j \beta_{j'j} \left(\frac{10}{N(2j+1)} \right)^{1/2} \frac{1}{K K'_j} \\ \theta_j &= \frac{v_j}{\sqrt{N}} \frac{1}{K''_j} \\ \theta_{jj'} &= u_j \beta_{j'j} \left(\frac{10}{2j+1} \right)^{1/2} \frac{1}{K K''_j} \end{aligned}$$

N is N_π or N_ν, depending on the transfer operator, and K, K'_j, K''_j are determined by

$$\begin{aligned} K &= \left(\sum_{jj'} \beta_{jj'}^2 \right)^{1/2} \\ \sum_{\alpha J} < \mathrm{odd};\alpha J || A^{\dagger j} || \mathrm{even};0_1^+ >^2 &= (2j+1) u_j^2 \\ \sum_{\alpha J} < \mathrm{even};0_1^+ || B^{\dagger j} || \mathrm{odd};\alpha J >^2 &= (2j+1) v_j^2 \end{aligned}$$

When the odd fermion is a hole with respect to the boson core, u_j and v_j have to be interchanged

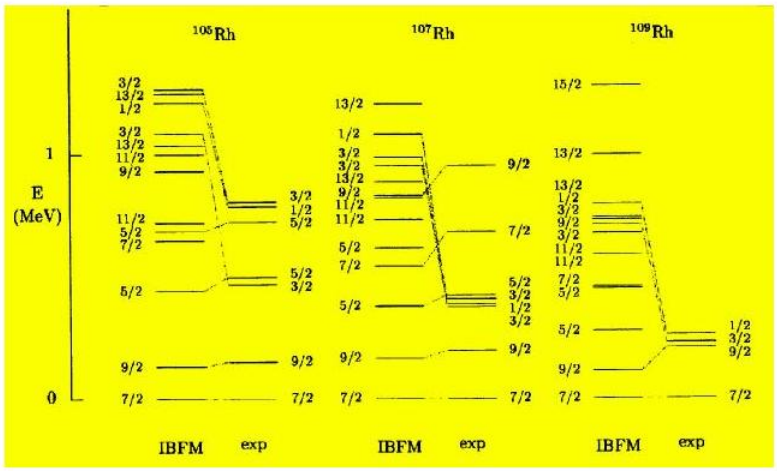
Beta-decay rates from ^{A}Cs to ^{A}Xe shown in terms of $\log_{10} ft$ values. The symbol • with the error bar denotes experimental data, while x presents the calculated value.



Rh ⟹ Pd

A = 105, 107, 109

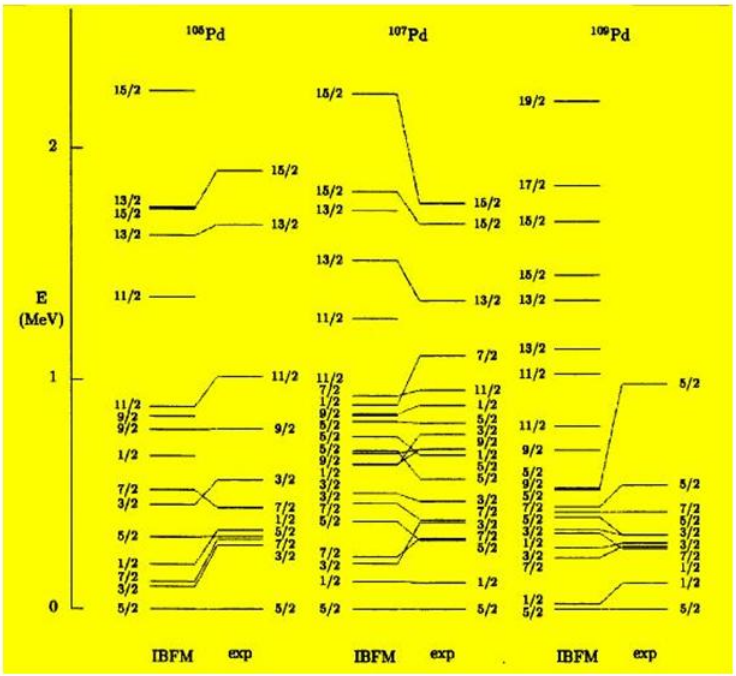
U(5) ⟷ O(6) nuclei



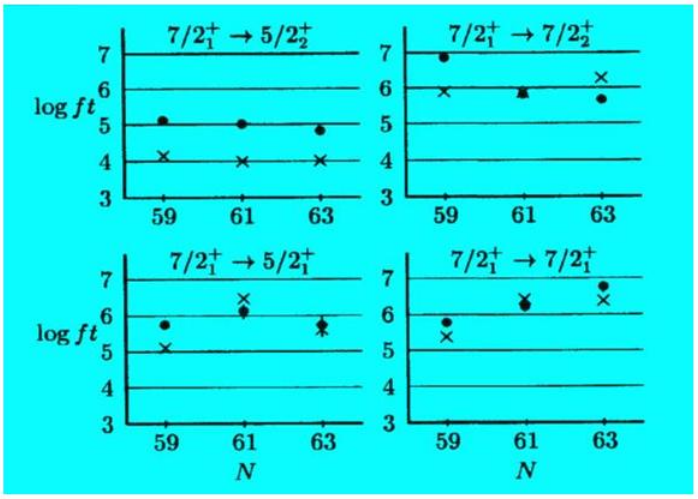
Positive parity levels

j – 1 anomaly !!!!

on $g_{9/2}$



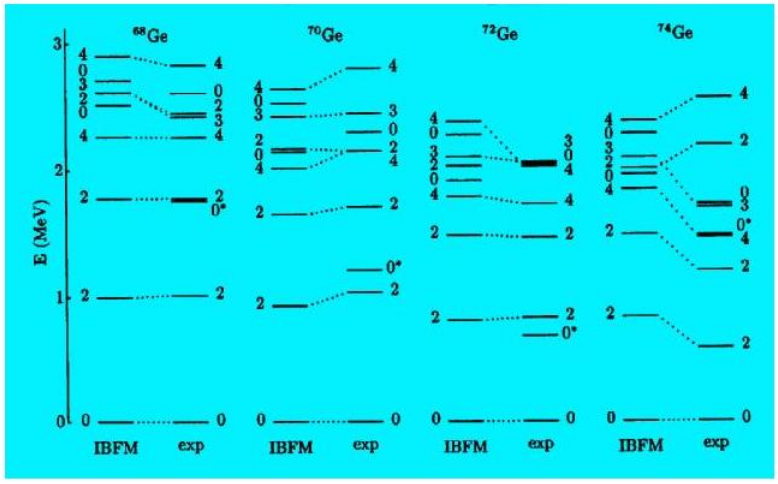
Positive parity levels



$\log_{10} ft$ values in the decays $_{45}\mathrm{Rh}_{N+1} \to {}_{46}\mathrm{Pd}_N$. The experimental data are presented by $\bullet$ while the calculated values are shown by $\times$.

As → Ge

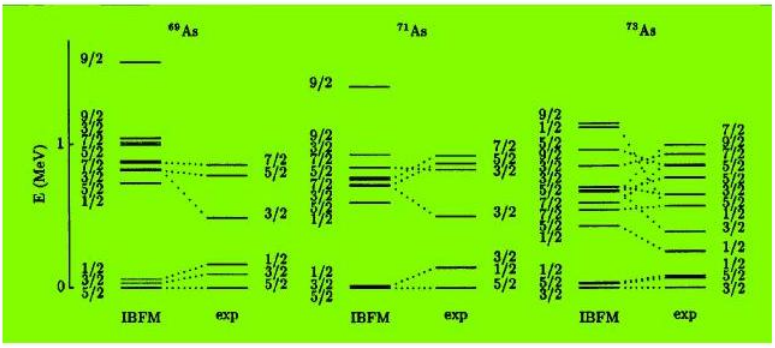
A = 69, 71, 73



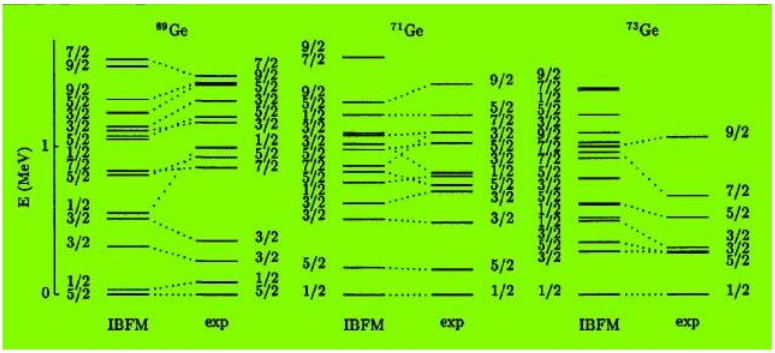
0_2^+ states are intruders !!!!

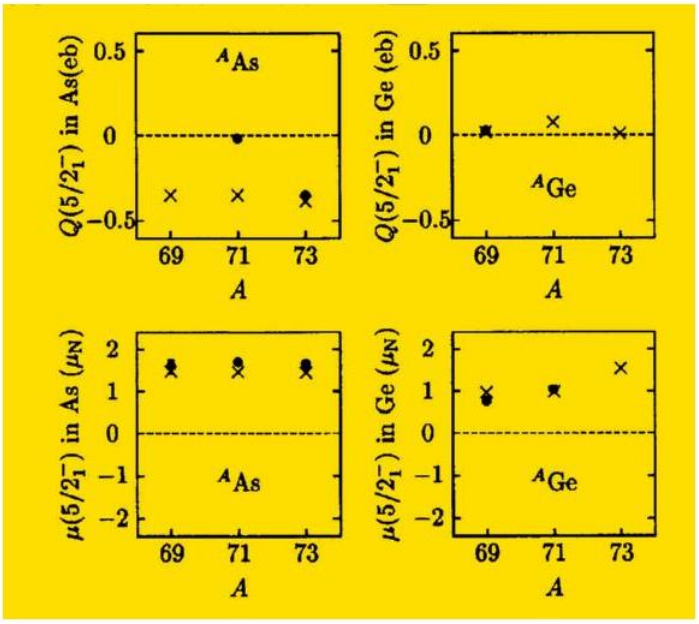
→ outside the boson space

Consequences ?????



Negative parity levels





The exclusion of intruder components does not influence strongly the theoretical values of static moments

and branching ratios

Branching ratios in ^{71}As

level (MeV)	transition	$I_\gamma(IBFM2)$	$I_\gamma(EXP)$
0.143	$1/2_1^- \to 5/2_1^-$	100	100
0.147	$3/2_1^- \to 1/2_1^-$	0.0	
	$3/2_1^- \to 5/2_1^-$	100	100
0.506	$3/2_2^- \to 3/2_1^-$	100	100 (5)
	$3/2_2^- \to 1/2_1^-$	7.1	27 (14)
	$3/2_2^- \to 5/2_1^-$	8.2	
0.829	$3/2_3^- \to 3/2_2^-$	9.3	
	$3/2_3^- \to 3/2_1^-$	100	100 (14)
	$3/2_3^- \to 1/2_1^-$	30.3	9.3 (7)
	$3/2_3^- \to 5/2_1^-$	29.4	
0.870	$5/2_2^- \to 3/2_3^-$	0.0	
	$5/2_2^- \to 3/2_2^-$	28.8	
	$5/2_2^- \to 3/2_1^-$	36.4	40 (1)
	$5/2_2^- \to 1/2_1^-$	27.0	1.8 (7)
	$5/2_2^- \to 5/2_1^-$	100	100.0(7)
0.925	$7/2_1^- \to 5/2_2^-$	0.0	
	$7/2_1^- \to 3/2_3^-$	0.0	
	$7/2_1^- \to 3/2_2^-$	0.0	
	$7/2_1^- \to 3/2_1^-$	1.1	5.8 (16)
	$7/2_1^- \to 5/2_1^-$	100	100 (3)

Branching ratios in ^{69}Ge

level (MeV)	transition	$I_\gamma(IBFM2)$	$I_\gamma(EXP)$
0.087	$1/2_1^- \to 5/2_1^-$	100	100
0.233	$3/2_1^- \to 1/2_1^-$	43.2	48.3 (13)
	$3/2_1^- \to 5/2_1^-$	100	100 (3)
0.374	$3/2_2^- \to 3/2_1^-$	0.7	4.6 (8)
	$3/2_2^- \to 1/2_1^-$	100	100.0 (15)
	$3/2_2^- \to 5/2_1^-$	0.1	31.5 (8)
0.862	$7/2_1^- \to 3/2_2^-$	0.4	0.76 (13)
	$7/2_1^- \to 3/2_1^-$	0.1	8.4 (21)
	$7/2_1^- \to 5/2_1^-$	100	100 (3)
0.933	$5/2_2^- \to 7/2_1^-$	0.0	
	$5/2_2^- \to 3/2_2^-$	0.5	32 (7)
	$5/2_2^- \to 3/2_1^-$	16.7	8
	$5/2_2^- \to 1/2_1^-$	35.5	24 (7)
	$5/2_2^- \to 5/2_1^-$	100	100 (5)
0.995	$1/2_2^- \to 5/2_2^-$	0.0	
	$1/2_2^- \to 3/2_2^-$	7.9	9 (6)
	$1/2_2^- \to 3/2_1^-$	26.8	41 (9)
	$1/2_2^- \to 1/2_1^-$	0.7	
	$1/2_2^- \to 5/2_1^-$	100	100 (21)

$\log_{10} ft$ values for levels in ^{69}Ge.

level	$\log_{10} ft$ $(IBFM2)$	$\log_{10} ft$ (EXP)
$3/2^-_1$	5.88	6.05 (2)
$3/2^-_2$	7.90	7.21 (5)
$3/2^-_3$	5.07	6.79 (4)
$3/2^-_4$	6.46	6.71 (6)
$3/2^-_5$	6.73	7.02 (6)
$5/2^-_1$	4.26	5.49 (2)
$5/2^-_2$	6.65	6.94 (7)
$5/2^-_3$	5.33	6.65 (5)
$5/2^-_4$	5.49	6.80 (6)
$7/2^-_1$	7.54	6.98 (5)
$7/2^-_2$	6.54	6.81 (5)
$7/2^-_3$	5.96	6.20 (5)

$\log_{10} ft$ values for levels in ^{71}Ge.

level	$\log_{10} ft$ $(IBFM2)$	$\log_{10} ft$ (EXP)
$3/2^-_1$	6.52	7.19 (1)
$3/2^-_2$	7.79	
$3/2^-_3$	5.73	
$3/2^-_4$	5.21	6.33 (1)
$3/2^-_5$	7.34	6.94 (1)
$5/2^-_1$	4.60	5.85 (1)
$5/2^-_2$	6.08	
$5/2^-_3$	5.63	6.87 (2)
$5/2^-_4$	5.55	6.84 (2)
$7/2^-_1$	7.60	8.79 (25)

The ground states of parent ^{69}As and ^{71}As nuclei are $5/2^-_1$ levels. The hierarchy of values for transitions into different states of each angular momentum is reproduced for ^{69}Ge (except for the transition to the $3/2^-_3$ level that is predicted to have a rather small $\log_{10} ft$ value). The same is true for ^{71}Ge. The theory predicts that the smallest $\log_{10} ft$ value among all $3/2^-$ levels in ^{71}Ge has the $3/2^-_4$ level. This result is in agreement with the experimental data. The only available experimental $\log_{10} ft$ value in ^{73}Ge is for the $1/2^-_1$ level ($\log_{10} ft = 5.4$). The corresponding theoretical value (4.27) is the smallest calculated.

Systematic effect : For most decays the calculated values are smaller than the experimental values

a) Wave functions ?

If one takes the transition operators without normalization parameters, then the difference between the calculated and experimental values are caused by the transition matrix elements, that in this case have to be overestimated. This may indicate that other components are admixed in the wave functions (for example those involving intruder states), which would decrease the amplitudes of the present IBFM2 components, leading to an increase of the theoretical $\log_{10} ft$ values.

⬇

Accurate test of wave functions

b) Transfer operators ?

- **Normalization factors ?**
- **Additional terms ?**
- **Normalization factors + Additional terms ?**

$$A_m^{\dagger(j)} = [\ \zeta_j a_{jm}^\dagger + \sum_{j'} \zeta_{jj'}\ (\ s^\dagger [\tilde{d} a_{j'}^\dagger]_m^{(j)} + \quad)\ ]$$

Overall normalization factor N ?

Normalization factor γ

a) Parameter
b) Microscopic

Additional term(s)

$\tilde{s}[d^\dagger a_{j'}^\dagger]_m^{(j)}$

or

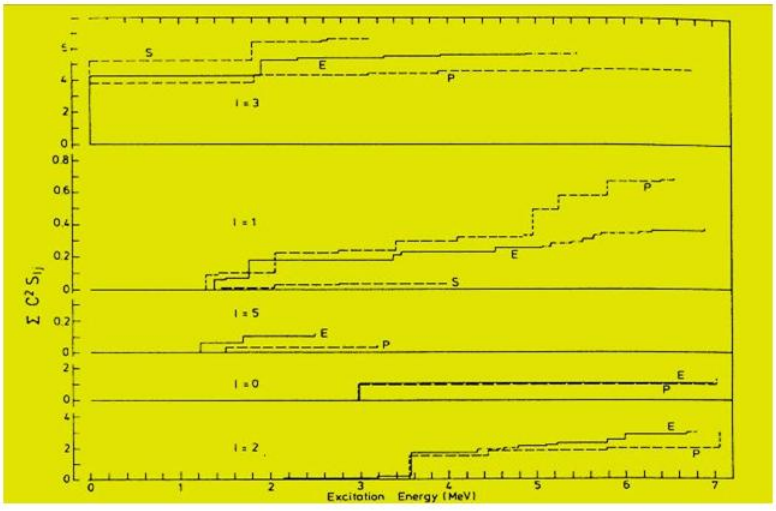
$\sum_{j',J} \phi_{jj'}^J [(a_{j'}^\dagger \times d^\dagger)^{(J)} \times \tilde{d}]_m^{(j)}$

or

.....

^{58}Ni (d, ^{3}He) ^{57}Co reaction

Normalization factor γ and the term $\tilde{s}[d^\dagger a_{j'}^\dagger]_m^{(j)}$

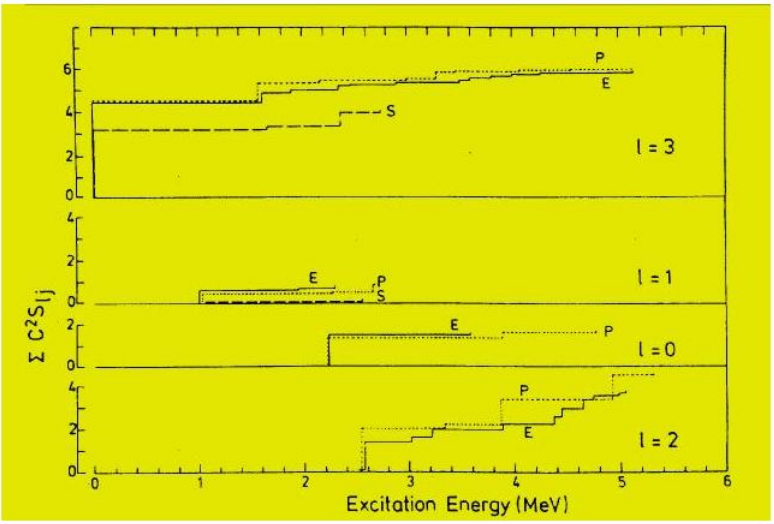


Sums of spectroscopic strengths

E experiment S shell model P IBFM1

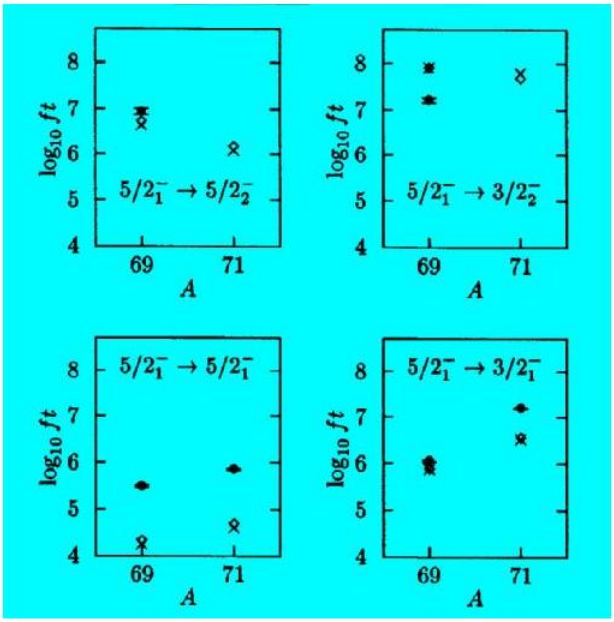
^{62}Ni (d, ^{3}He) ^{61}Co reaction

Normalization factor γ and the term $\tilde{s}[d^{\dagger}a^{\dagger}_{j'}]^{(j)}_{m}$



Sums of spectroscopic strengths

E experiment S shell model P IBFM1



Log_{10} ft values of the β-decay from the As to the Ge isotopes. The symbol • shows the experimental values with their uncertainties, while the symbol x shows the results of calculations with the conventional operators. The symbol ○ shows the results of calculations with the additional d boson number conserving terms.

The effect of the additional term

$$\sum_{j',J} \phi^{J}_{jj'}[(a^{\dagger}_{j'} \times d^{\dagger})^{(J)} \times \tilde{d}]^{(j)}_{m}$$

is small

CONCLUSIONS

The extensions of IBM with fermion degrees of freedom provide a consistent description of nuclear structure phenomena in:

- spherical nuclei
- deformed nuclei
- transitional nuclei

- **The structure results from a consistent calculation that includes interaction strengths obtained in the analysis of neighbouring nuclei**
- **All calculations are performed in laboratory frame, and therefore the results can be directly compared with experimental data**
- **The models can be related to the shell models**
- **The symmetry approach can be applied in special cases**
- **There is strong evidence that collective and single-particle degrees of freedom are closely related**

5.

Experimental Nuclear Structure

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Experimental Nuclear Structure-Part I

Filip G. Kondev

kondev@anl.gov

Workshop on "Nuclear Structure and Decay Data: Theory and Evaluation", Trieste, Italy

28 April – 9 May , 2008

Outline

I) Lecture I: Experimental nuclear structure physics
- **Introduction**
- **Nuclear reactions – production of excited nuclear states**
- **Techniques for lifetime measurements**
  - *Coulomb excitation, electronic, activity, indirect*

II) Lecture II: Contemporary Nuclear Structure Physics at the Extreme
- **Spectroscopy of nuclear K-isomers**
- **Physics with large γ–ray arrays**
- **Gamma-ray tracking – the future of γ–ray spectroscopy**

Have attempted to avoid formula, jargon and material covered by other lecturers – will give many examples

Please feel free to interrupt at any time!

Some Useful Books

"Handbook of nuclear spectroscopy", J. Kantele,1995

"Radiation detection and measurements", G.F. Knoll, 1989

"In-beam gamma-ray spectroscopy", H. Morinaga and T. Yamazaki, 1976

"Gamma-ray and electron spectroscopy in Nuclear Physics", H. Ejiri and M.J.A. de Voigt, 1989

"Techniques in Nuclear Structure Physics", J.B.A. England, 1964

"Techniques for Nuclear and Particle Physics Experiments", W.R. Leo, 1987

"Nuclear Spectroscopy and Reactions", Ed. J. Cerny, Vols. A-C

"Alpha-, Beta- and Gamma-ray Spectroscopy", Ed. K. Siegbahn, 1965

"The Electromagnetic Interaction in Nuclear Spectroscopy", Ed. W.D. Hamilton, 1975

Plenty of information on the Web

Input from many colleagues

R.V.F. Janssens, C.J. Lister and I. Ahmad, Argonne National Laboratory, USA

M.A. Riley, Florida State University, USA

I.Y. Lee, Lawrence Berkeley National Laboratory, USA

D. Radford, Oak Ridge National Laboratory, USA

A. Heinz, Yale University, USA

C. Svensson, University of Guelph, Canada

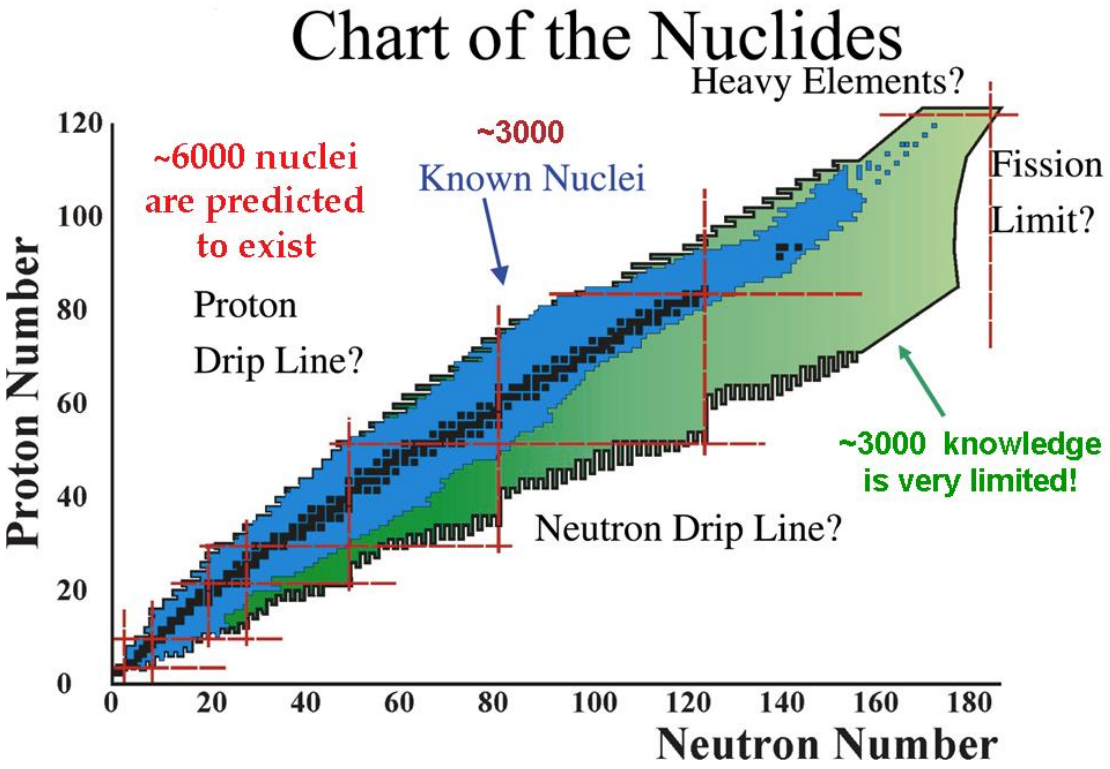
G.D. Dracoulis and T. Kibedi, Australian National University, Australia

J. Simpson, Daresbury Laboratory, UK

E. Paul, University of Liverpool, UK

P. Regan, University of Surrey, UK

and many others …



Introduction

- The nucleus is one of the most interesting quantum few-body systems in nature
- Brings together many types of behaviour - almost all of which are found in other systems
- The major elementary excitations in nuclei can be associated with single-particle and collective degrees of freedom. While these modes can exist in isolation, the interaction between them gives nuclear spectroscopy a rich diversity

The Nucleus is Unique!

- **This** uniqueness arises on the one hand because all forces of nature are present - strong, weak, electromagnetic and even gravity if one considers condensed stellar objects as a huge number of nuclei held together by gravitational attraction, in contrast to all other known physical objects
- On the other hand, the small number of nucleons leads to specific finite-system effects, where even a few particles can change the whole system

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The Nucleus and other many-body systems

- **The physics of the nucleus is not completely separated from the other many-body systems known in nature**
  - ✓ **A variety of nuclear properties can be described by the shell model, where nucleons move independently within their average potential, in close analogy with the atomic shell model**
  - ✓ **The nucleus often behaves collectively, like a fluid - even a superfluid – in fact the smallest superfluid object known in nature and there are close analogies both to condensed matter physics and to familiar macroscopic systems, such as the liquid drop**

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To summarize …

NUCLEAR PHYSICS *IS A BIG CHALLENGE*

because of complicated forces, and the energy scale and sizes involved

The challenge is to understand how nucleon-nucleon interactions build to create the mean field or how single-particle motions build collective effects such as pairing, vibrations and shapes

NUCLEAR PHYSICS *IS IMPORTANT*

(intellectually, astrophysics, energy production and security)

THIS IS A GREAT TIME IN NUCLEAR PHYSICS

with new (RIB) facilities just around the corner, we have a chance to make major contributions to our knowledge - with advances in theory we have a great opportuniy to understand everthing - by compiling and evaluating data we support various applications, assist scientific discoveries and preserve knowledge for future generations

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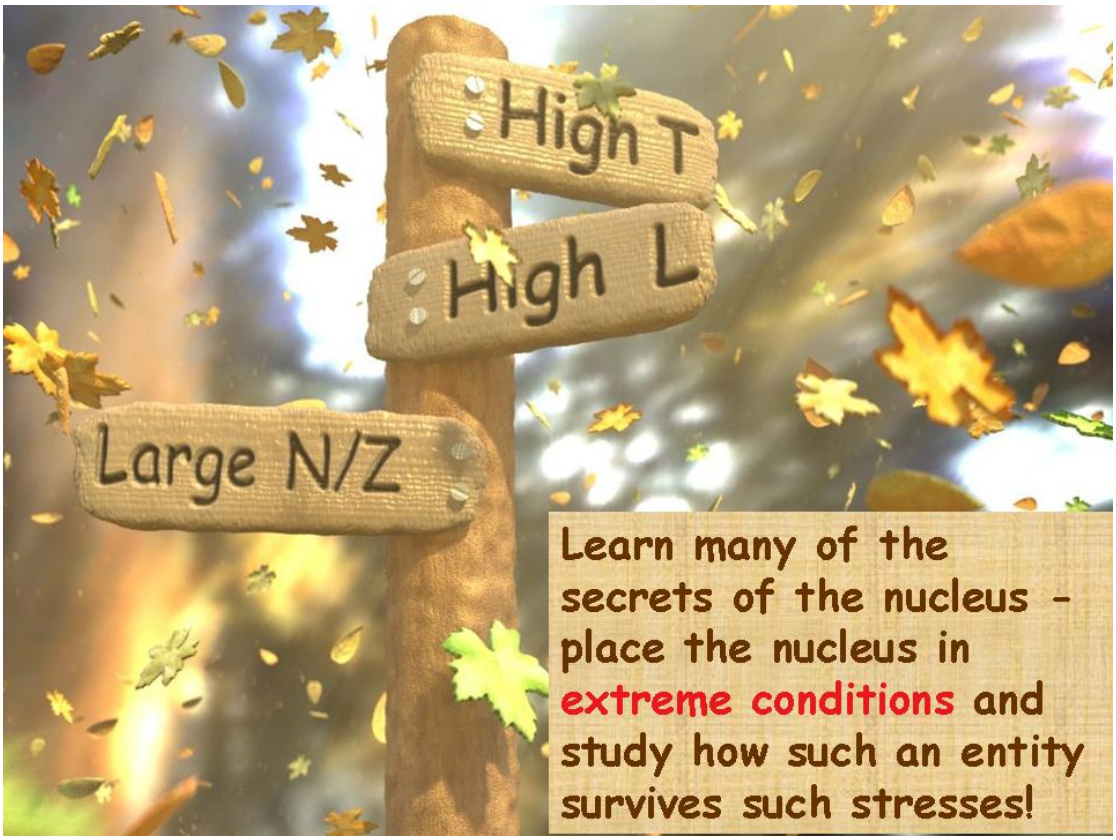
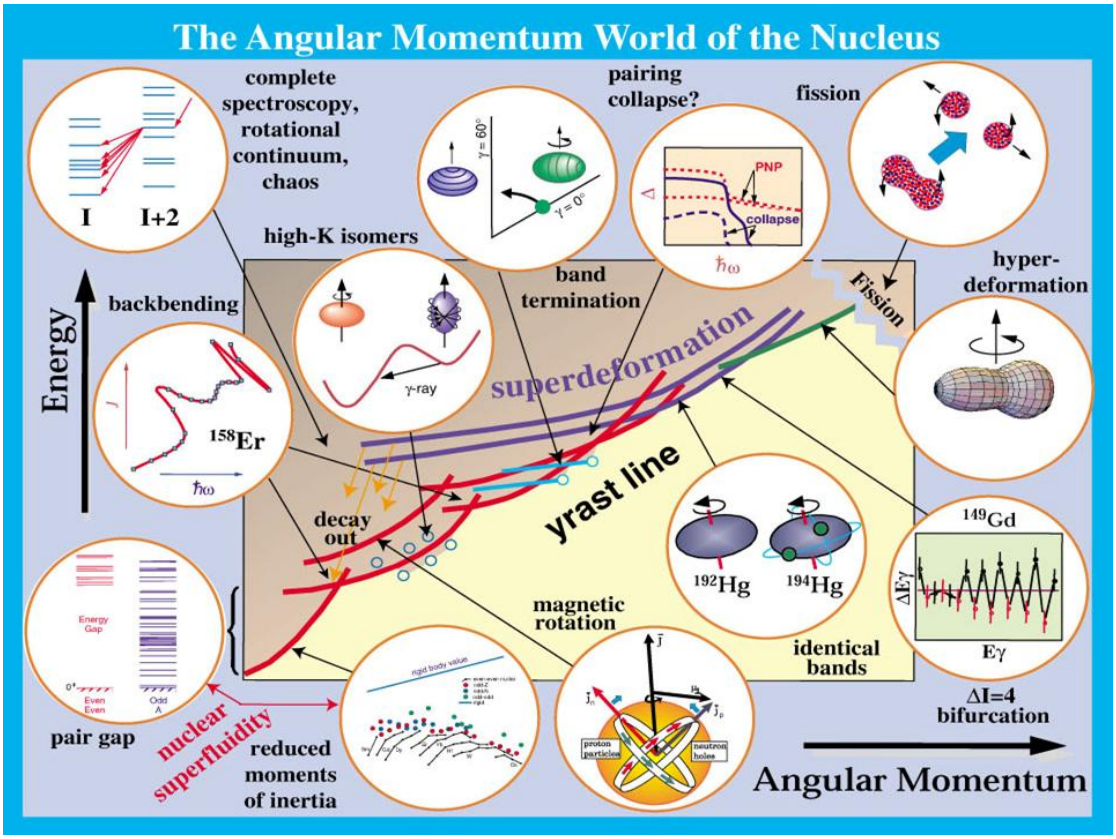
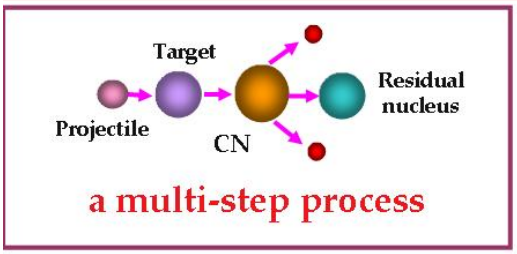
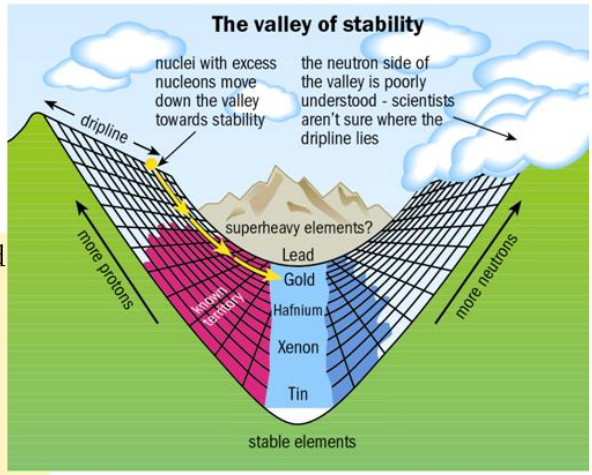
9





Nuclear Reactions – very schematic!

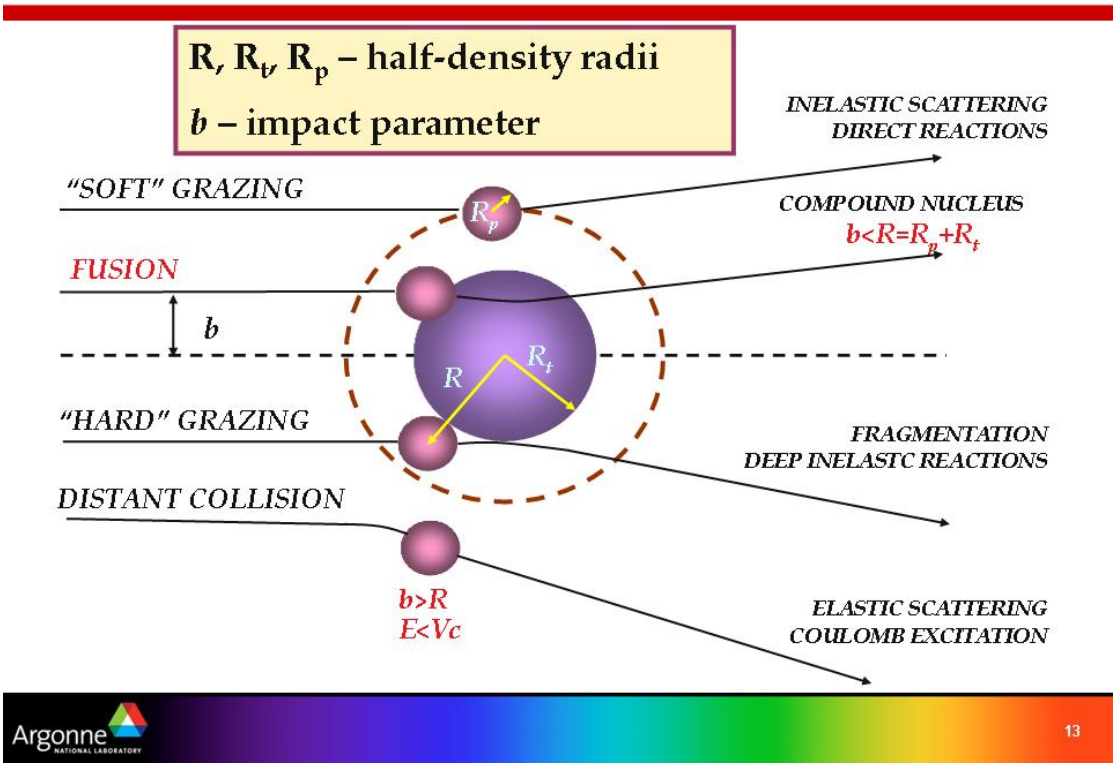


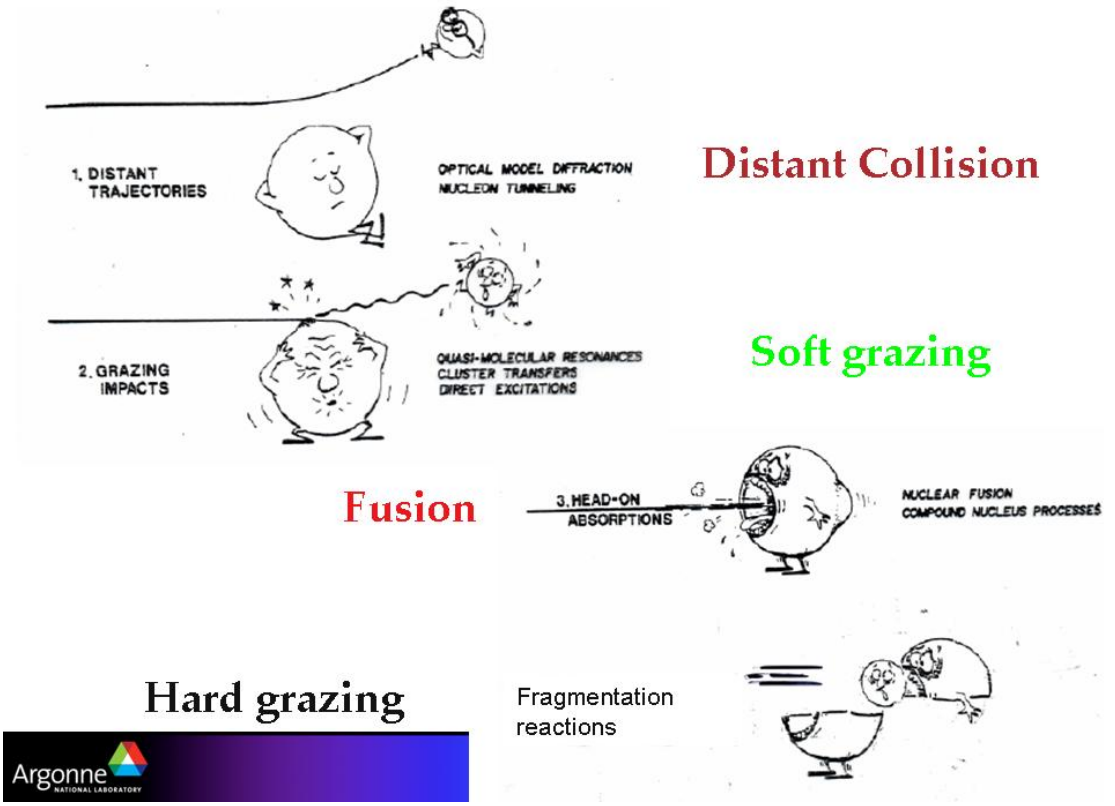


- Gamma-rays and neutron-induced
  - ✓ no Coulomb barrier
  - ✓ low-spin states
- Light charged particles - p, d, t, α
  - ✓ Coulomb barrier
  - ✓ low-spin states

- **Heavy Ions** (1970 - ????)
  - ✓ high-spin phenomena
  - ✓ nuclei away from the line of stability

HI Reactions – Classical Picture





Heavy Ions reactions at the Coulomb barrier

- properties of the collision can be quite well estimated by adopting conservation of momentum and energy

$$E_{cm} = M_t / (M_b + M_t)\, E_{lab}$$

- energy scale is determined by Coulomb barrier, V_{cb}

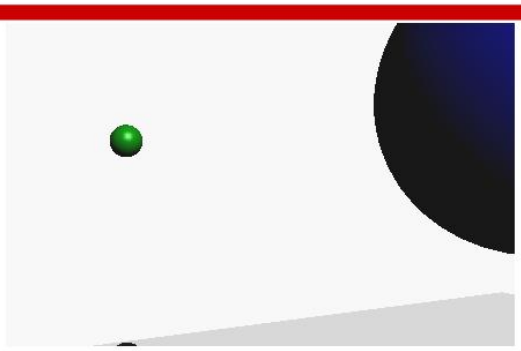
$$V_{cb} = (4\pi\varepsilon)^{-1} Z_b Z_t e^2 / R = 1.44\, Z_b Z_t / 1.16\, [(A_b^{1/3} + A_t^{1/3}) + 2] \text{ MeV}$$

$$L_{max} = 0.22\, R\, [\, \mu\, (E_{cm} - V_{cb})\,]^{1/2}\ \hbar$$

- excitation energy of residues is usually lowered by the Q-value and kinetic energy of "evaporated" particles

$$E^* = E_{cm} + Q - K.E.$$

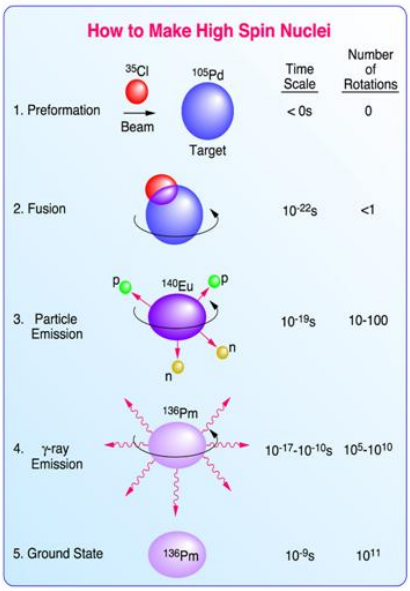
HI Fusion-Evaporation Reactions



$$\sigma_R = \pi\lambda\!\!\!^{-2} \sum_{l=0}^{l\max} (2l+1) T_l = \pi\lambda\!\!\!^{-2} (l_{\max}+1)^2$$

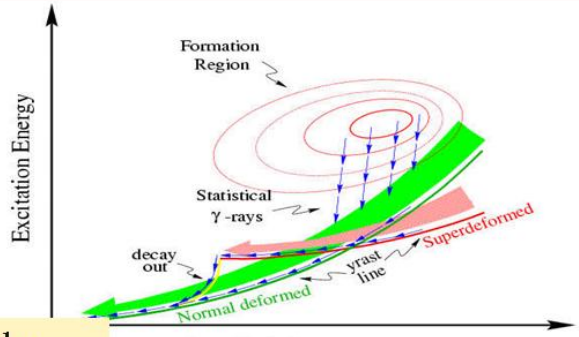
$$\lambda\!\!\!^{-} = \hbar / \sqrt{2\mu E_{CM}}\,, \mu = \frac{A_1 A_2}{A_1 + A_2}$$

$$l_{\max}^2 = \left(\frac{2\mu R^2}{\hbar^2}\right)(E_{CM} - V_C)$$



Decay of the Compound Nucleus

- Heavy-Ion fusion-evaporation reactions: final nucleus is often left with L~60-80 hbar and E^*~30-50 MeV



- The excited nucleus cools off by emitting γ rays - the typical number is quite large, usually 30-40, with an average energy of ~1-2 MeV. Not a trivial task to detect all of them - the big advantage comes with the large γ–ray arrays!

Channel Selection for γ–ray spectroscopy

Detection of Light Charged Particles (α,p,n)

PROS: efficient, flexible, powerful ... inexpensive

CONS: count-rate limited, contaminants (carbon etc, isotopic impurities) makes absolute identification of new nuclei difficult

CROSS-SECTION LOWER LIMIT: ~100 μb that is $\sim 10^{-4}$b

Detection of Residues in Vacuum Mass Separator

PROS: true M/q, even true mass measurements. With suitable focal plane detector can be ULTRA sensitive. Suppresses contaminants

CONS: low efficiency

CROSS SECTION LOWER LIMIT: ~100 nb that is $\sim 10^{-7}$b

Detection of Residues in Gas Filled Separator

PROS: better efficiency (compared to vacuum separators)

CONS: loss of mass information and cleanliness. Focal plane counters clean up the data with a good sensitivity in some cases (heavy nuclei)

Some Channel Selection Detectors

Light charged-particle detector Microball – 96 CsI with photo diodes

USA

Argonne FMA

USA

Jyvaskyla RITU

Europe

Calculate Reaction Rates

Reaction Yield: $Y = I_b \times N_t \times \sigma$ [nuclei/s]

$I_b = i/(eq)$; with i - electric current [A], q - charge state, e = $1.6\ 10^{-19}$ [C]

$N_t = [N_a/A]\ \rho x$; with N_a = Avogadros #, A = mass, ρ = density [g/cm^3] and x = thickness [cm] of the target

σ– reaction cross section [cm^2] .... note 1 [barn] is 10^{-24} [cm^2]

Accumulated data: $D = Y \times Time \times Efficiency$ [counts]

A typical "close to the line of stability" experiment may have:

i=100 [nA], q=10, A=100, $\rho x = 10^{-3}$ [g/cm^2], σ=1 [barn] and efficiency of 10 % produces

~3.8×10^4 [counts/sec], BUT

A typical "far from the line of stability" experiment may have:

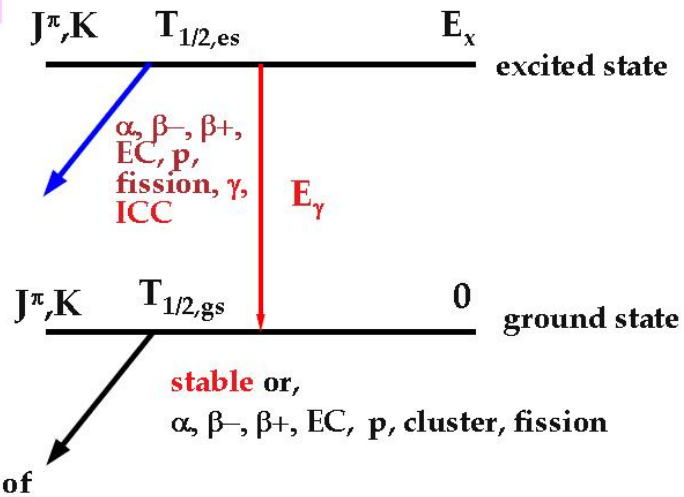
σ=100 [nb], so ccumulated data of ~14 [counts/hour];

σ=10 [pb] gives ~2 counts every 10 weeks!!!.....present situation for producing heaviest elements

Basic knowledge

What we want to know?

- Excitation energy
- Quantum numbers and their projections
- Lifetime
- Branching ratios



How?

- By measuring properties of signature radiations

What is Stable?

A surprisingly difficult question with a somewhat arbitrary answer!
CAN'T decay to something else, BUT

CAN'T decay is a philosophical issue

✓ Violation of some quantity which **we believe** is conserved, such as Energy, Spin, Parity, Charge, Baryon or Lepton number, etc.

DOESN'T decay is an experimental issue that backs up beliefs

Activity: $A=dN/dt = \lambda N$

✓ Activity of 1 mole of material (6.02×10^{23} atoms) with $T_{1/2} = 10^9$ y ($\lambda = 2.2 \times 10^{-17}$ s^{-1}) is ~0.4 mCi (1 Ci = 3.7×10^{10} dps) .... a blazing source!

✓ Current limit on proton half-life, based on just counting a tank of water, is $T_{1/2} > 1.5 \times 10^{25}$ y

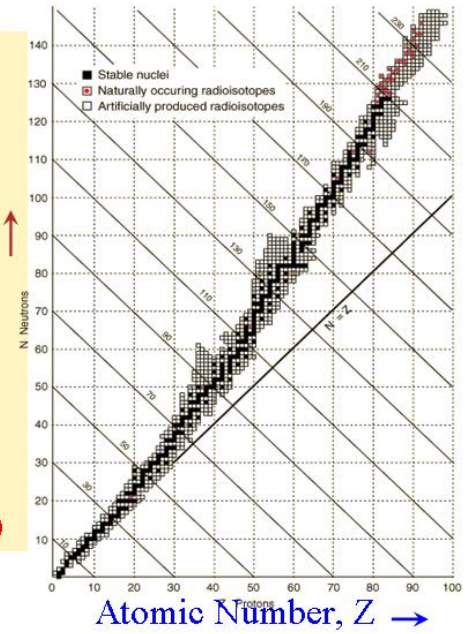
Stable Nuclei: Segre's Chart

~280 Nuclei have half-lives >10^6 years

So they are (quite) **stable** against:

- ✓Decay of their constituents (p,n)
- ✓Weak decay (β^+, β^- and EC)
- ✓α decay
- ✓More complex cluster emission
- ✓Fission

(mostly because of energy conservation)



Mean Lifetime

$$f_{decay}(t) = \frac{Ae^{-\lambda t}}{\int_0^\infty Ae^{-\lambda t}\,dt} = \lambda e^{-\lambda t}$$

Probability for decay of a nuclear state (normalized distribution function); λ – decay constant

$$P_n(t) = \int_0^t \lambda e^{-\lambda t'} dt'$$

Probability that a nucleus will decay within time t

$$1 - P_n(t) = 1 - \int_0^t \lambda e^{-\lambda t'} dt' = e^{-\lambda t}$$

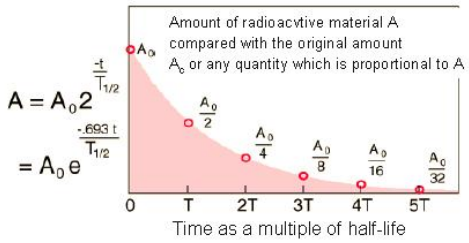
Probability that a nucleus will remain at time t

$$< t >= \tau = \int_0^\infty t e^{-\lambda t} dt = \frac{1}{\lambda}$$

The average survival time (mean lifetime - τ) is then the mean value of this probability

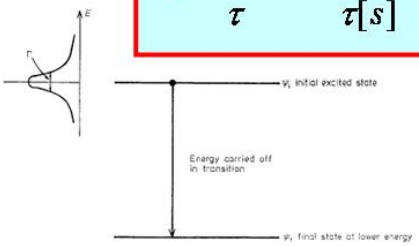
Half-life & Decay Width

$T_{1/2}$: the time required for half the atoms in a radioactive substance to disintegrate



relation between τ, $T_{1/2}$ and λ $\tau = \frac{T_{1/2}}{\ln 2} = \frac{1}{\lambda}$

$$\Gamma = \frac{\hbar}{\tau} = \frac{6.58\times10^{-16}}{\tau[s]} \quad [\text{eV}]$$



$$\Gamma \propto |\langle \psi_1 | M | \psi_2 \rangle|^2$$

Determine the matrix element describing the mode of decay between the initial and final state

log ft values in β-decay

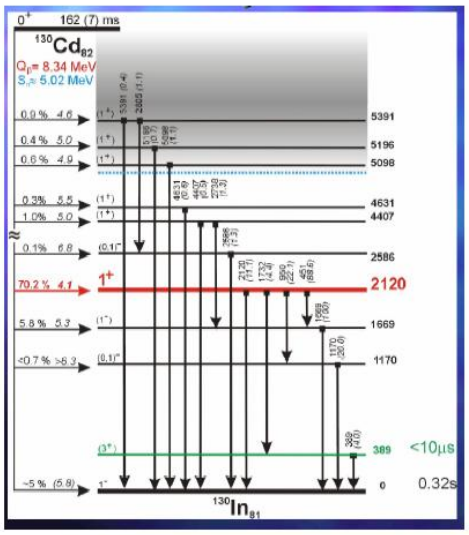
$$\log ft = \log f + \log t$$

$t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}}{BR_i}$ partial half-life of a given β^- (β^+,EC) decay branch

$f \equiv f_\beta \equiv f_n, n = 0,1,2\ldots$

statistical rate function (phase-space factor): energy and nuclear structure determine the decay transition

Decay Mode	Type	log *f*
β–	**allowed**	$\log f_0^-$
β–	**1st-forbid**	$\log f_0^- + \log(f_1^-/f_0^-)$
EC+β+	**allowed**	$\log(f_0^{EC} + f_0^+)$



$f_0^-, f_1^-, etc.$ N.B. Gove and M. J. Martin, Nuclear Data Tables **10** (1971) 205

Hindrance Factor in α–decay

$$|I_i - I_f| \le L \le |I_i + I_f|$$

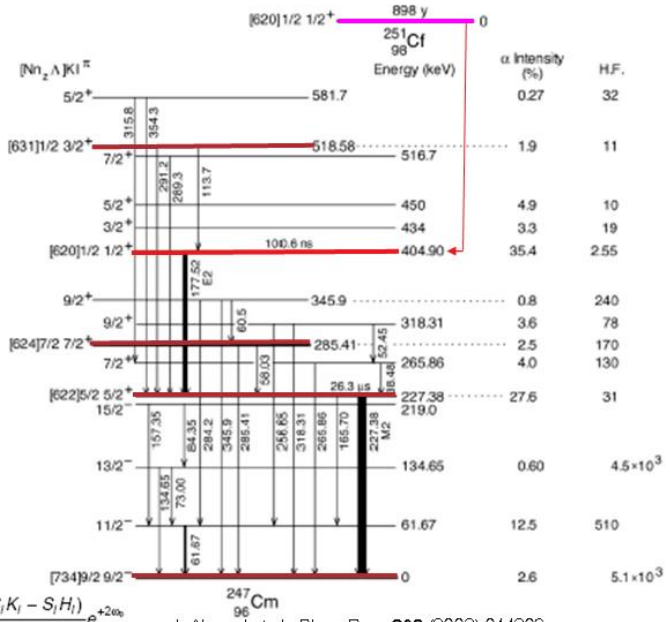
$$\pi_i \pi_f = (-1)^L$$

Strong dependence on L

L=0 - unhindered decay (fast)

$$HF_i = \frac{T_{1/2}^{Exp}(\alpha_i)}{T_{1/2}^{Theory}} = \frac{T_{1/2}^{Exp} / BR_i}{T_{1/2}^{Theory}}$$

$T_{1/2}^{Theory}$ M.A. Preston, Phys. Rev. **71** (1947) 865



$$t_{1/2}^{\alpha} = \ln 2 \frac{r_0}{2v} \frac{\mu^2(H_i^2 + K_i^2) + \tan^2\alpha_0(C_i^2 + S_i^2) + 2\mu\tan\alpha_0(C_i K_i - S_i H_i)}{\mu^2\tan\alpha_0(H_i C_i + K_i S_i) Q_i} e^{+2\omega_0}$$

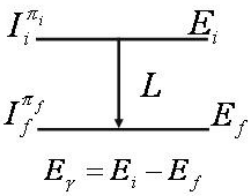
I. Ahmad et al., Phys. Rev. **C68** (2003) 044306

γ–ray decay

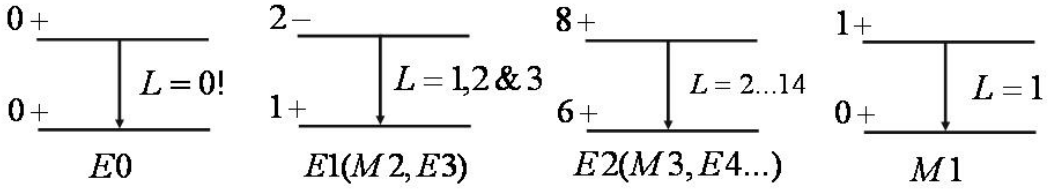
$$|I_i - I_f| \le L \le |I_i + I_f|$$

$$\Delta\pi(EL) = (-1)^L \qquad \Delta\pi(ML) = (-1)^{L+1}$$

electric multipole magnetic multipole



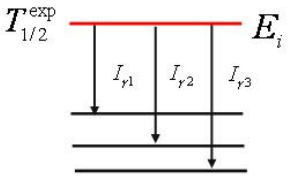
dipole	quadrupole	octupole	hexadecapole	
E1:L=1,yes	E2:L=2,no	E3:L=3,yes	E4:L=4,no	E5:L=5,yes
M1:L=1,no	M2:L=2,yes	M3:L=3,no	M4:L=4,yes	M5:L=5,no



Partial lifetime & Transition Probability

$$T_{1/2}^{\gamma} = T_{1/2}^{\exp} / BR_{\gamma} = T_{1/2}^{\exp} \times \frac{\sum I_{\gamma_i} \times (1+\alpha_{Ti})}{I_{\gamma}}$$

partial half-life



$$P_{\gamma}(XL: I_i \rightarrow I_f) = \frac{\ln 2}{T_{1/2}^{\gamma}} = \frac{8\pi(L+1)}{L[(2L+1)!!]^2}\left(\frac{E_{\gamma}}{\hbar c}\right)^{2L+1} B(XL: I_i \rightarrow I_f)$$

Partial γ–ray Transition Probability Reduced Transition Probability

$$B(XL: I_i \rightarrow I_f) = \frac{\left|\langle I_i \| M(XL) \| I_f \rangle\right|^2}{2I_i + 1}$$

contains nuclear structure information

Hindrance Factor in γ–ray decay

$$F_{W(N)} = \frac{B(XL)_{Theory}}{B(XL)_{Exp}} = \frac{T_{1/2}^{\gamma}(XL)_{Exp}}{T_{1/2}^{\gamma}(XL)_{Theory}}$$

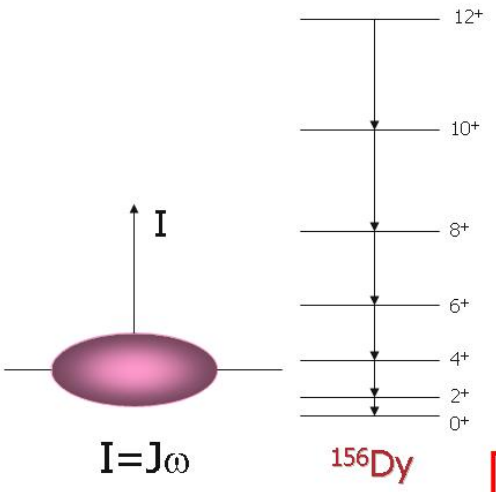
... usually an upper limit, but ...

Hindrance Factor: Weisskopf (W): based on spherical shell model potential

Nilsson (N): based on deformed Nilsson model potential

EL	$B(EL)_W, e^2 fm^{2L}$	$T_{1/2}^{\gamma}(EL)_W$, sec	ML	$B(ML)_W, \mu_N^2 fm^{2L-2}$	$T_{1/2}^{\gamma}(ML)_W$, sec
E1	$0.06446A^{2/3}$	$6.762A^{-2/3}E_{\gamma}^{-3}\times10^{-15}$	M1	1.7905	$2.202E_{\gamma}^{-3}\times10^{-14}$
E2	$0.0594A^{4/3}$	$9.523A^{-4/3}E_{\gamma}^{-5}\times10^{-9}$	M2	$1.6501A^{2/3}$	$3.100A^{-2/3}E_{\gamma}^{-5}\times10^{-8}$
E3	$0.0594A^{2}$	$2.044A^{-2}E_{\gamma}^{-7}\times10^{-2}$	M3	$1.6501A^{4/3}$	$6.655A^{-4/3}E_{\gamma}^{-7}\times10^{-2}$
E4	$0.06285A^{8/3}$	$6.499A^{-8/3}E_{\gamma}^{-9}\times10^{4}$	M4	$1.7458A^{2}$	$2.116A^{-2}E_{\gamma}^{-9}\times10^{5}$
E5	$0.06929A^{10/3}$	$2.893A^{-10/3}E_{\gamma}^{-11}\times10^{11}$	M5	$1.9247A^{8/3}$	$9.419A^{-8/3}E_{\gamma}^{-11}\times10^{11}$

Quadrupole Deformation



$E_I = \hbar^2/2J\ I(I+1)$

B(E2) ~ 200 W.U.

deformed nucleus

$$B(E2) = \frac{8.16\times10^{13}}{E_\gamma^5[keV]\tau_\gamma[ps]}[e^2b^2]$$

$$B(E2; KI_i \rightarrow KI_f) = \frac{5}{16\pi}Q_0^2\left\langle I_i K 20 \middle| I_f K \right\rangle^2$$

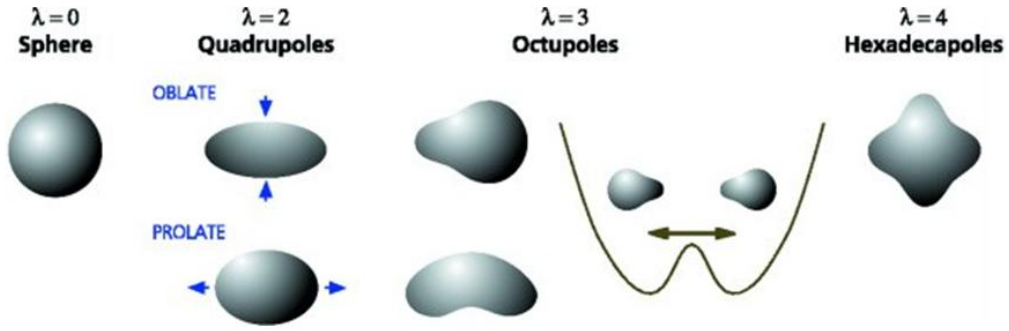
(from collective models)

$$\beta_2 \approx -7\sqrt{\frac{\pi}{80}} + \sqrt{\frac{49\pi}{80} + \frac{7\pi Q_0}{6eZr_0^2A^{2/3}}}$$

$$\tau_\gamma[ps] = (1.58\pm0.28)\times10^{14}E_{2_1^+}^{-4}[keV]Z^{-2}A^{2/3}$$

$$\beta_2 = \frac{466\pm41}{A\times\sqrt{E_{2_1^+}[keV]}}$$

Octupole Deformation

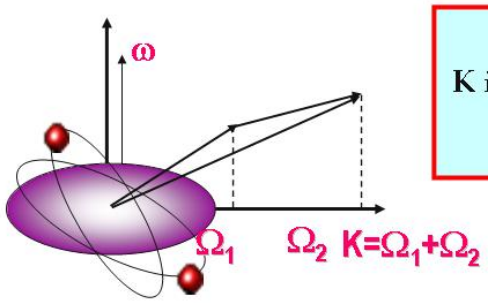


$$\tau_{E3}[s] = 0.012264\times E_{3_1^-}^{-7}\times[B(E3)\uparrow]^{-1}$$

$$E_{3_1^-}[MeV]; B(E3)\uparrow[e^2fm^6]$$

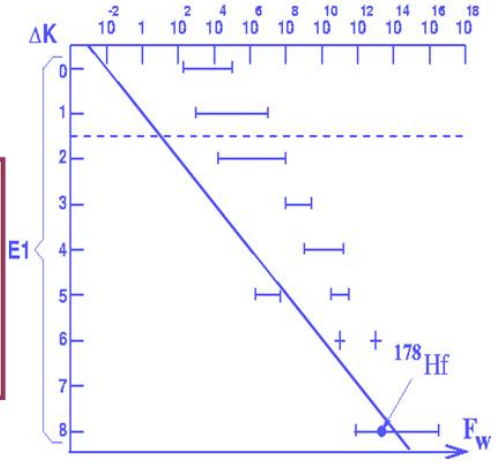
$$\beta_3 = \frac{4\pi}{ZR^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$$

K-forbidden decay

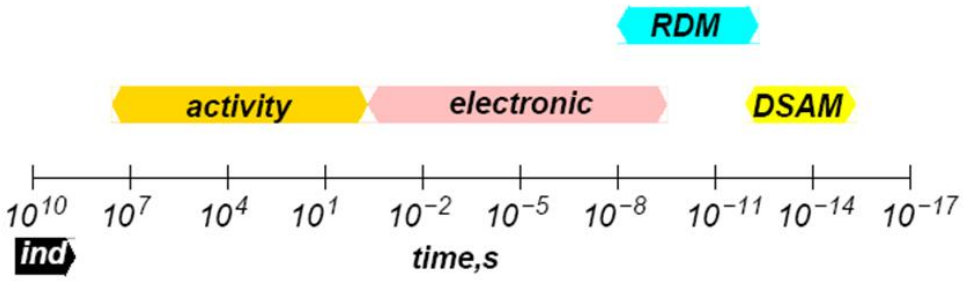


Deformed, axially symmetric nuclei
K is approximately a good quantum number
each state has not only
J^{π} **but also** K

- The solid line shows the dependence of F_W on ΔK for some E1 transitions according to an empirical rule: $\log F_W = 2\{|\Delta K| - \lambda\} = 2\nu$
- F_W values increase approximately by a factor of 100 per degree of K forbiddenness
- $f_\nu = (F_W)^{1/\nu}$ – reduced hindrance per degree of K forbiddenness



Experimental techniques



Others:

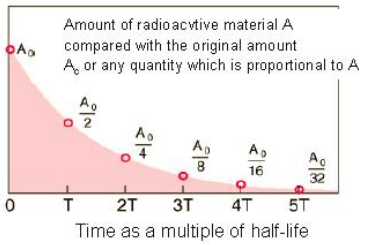
- Direct width measurements
- Inelastic electron scattering
- Blocking technique
- Mössbauer technique

Activity measurements

Time Range: a few seconds up to several years

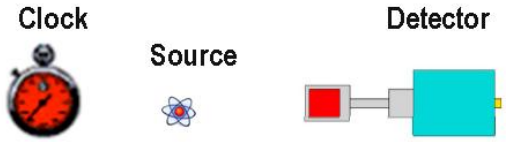
$$A = dN/dt = \lambda N = A_0 e^{-t/\tau}$$

- Statistical uncertainties are usually small
- Systematic uncertainties (dead time, geometry, etc.) dominate



usually want to follow at least 5 x $T_{1/2}$

Tag on specific signature radiations (α, β, ce or γ) in "singles" mode

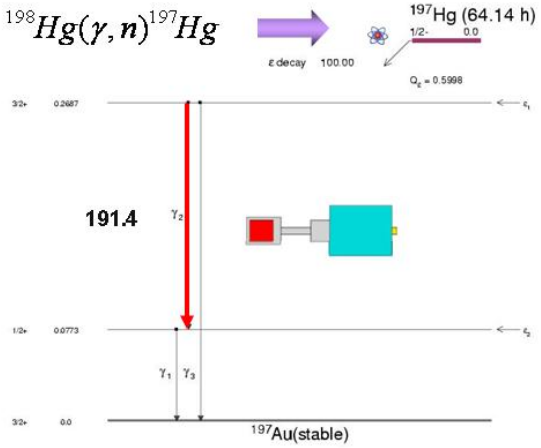


Activity Measurements: Example 1

PHYSICAL REVIEW C, VOLUME 63, 047307

Half-lives of Au, Hg, and Pb isotopes from photoactivation

K. Lindenberg, F. Neumann, D. Galaviz, T. Hartmann, P. Mohr, K. Vogt, S. Volz, and A. Zilges
Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 9, D-64289 Darmstadt, Germany



- ✓ More than 270 spectra measured
- ✓ Followed 4 x $T_{1/2}$

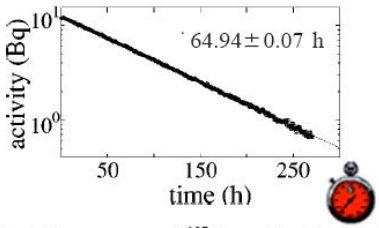
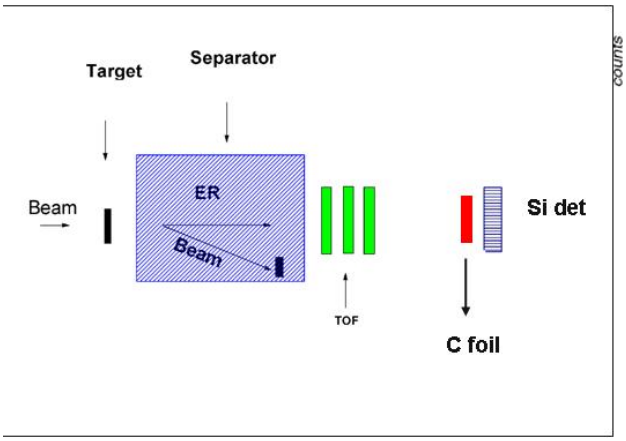
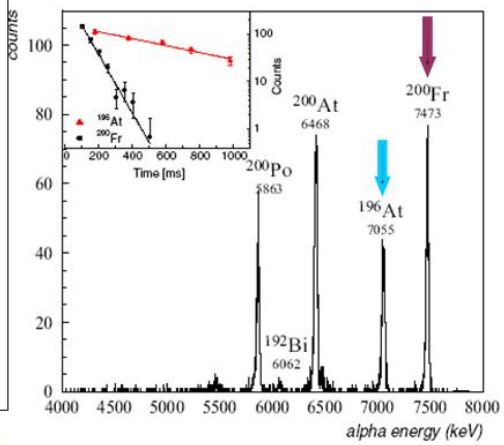


FIG. 3. Decay curve of ^{197}Hg at E_γ=191.4 keV.

Activity measurements: Example 2





1 GeV pulsed proton beam on 51 g/cm2 ThCx target

on-line mass separation (ISOLDE)/CERN

H. De Witte et al., EPJ A23 (2005) 243

Isotope	Energy (keV)	$T_{1/2}$	Reference
^{200}Fr	7473(12)	49(4) ms	this work
	7500(30)	570^{+270}_{-140} ms	[4]
	7468(9)	19^{+13}_{-6} ms	[5]

Very long-lived cases – Example 1

Time Range: longer than 10^2 y

$$A = \lambda N \qquad T_{1/2} = \ln 2 \frac{N}{A}$$

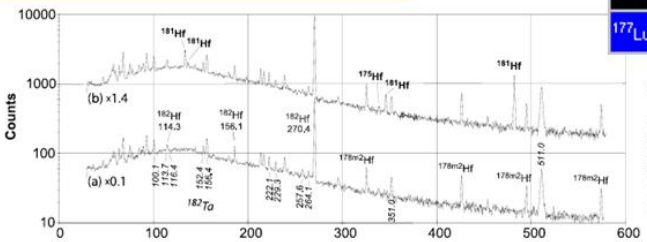
number of atoms estimated by other means, e.g. mass spectrometry

VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

New Half-Life Measurement of ^{182}Hf: Improved Chronometer for the Early Solar System

C. Vockenhuber,[1,*] F. Oberli,[2] M. Bichler,[3] I. Ahmad,[4] G. Quitté,[2] M. Meier,[2] A. N. Halliday,[2] D.-C. Lee,[5] W. Kutschera,[1] P. Steier,[1] R. J. Gehrke,[6] and R. G. Helmer[6]

^{180}W	^{181}W	^{182}W	^{183}W	^{184}W	^{185}W	^{186}W	
^{179}Ta	^{180}Ta	^{181}Ta	^{182}Ta	^{183}Ta	^{184}Ta	^{185}Ta	
^{178}Hf	^{179}Hf	^{180}Hf	^{181}Hf	^{182}Hf	^{183}Hf	^{184}Hf	
^{177}Lu	^{178}Lu	^{179}Lu	^{180}Lu	^{181}Lu	^{182}Lu	^{183}Lu	



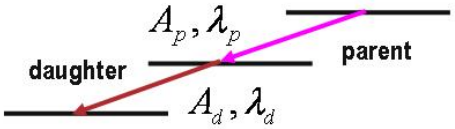
Material	^{174}Hf	^{176}Hf	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf	^{182}Hf
	Atomic abundance (%)						
Helmer 1	≈ 0.0058	4.791	0.605	29.06	25.77	39.64	0.124
Helmer 2	≈ 0.00014	4.377	0.149	17.15	31.30	46.91	0.112
Natural	0.16	5.21	18.60	27.30	13.63	35.10	

TABLE II. The half-life of ^{182}Hf from the two measurements. All uncertainties are 1σ uncertainties.

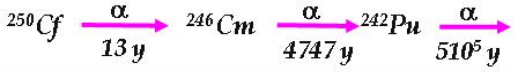
Material	Method	Half-life ($\times 10^6$ yr)	Uncorrelated uncertainty ($\times 10^6$ yr)	Total uncertainty ($\times 10^6$ yr)
Helmer 1	Neutron activation + activity measurement	9.034	±0.241	±0.251
Helmer 2	Isotope dilution + activity measurement	8.896	±0.057	±0.089
	Weighted mean	8.904	±0.056	±0.088

Very long-lived cases – Example 2

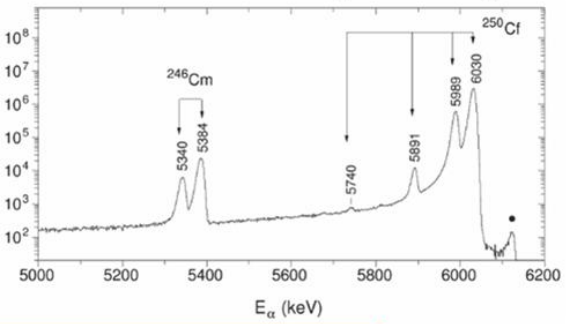
$$\frac{A_p(t)}{A_d(t)} = \frac{\lambda_d}{\lambda_d - \lambda_p}(1 - e^{-(\lambda_d - \lambda_p)t})$$



$T_{1/2}(^{250}Cf)$=13.05 (9) y



- mass-separated source
- alpha-decay counting technique

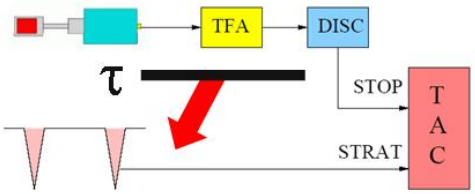


$T_{1/2}$ = 4706 (40) years / Compared to values ranging from $T_{1/2}$ = 2300 up to 6620 years

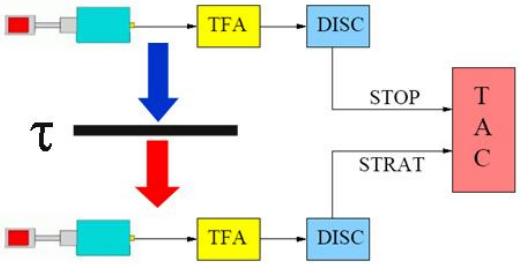
Electronic techniques

Time Range: tens of ps up to a few seconds

The "Clock" - TAC, TDC (START/STOP); Digital Clock



"singles" – E_γ-time, E_α-time

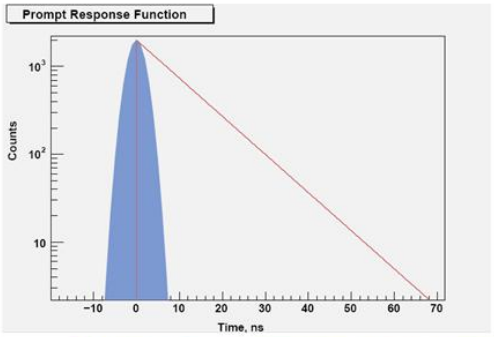


"coincidence" – $E_{\gamma1}$-$E_{\gamma2}$-Δt ; $E_{\alpha1}$-$E_{\gamma1}$-Δt
$E_{\alpha1}$-$E_{\alpha2}$-Δt

Difficulties at the boundaries: e.g. for very short– and very long-lived cases!

Prompt Response Function

- all detectors and auxiliary electronics show **statistical fluctuations** in the time necessary to develop an appropriate pulse for the "clock"
  - depend on the **characteristics of the detectors**: e.g. **light output for scintillators, bias voltage, detector geometry, etc.**
  - instrumental **imperfections in the electronics** – e.g. **noise in the preamplifiers**



Some typical values

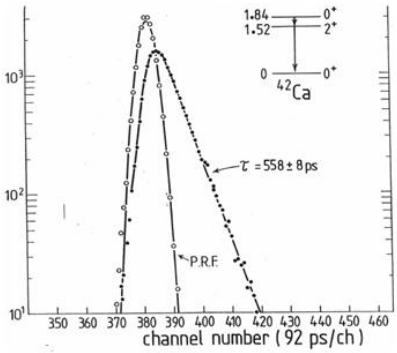
Detector	FWHM, ps
plastic scintillators	~100
BaF_2	~100
Si	~200
Na(I)	~500
Ge	0.6-9 ns

Prompt Response Function: Ge detectors

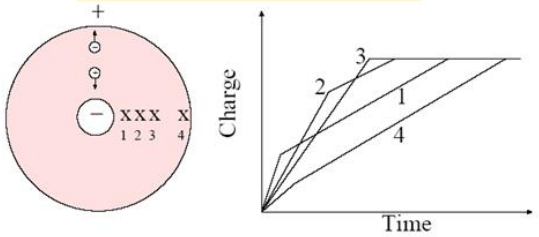
$$F(x,\lambda) = \int_{-\infty}^{\infty} f(t,\lambda)P(x-t)dt$$

$$f(t,\lambda) = \lambda e^{-\lambda t}(t \geq 0) or = 0(t < 0)$$ decay

PRF $$P(z) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(z/\sigma)^2}$$



schematic illustration

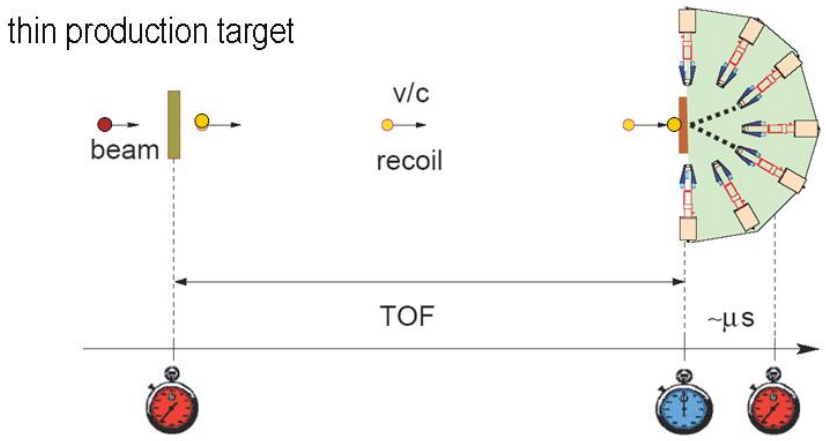


PRF depends on:

- size of the detector
- energy of the γ ray

Recoil-shadow technique

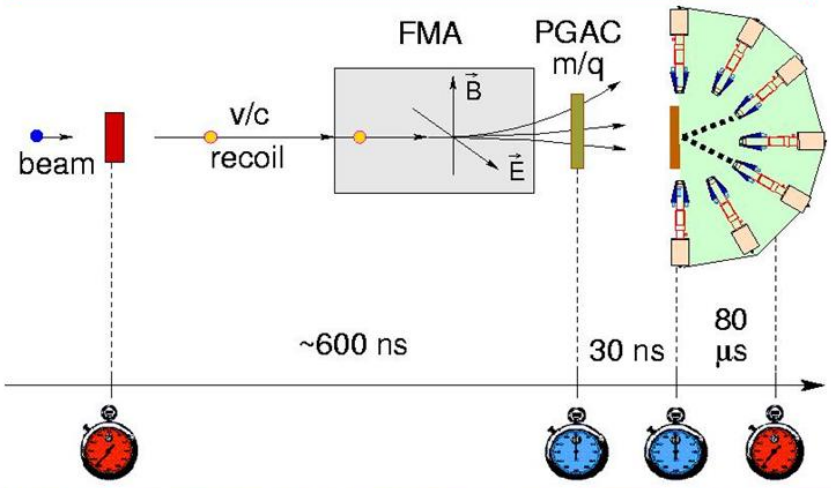
the shortest lifetime that can be measured is limited by the TOF



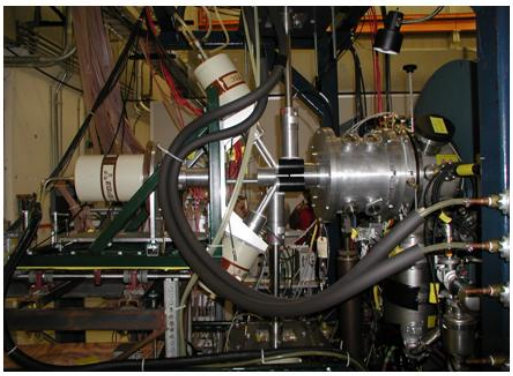
One example: ^{140}Dy experiment at ANL

^{54}Fe + ^{92}Mo @ 245 MeV

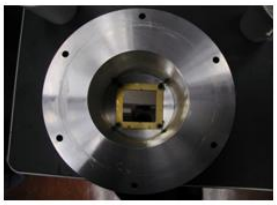
α2n channel, mass 140 only 5% from the total CS



Some of the equipment used …



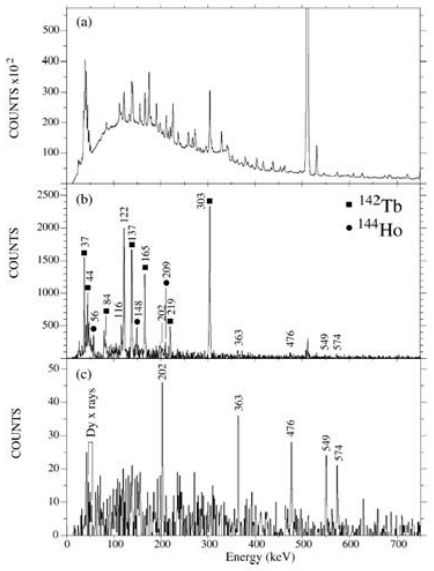
1 70% Gammasphere HpGe detector
4 25% golf-club style HPGe detectors
2 LEPS detectors
1 2"x2" large area Si detector

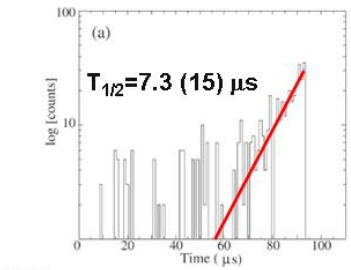


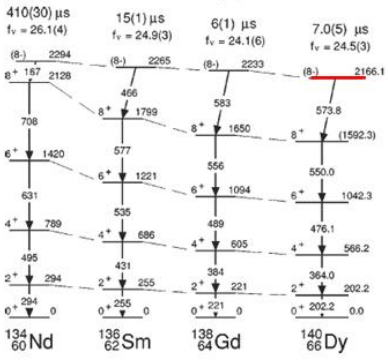
2"x2" Si Detector

^{140}Dy: Experimental Results

D.M. Cullen et al., Phys. Lett. B529 (2002)

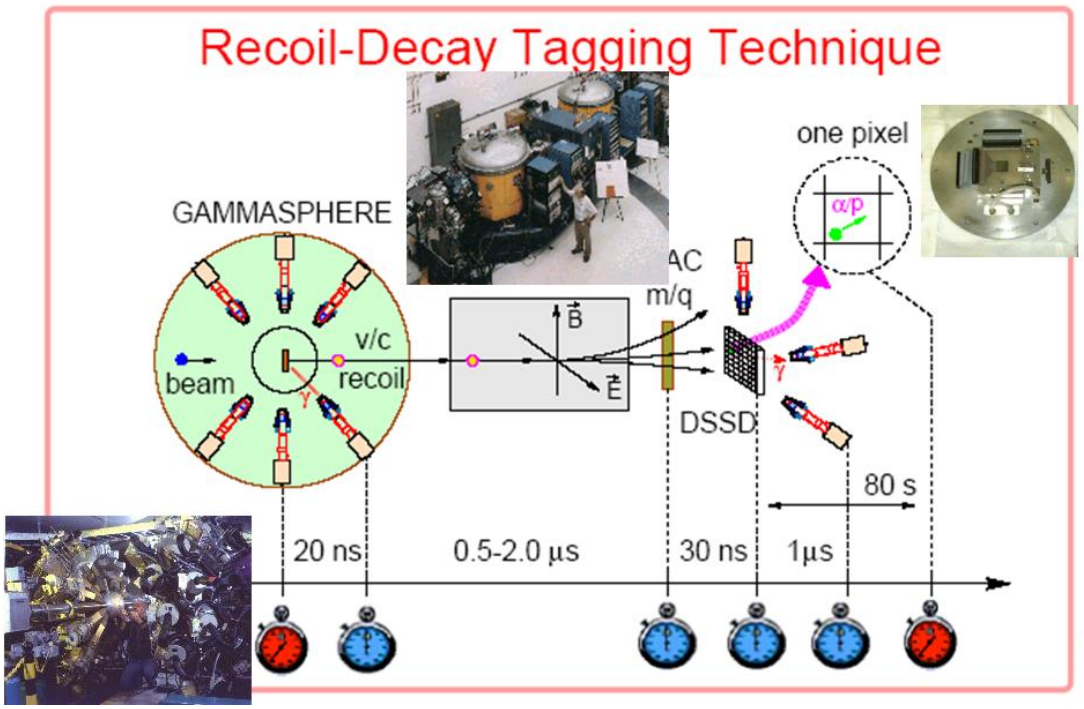




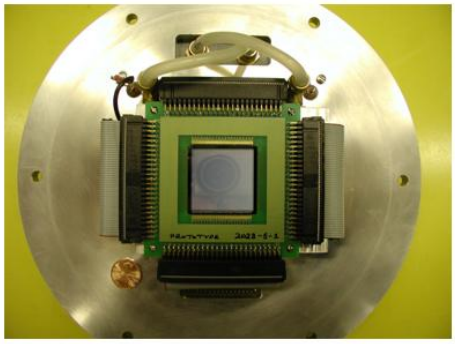


Similar results by the ORNL group, Krolas et al., PRC 65, 2002

Recoil-decay tagging

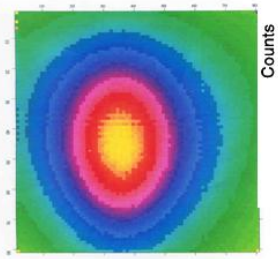


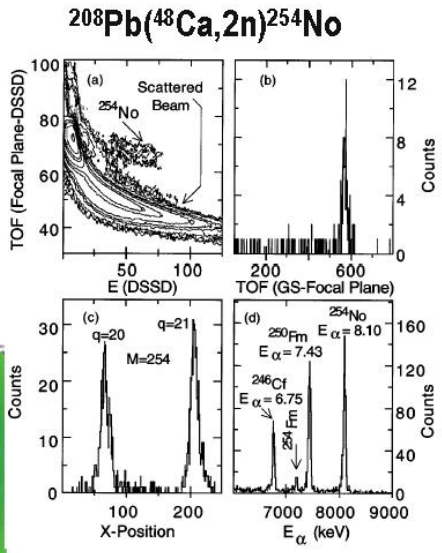
Heart of RDT: DSSD



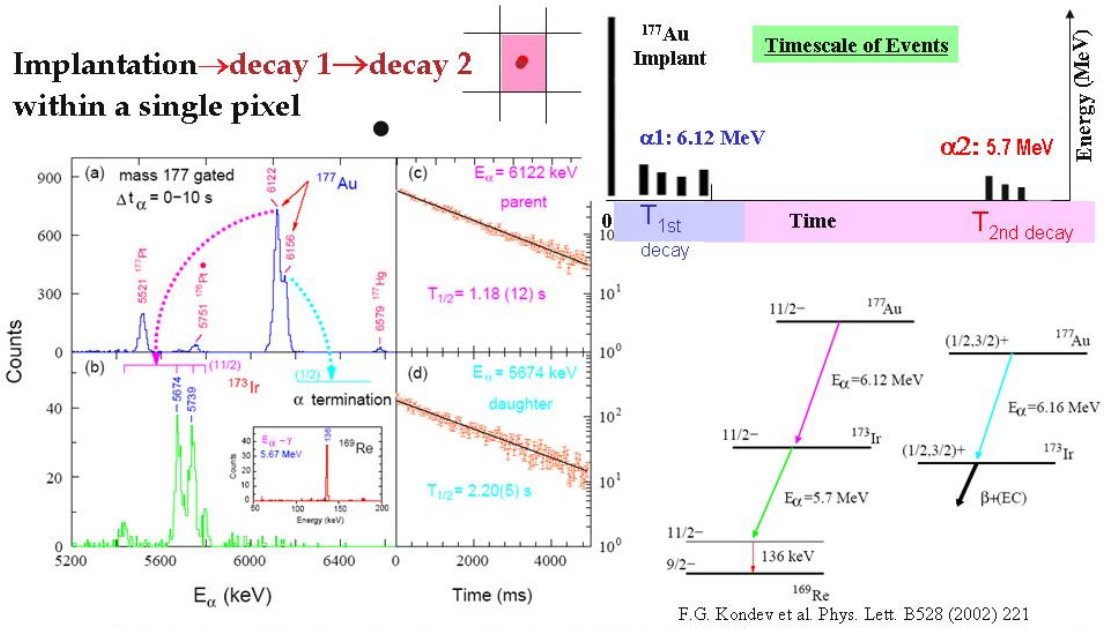
80 x 80 detector 300 μm strips, each with high, low, and delay line amplifiers for implant, decay and fast-decay recognition.

Data from DSSD showing implant pattern 40 cm beyond the focal plane





α–α (parent-daughter) correlations



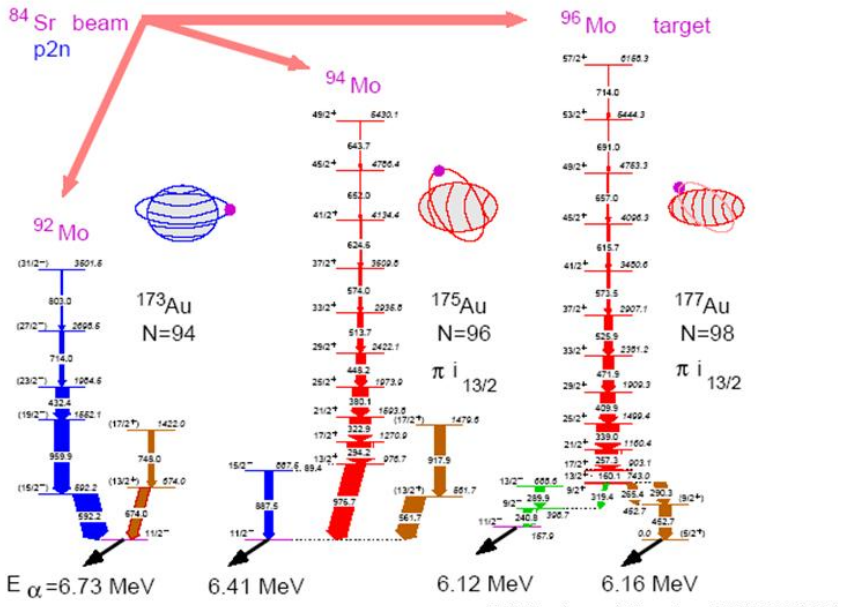
F.G. Kondev et al. Phys. Lett. B528 (2002) 221

Neutron deficient nuclei

Severe complications

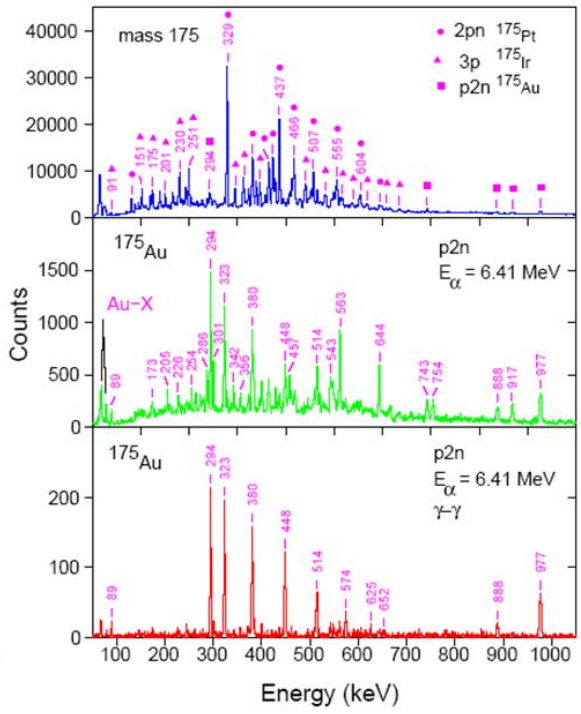
- Charged particle emission:
  - → Fusion-evaporation cross section is fragmented into many channels.
    - → limits the absolute production
- Fission process: *fissibility parameter* ~ Z^2/A
  - → Depletion of the high-l values.
    - → Limits the population of residues at high angular momentum
  - → Huge, unwanted background

Odd-Z Au (Z=79) isotopes

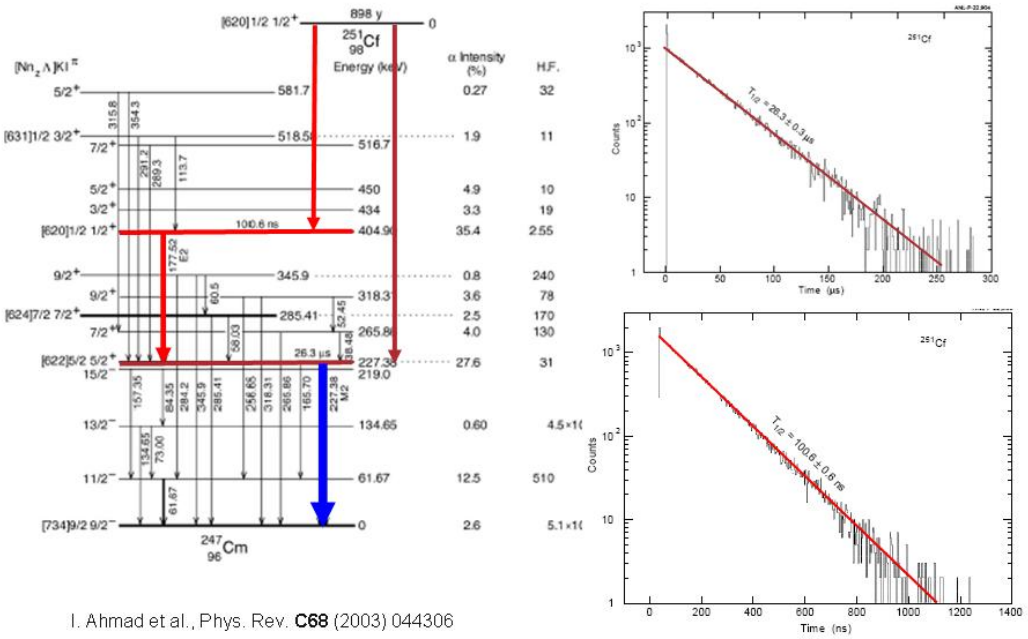


F.G. Kondev et al. Phys. Lett. B528 (2002) 221

Odd-Z Au (Z=79) isotopes – sample spectra



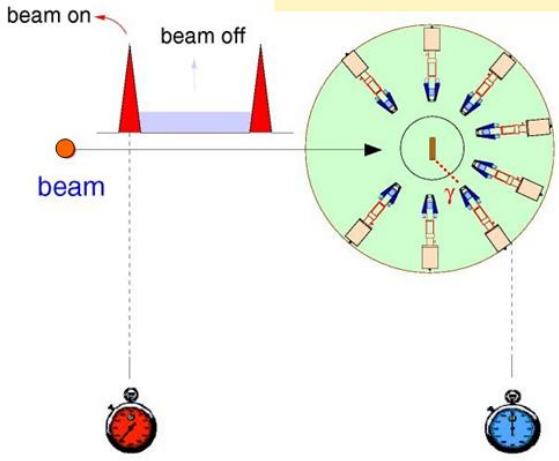
$\alpha-\gamma$ correlations



I. Ahmad et al., Phys. Rev. **C68** (2003) 044306

Pulsed beam technique

shortest lifetime that can be measured is limited by the width of the pulsed beam

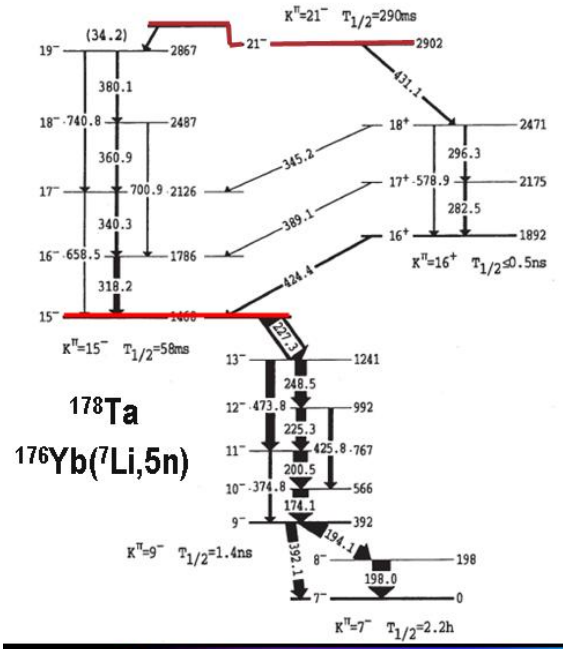


- **Less effective, but …**
  - ✓ **well defined "clock"**
  - ✓ **sensitive to in-beam and decay events**

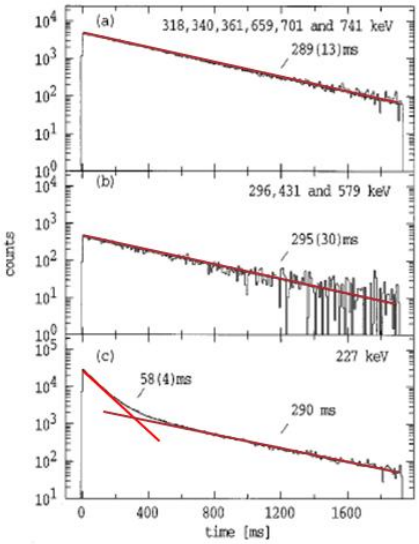
- "singles": γ–time
- coincidence: γ–γ–time

longest lifetime that can be measured is limited by the time interval between the beam pulses

Pulsed beam: γ–time



F.G. Kondev et al. Phys. Rev. C54 (1996) R459



reveals the time history of levels above the 58 ms isomer !

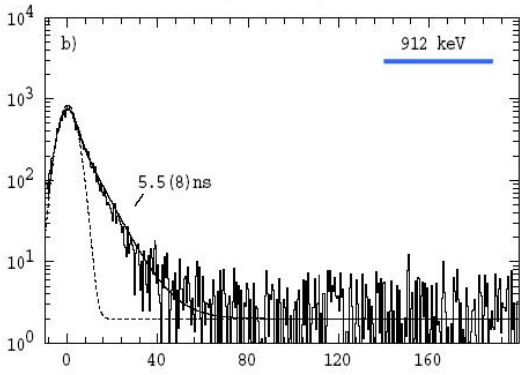
Pulsed beam: γ–time (short-lived)

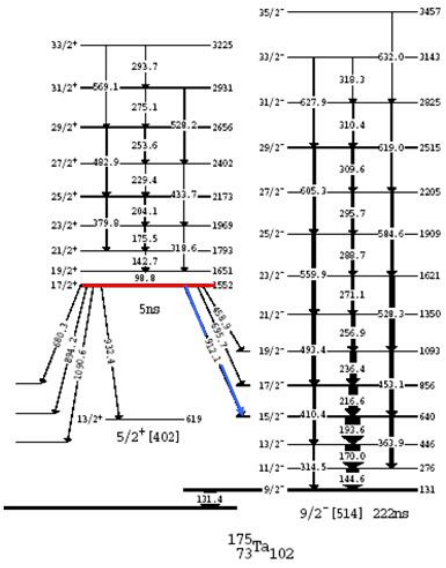
Importance of PRF

depends on E_γ for a single transition

^{175}Ta

^{170}Er(^{10}B,5n)

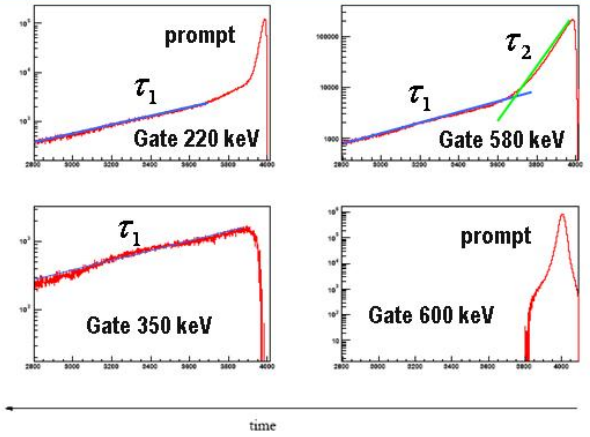


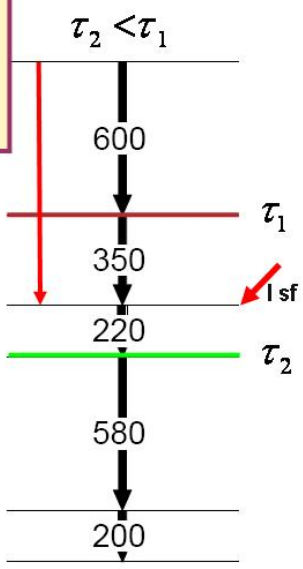


F.G. Kondev et al. Nucl. Phys. A601 (1996) 195

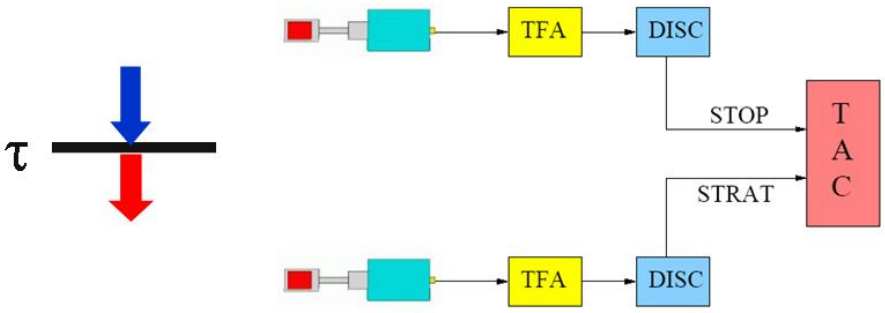
Limitations: Pulsed beam γ–time

- Complicated when more than one isomer is present
- Complicated because of contaminants
- Limited time range – e.g. TAC (Ortec 567) – 3 ms
- Rate-dependent time distortions



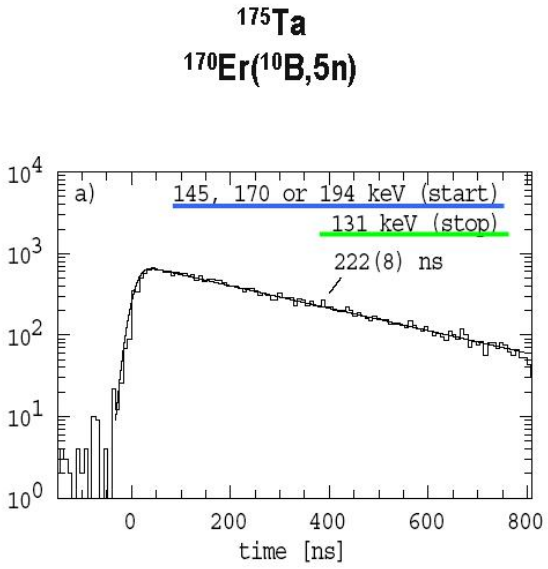


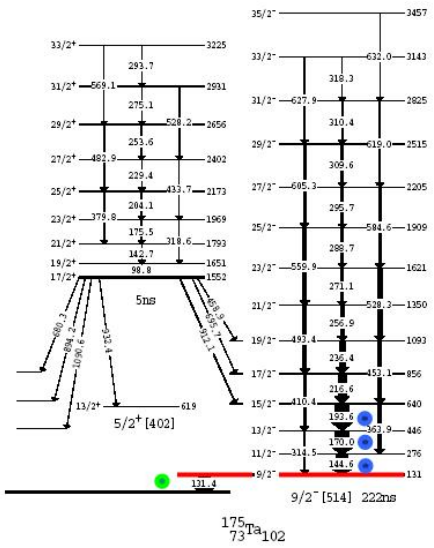
Pulsed beam: γ–γ–time technique



"coincidence" – $E_{\gamma 1}$-$E_{\gamma 2}$-Δt ; $E_{\alpha 1}$-$E_{\gamma 1}$-Δt
$E_{\alpha 1}$-$E_{\alpha 2}$-Δt

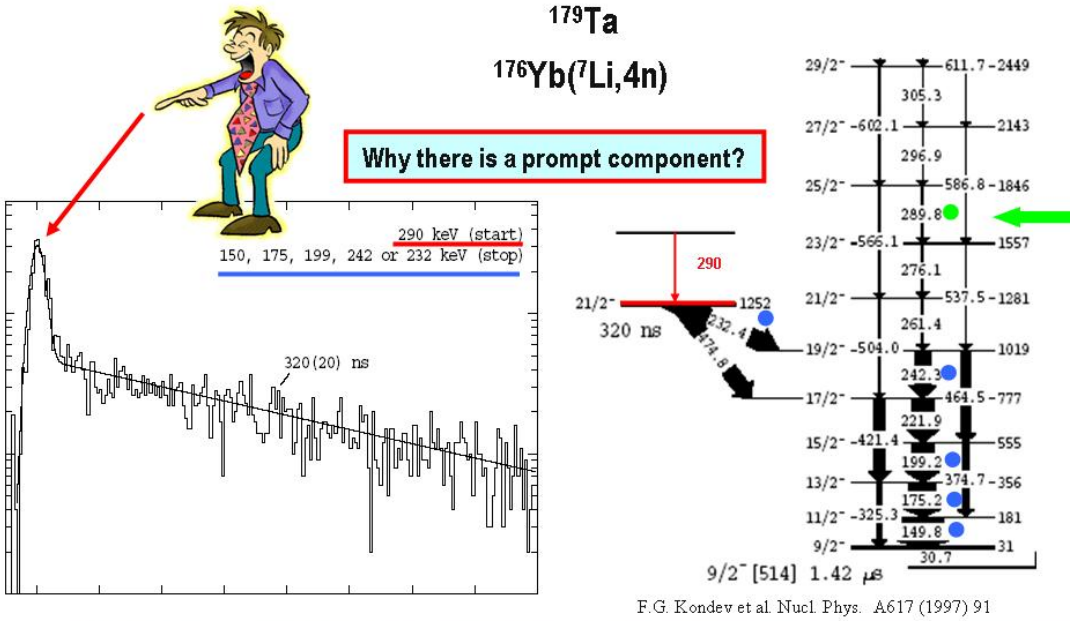
γ–γ–time: decay of the 9/2- isomer in ^{175}Ta





F.G. Kondev et al. Nucl. Phys. A601 (1996) 195

γ–γ–time: decay of 21/2- isomer in ^{179}Ta



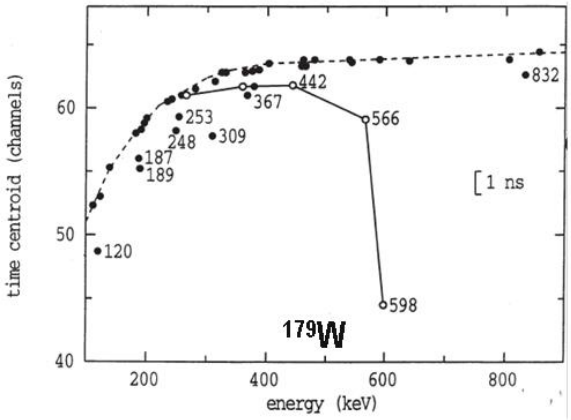
F.G. Kondev et al. Nucl. Phys. A617 (1997) 91

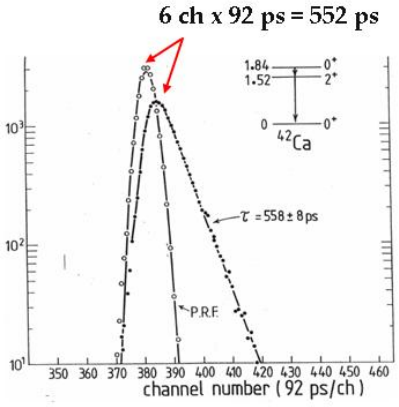
Centroid-shift technique: γ–time

Time Range: near PRF

$$F(x,\lambda) = \int_{-\infty}^{\infty} f(t,\lambda)P(x-t)dt \qquad M_r(F(t)) = \int_{-\infty}^{\infty} t^r F(t)dt \qquad \tau = M_1(F(t)) - M_1(P(t))$$

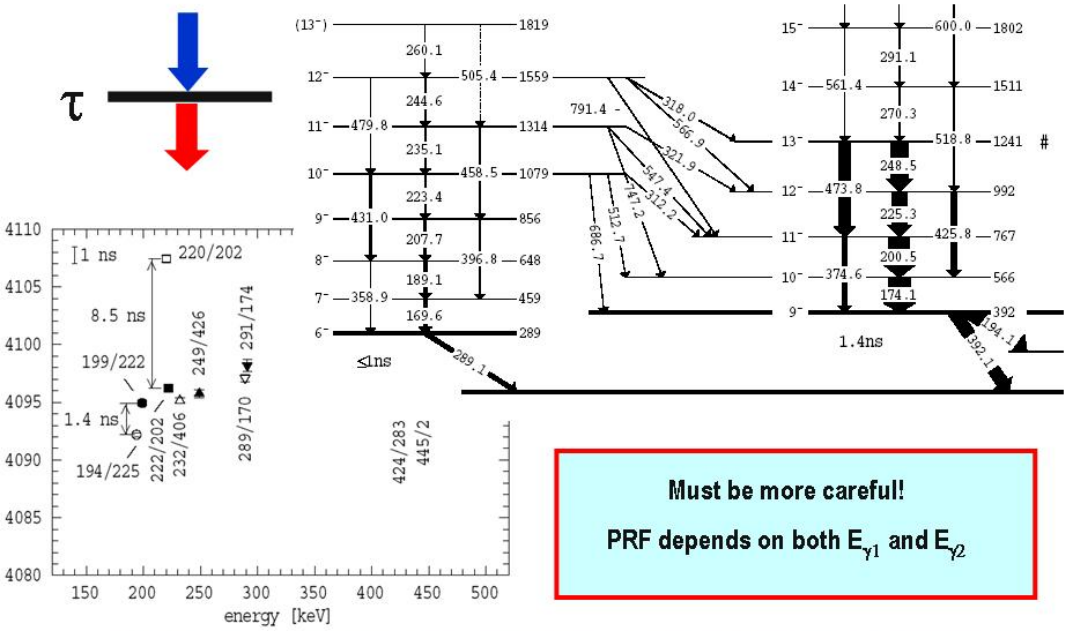
Introduced by Z. Bay, Phys. Rev. 77 (1950) 419





P.M. Walker et al. Nucl. Phys. A (1996)

Centroid-shift technique: γ–γ–time



Must be more careful!

PRF depends on both $E_{\gamma 1}$ and $E_{\gamma 2}$

F.G. Kondev et al. Nucl. Phys. A632 (1998) 473

Coulomb excitation

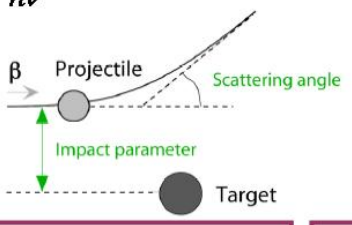
Time Range: up to hundreds of ps

$$E < V_{cb}$$

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v} >> 1$$

^{19}F(1 MeV) on ^{238}U η~1.6

^{40}Ar(152 MeV) on ^{238}U η~130



Observables
- Number of gamma rays detected (N_γ)
- Number of beam particles detected (N_{beam})
- Energy of de-excitation gamma ray (E_γ)

Experimental results
- Coulomb excitation cross section (σ)
- Reduced transition probability B(E2,↑)
- Energy of excited state

$$\sigma = \frac{N_\gamma}{\varepsilon} \frac{1}{N_{target} N_{beam}}$$

$$\sigma_{0\to 2} \approx \left(\frac{Z_{target} e^2}{\hbar c} \right)^2 \frac{\pi}{e^2 b_{min}^2} \mathrm{B(E\,2,0^+ \to 2^+)}$$

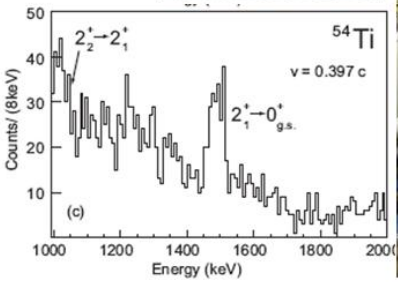
Details in: Winther and Alder, Nucl. Phys. A **319** 518 (1979).

Intermediate energy Coulomb excitations

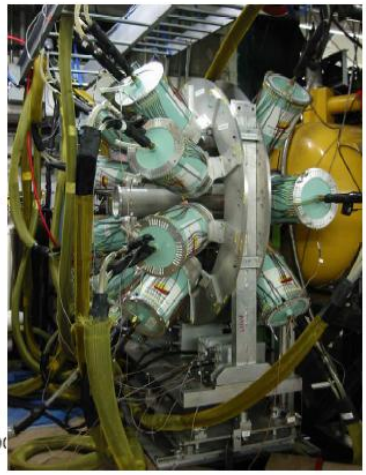
Primary beam: ^{76}Ge @ 130 MeV/nucl.
Secondary beam: ^{54}Ti @ 88 MeV/nucl.
β=0.406
^{197}Au target thickness: 257.67 mg/cm^2
Θ_{max} = 3.20° (CM)
Number of ^{54}Ti particles detected: 91.665E6

Measured for ^{54}Ti
- E_γ = 1497(4) keV
- $\sigma(\theta<\Theta_{max})$ = 83(15) mb
- B(E2, ↑) = 357(63) e^{2}fm^4

$$\tau = 1.5(3)\,ps$$



SeGA
(Segmented Germanium Array)—Eighteen 32-fold segmented HP germanium detectors



Experimental Nuclear Structure

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Experimental Nuclear Structure Part II

Filip G. Kondev

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Workshop on "Nuclear Structure and Decay Data: Theory and Evaluation", Trieste, Italy

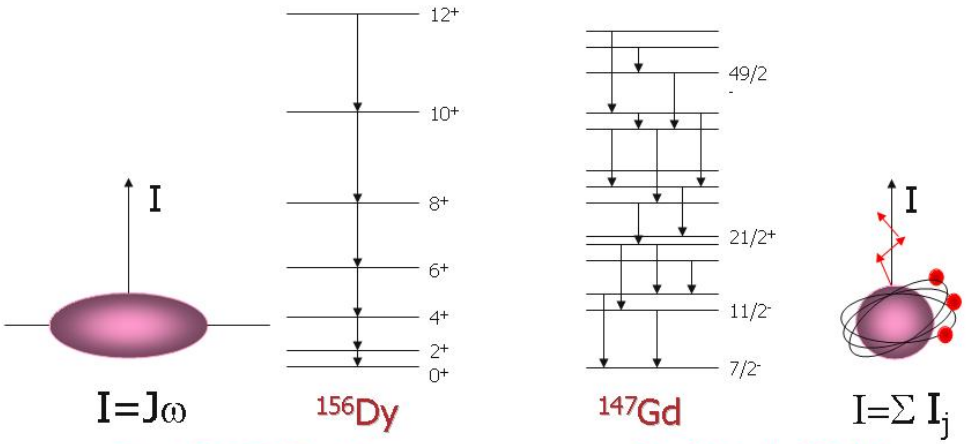
28 April – 9 May 2008

Outline

I) Lecture I: Experimental nuclear structure techniques
- Introduction
- Nuclear reactions – production of excited nuclear states
- Techniques for lifetime measurements
  - ✓ *Coulomb excitation, electronic, activity, indirect*

II) Lecture II: Contemporary Nuclear Structure Physics at the Extreme
- Spectroscopy of nuclear K-isomers
- Physics with large γ–ray arrays
- Gamma-ray tracking – the future of γ–ray spectroscopy

Generation of Angular Momentum in Nuclei



$I=J\omega$ ^{156}Dy ^{147}Gd $I=\Sigma I_j$

$E_I=\hbar^2/2J\ I(I+1)$

$B(E2) \sim 200$ W.U.

$E_I=\Sigma e_j + \Sigma\Sigma V_{jk}$

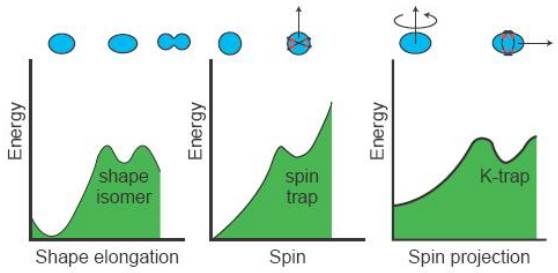
deformed nucleus spherical nucleus

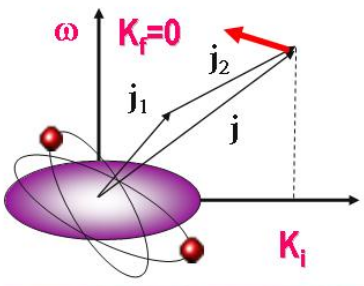
What is a Nuclear Isomer?

Nuclear Isomer – a *long-lived excited nuclear state* ($T_{1/2} > 1$ *ns*) *that can decay by emission of* α, β, γ, *p, fission, cluster*

First one discovered by O. Hahn in Berlin in 1921 – decay of ^{234}***Pa (70 s)***
von Weizsacker, A. Bohr & B. Mottelson

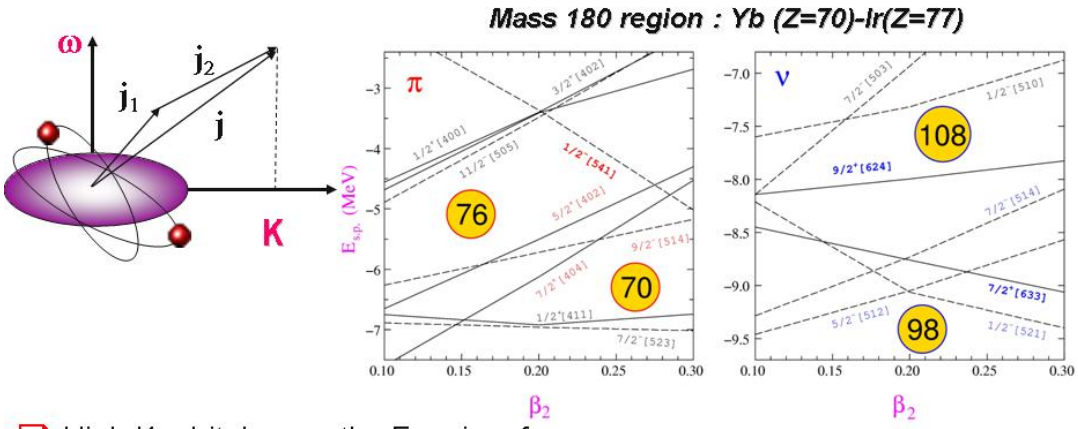
$$1/\tau \sim E_\gamma^{2\lambda+1} |\langle \psi_f | \mathbf{T} | \psi_i \rangle|^2$$





K-isomers: Where to find them?

- Deformed nuclei with axially-symmetric shape

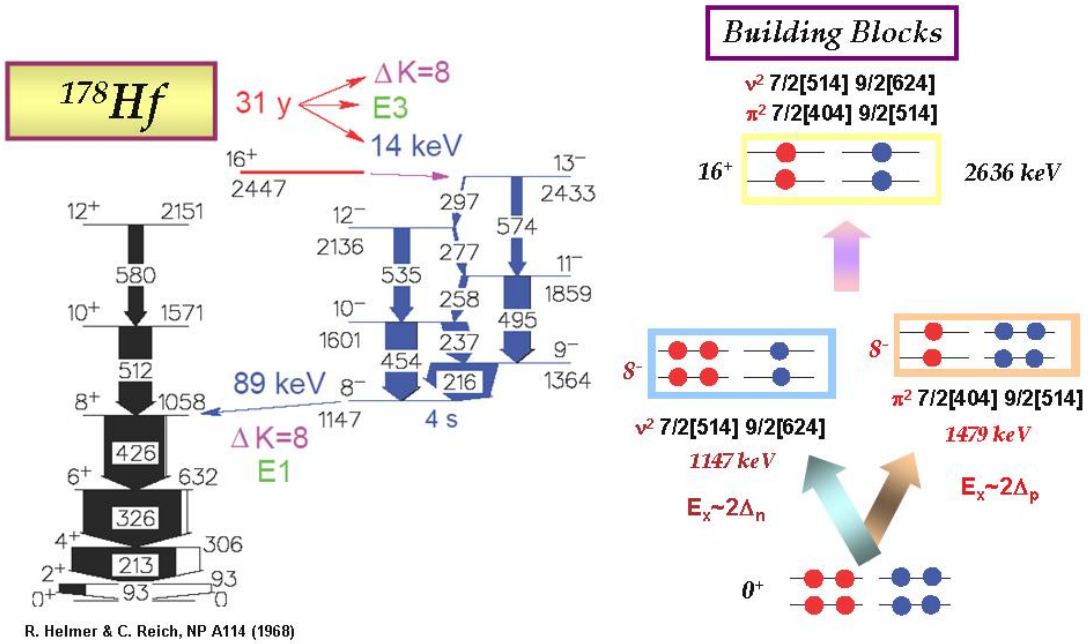


- High-K orbitals near the Fermi surface

π 5/2[402], 7/2[404], 9/2[514]
ν 5/2[512], 7/2[514], 7/2[633], 9/2[624]

→ 7-qp
K=49/2

K-isomers – building blocks

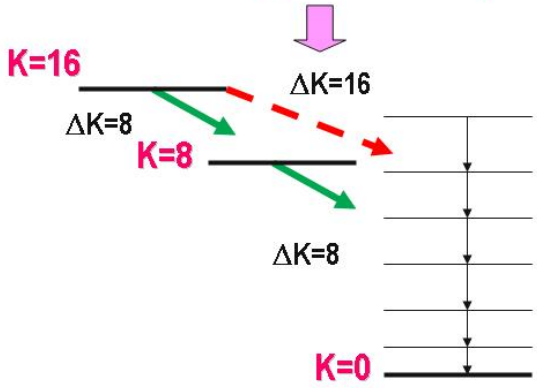


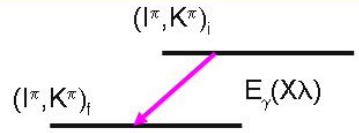
R. Helmer & C. Reich, NP A114 (1968)

K Selection Rule and Reduced Hindrance

K-isomer decay usually proceeds by minimizing ΔK

Usually not this way!





$\nu=\Delta K-\lambda$ – degree of K-forbiddenness

$F=\tau^{\gamma}(X\lambda)/\tau^{w}(X\lambda)$ – hindrance factor

$f_\nu=(F)^{1/\nu}$ – reduced hindrance per degree of K-forbiddenness – gives yardstick for "goodness" of the K-quantum number

for M1 and E2 decays

$20< f_\nu <100$ – K-hindered decay

$f_\nu<10$ - anomalous decay

$f_\nu>100$ – perhaps something is wrong!

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Motivation: Why Study Isomers?

- **Powerful spectroscopy tool - highly selective "devices"**
- **Interesting physics**
  - ✓ Mapping of intrinsic orbitals close to and remote from the Fermi surface provides an indirect probe of deformation and potentials used in mean-field descriptions
  - ✓ Limits to the existence of high-K states, both at high excitation energy and as a function of proton and neutron number, and the competition between collective and intrinsic excitation.
  - ✓ Question of the dilution of the K-quantum number due to both random interactions in regions of high-level density, and to chance degeneracy in regions of low level density.
  - ✓ Isomers act as seniority- and configuration-dependent probes of the major residual interactions in deformed nuclei, specifically pairing and spin-spin interactions.

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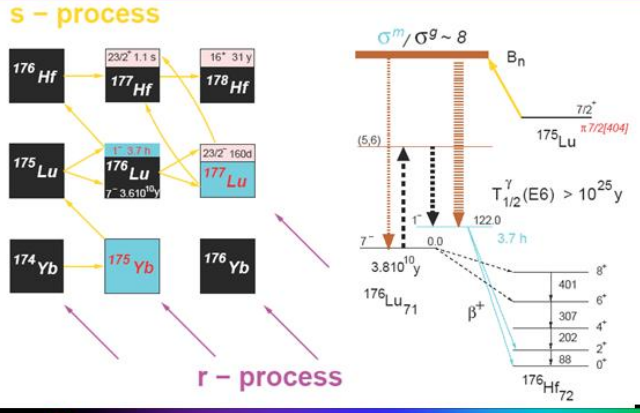
Why Study Isomers? – cont.

❑ Interesting astrophysics applications: stellar thermometers and chronometers

✓There is considerable interest in the role of nuclear structure effects (the precise disposition of excited states, lifetimes etc.) and the role of the K-quantum number in the formation (destruction) of nuclei along the s- and r-path nucleosynthesis



✓nucleosynthesis of ^{180}Ta – the rarest "stable" isotope in the nature

✓ nucleosynthesis of ^{187}Re and nearby nuclei (e.g. ^{186}Re)

Why Study Isomers? – cont.

Applications

- ❑ Activation analysis
- ❑ Medicine
- ❑ Detector calibration standards – high-multiplicity – tracking?
- ❑ Gamma-ray lasers/batteries?
- ❑ Energy production, batteries, etc.

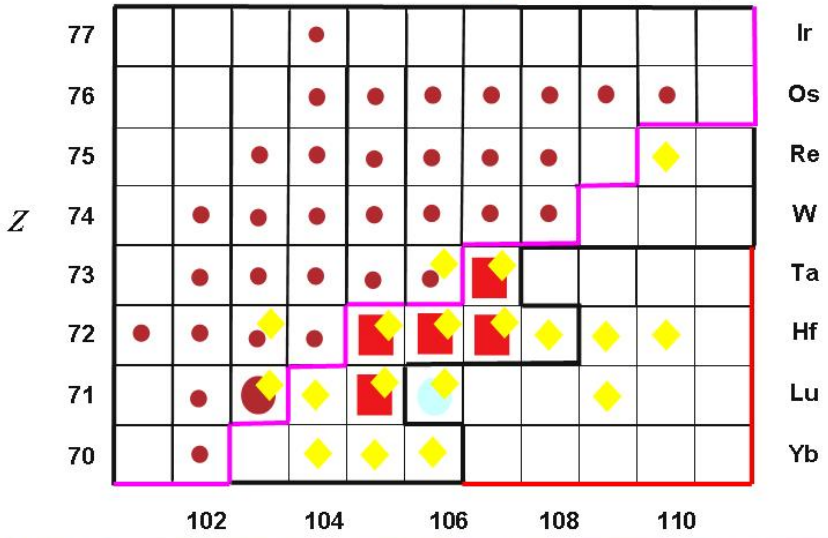
Exotic Studies

- ❑ Radioactive targets – high-spin/seniority, e.g. ^{178m2}Hf, ^{177m}Lu
- ❑ Radioactive beams – the future - physics at extreme conditions

K-isomers in the A~180 region

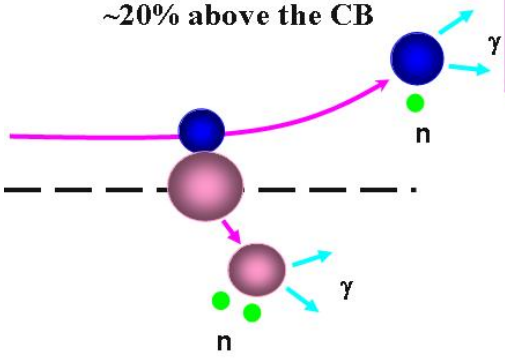
✓ Seniority 2 and higher
✓ $T_{1/2}$ < 1 s (small) / $T_{1/2}$ > 1 s (large)

● HI,xn – fusion evaporation
◆ DIC & MNT
■ Incomplete fusion



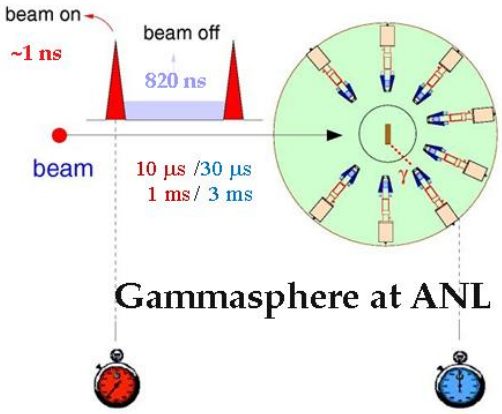
DIC & MNT Experiments at ANL

Beam: ^{136}Xe @ 820 MeV
~20% above the CB



Pulsed Beam Technique

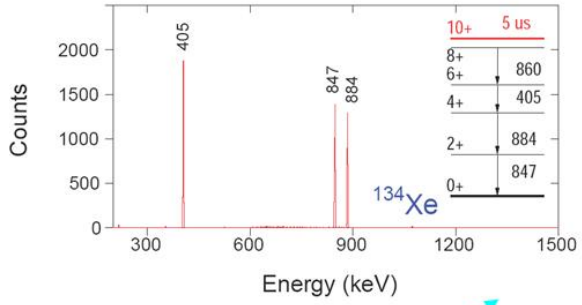
- ❑ well defined "clock"
- ❑ sensitive to in-beam and decay events

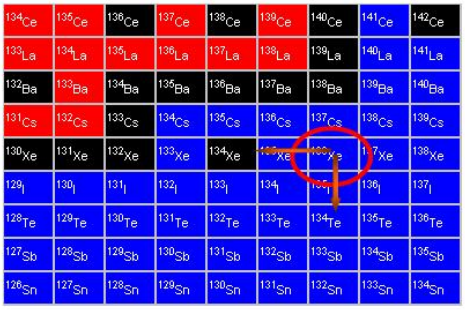


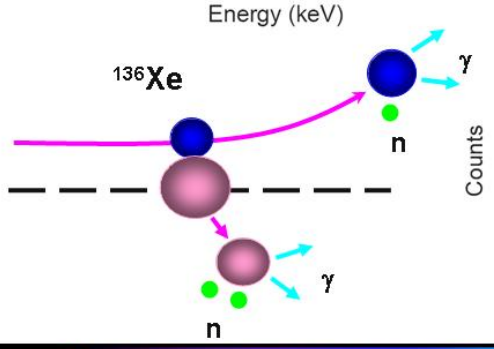
Gammasphere at ANL

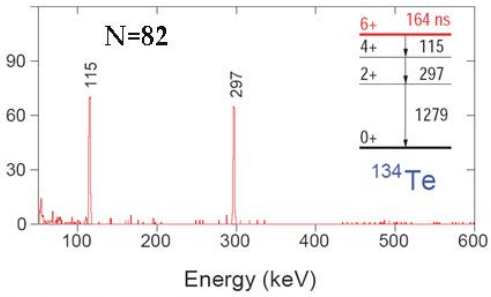
Targets: ^{176}Lu (enriched up to 50 %),
^{175}Lu, ^{174}Yb (gsfma112)
^{176}Yb, ^{185}Re (gsfma149)
^{187}Re, ^{186}W, ^{192}Os (gsfma184)

Projectile-like nuclei

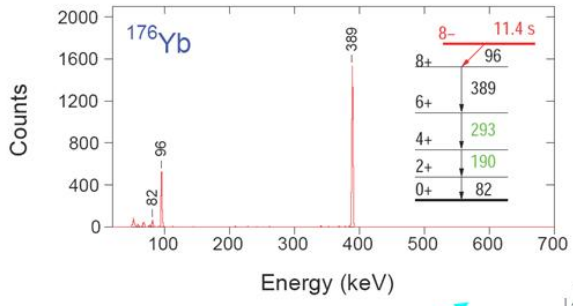


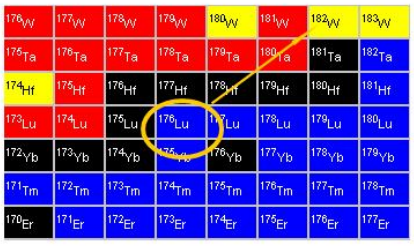


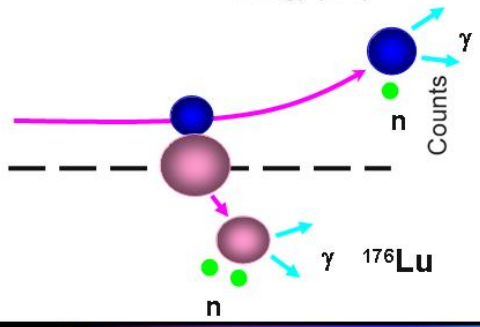


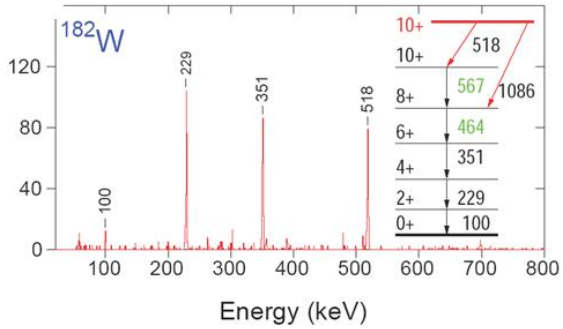


Target-like nuclei

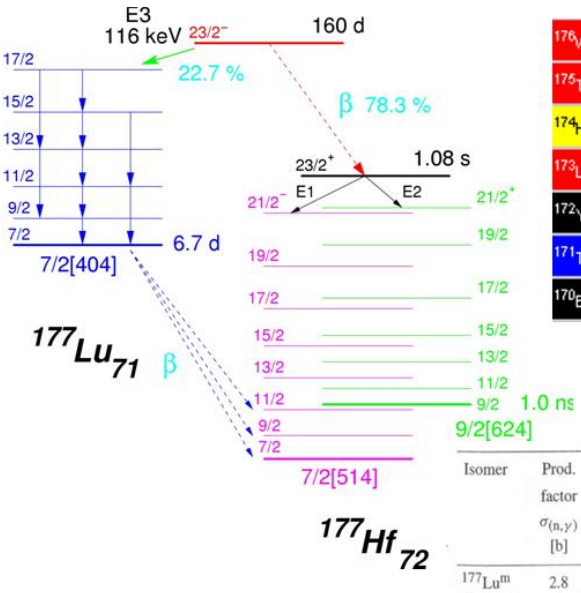


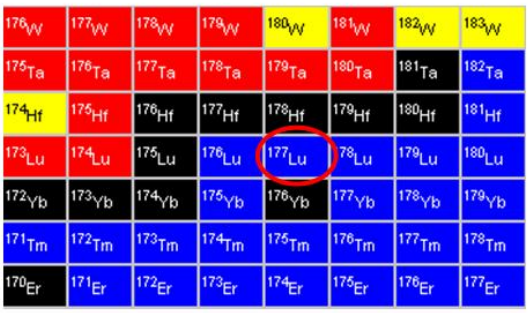






The case of ^{177}Lu





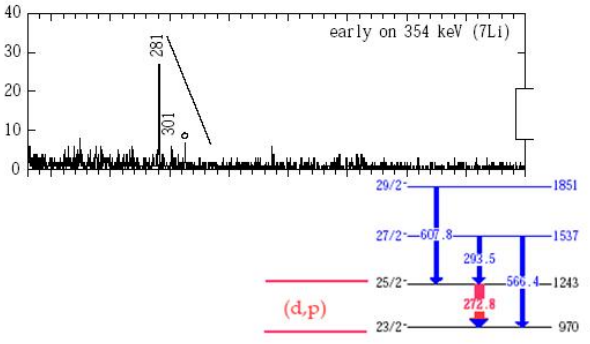
M. Jorgensen et al., Phys. Lett. 1 (1962) 321

J.J. Carroll *et al.*, *Hyp. Int.* 135 (2001) 3

Isomer	Prod. factor $\sigma_{(n,\gamma)}$ [b]	Storage factor E_s [keV]	Storage factor $T_{1/2}$ [y]	Triggering factor* ICS$_{trig}$ [eV b]	Triggering factor* E_{trig} [keV]		Output factor $\langle E_\gamma \rangle$ [keV]	Overall figure of merit
^{177}Lu^{m}	2.8	970	0.44	427	~10^4	<100	100	230	0.056
^{178}Hf^{m2}	~10^{-6}	2,446	31	75,826	$\leqslant 3 \times 10^4$	~10	3,000	300	0.00014

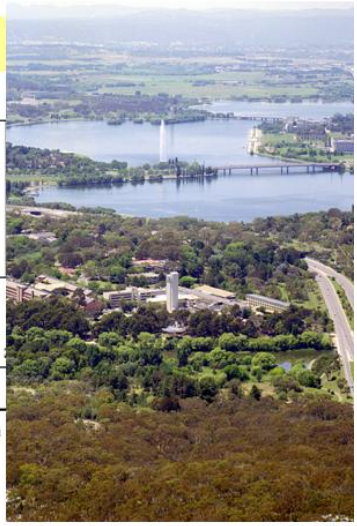
Structures above the K$^{\pi}$=23/2- isomer

^{177}Lu from incomplete fusion



7/2⁻ [514]
9/2⁺[624] ν 2
7/2⁺ [404] π

23/2⁻



M.Minor et al., Phys. Rev. C3 (1971) 766

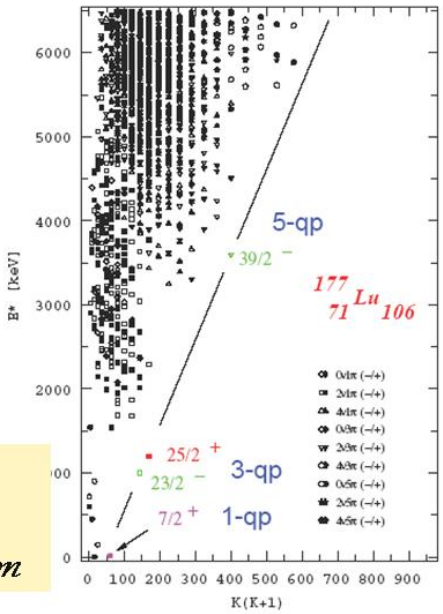
α–γ–γ–time coincidences 4π particle-detector array;
37 MeV 7Li ; angular momentum in 6-13 h - breakup-compound

^{176}Yb(^{7}Li,α2n) McGoram ANU PhD; to be published

How to get the 23/2- band?

^{176}W	^{177}W	^{178}W	^{179}W	^{180}W	^{181}W	^{182}W	^{183}W
^{175}Ta	^{176}Ta	^{177}Ta	^{178}Ta	^{179}Ta	^{180}Ta	^{181}Ta	^{182}Ta
^{174}Hf	^{175}Hf	^{176}Hf	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf	^{181}Hf
^{173}Lu	^{174}Lu	^{175}Lu	^{176}Lu	^{177}Lu	^{178}Lu	^{179}Lu	^{180}Lu
^{172}Yb	^{173}Yb	^{174}Yb	^{175}Yb	^{176}Yb	^{177}Yb	^{178}Yb	^{179}Yb
^{171}Tm	^{172}Tm	^{173}Tm	^{174}Tm	^{175}Tm	^{176}Tm	^{177}Tm	^{178}Tm
^{170}Er	^{171}Er	^{172}Er	^{173}Er	^{174}Er	^{175}Er	^{176}Er	^{177}Er

Predictions (unpublished) made some 10 years ago!



Deformed shell-model

- ✓ Nilsson single-particle levels
- ✓ Pairing – Lipkin-Nogami prescription

Evidence for β– decaying isomer?

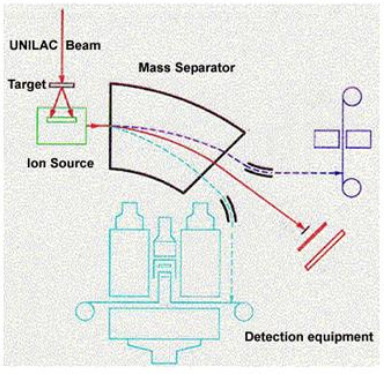
PHYSICAL REVIEW C **69**, 024320 (2004)

Evidence for a high-spin β-decaying isomer in ^{177}Lu

Sareh D. Al-Garni,[1,*] P. H. Regan,[1,†] P. M. Walker,[1] E. Roeckl,[2] R. Kirchner,[2] F. R. Xu,[3] L. Batist,[2,4] A. Blazhev,[2,5] R. Borcea,[2] D. M. Cullen,[6,7] J. Döring,[2] H. M. El-Masri,[1] J. Garces Narro,[1] H. Grawe,[2] M. La Commara,[2,8] C. Mazzocchi,[2,9] I. Mukha,[2,10] C. J. Pearson,[1] C. Plettner,[2] K. Schmidt,[2] W.-D. Schmidt-Ott,[11] Y. Shimbara,[12] C. Wheldon,[1,2,6] R. Wood,[1] and S. C. Wooding[1,2]

S. Al-Garni, P.M. Walker et al., INPC 2001, Berkeley, p. 854

GSI



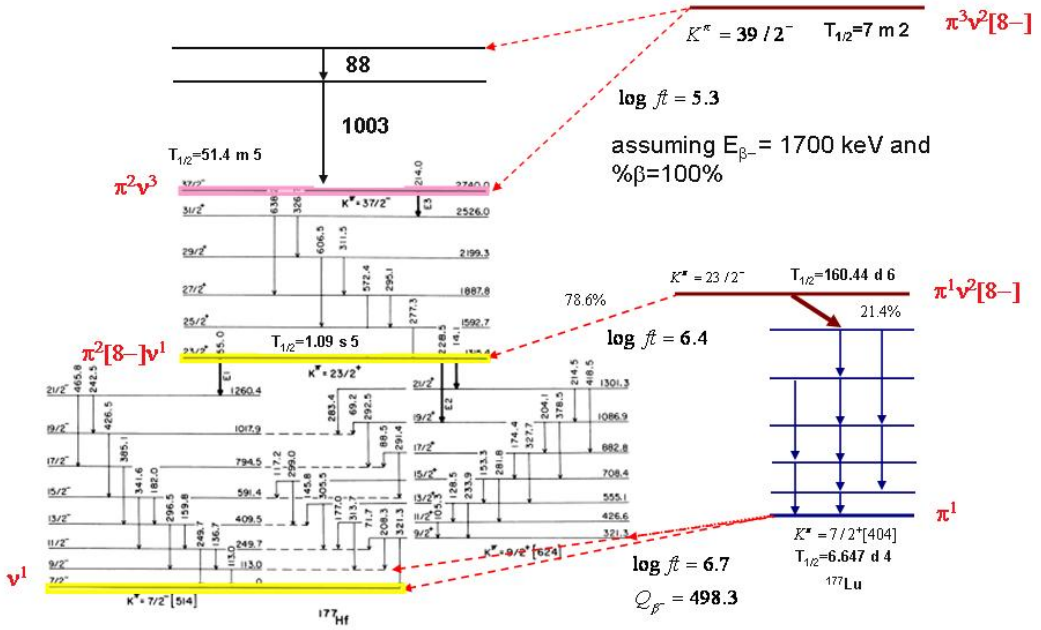
11.4 MeV/nucleon ^{136}Xe beam:

- ✓40 mg/cm^2 enriched ^{186}W target
- ✓30 mg/cm^2 natural Ta target

tape-cycle periods:

- ✓from 8 to 16000 s

Evidence for β– decaying isomer? - cont

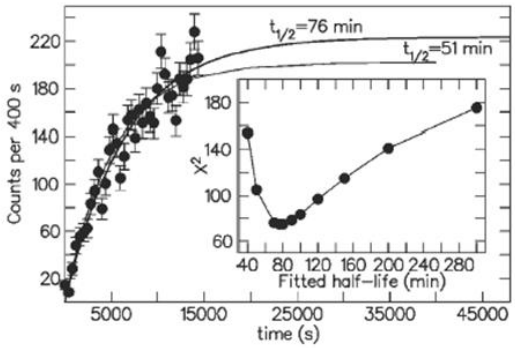


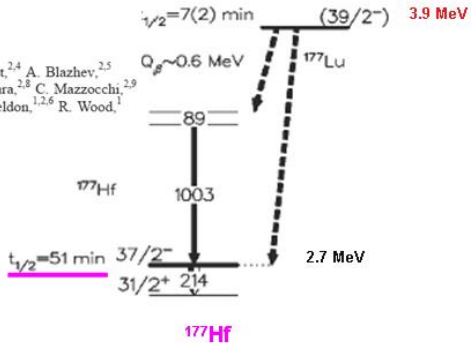
What is the evidence?

PHYSICAL REVIEW C 69, 024320 (2004)

Evidence for a high-spin β-decaying isomer in ^{177}Lu

Sareh D. Al-Garni,[1,*] P. H. Regan,[1,†] P. M. Walker,[1] E. Roeckl,[2] R. Kirchner,[2] F. R. Xu,[3] L. Batist,[2,4] A. Blazhev,[2,5] R. Borcea,[2] D. M. Cullen,[6,7] J. Döring,[2] H. M. El-Masri,[1] J. Garces Narro,[1] H. Grawe,[2] M. La Commara,[2,8] C. Mazzocchi,[2,9] I. Mukha,[2,10] C. J. Pearson,[1] C. Plettner,[2] K. Schmidt,[2] W.-D. Schmidt-Ott,[11] Y. Shimbara,[12] C. Wheldon,[1,2,6] R. Wood,[1] and S. C. Wooding[1,2]



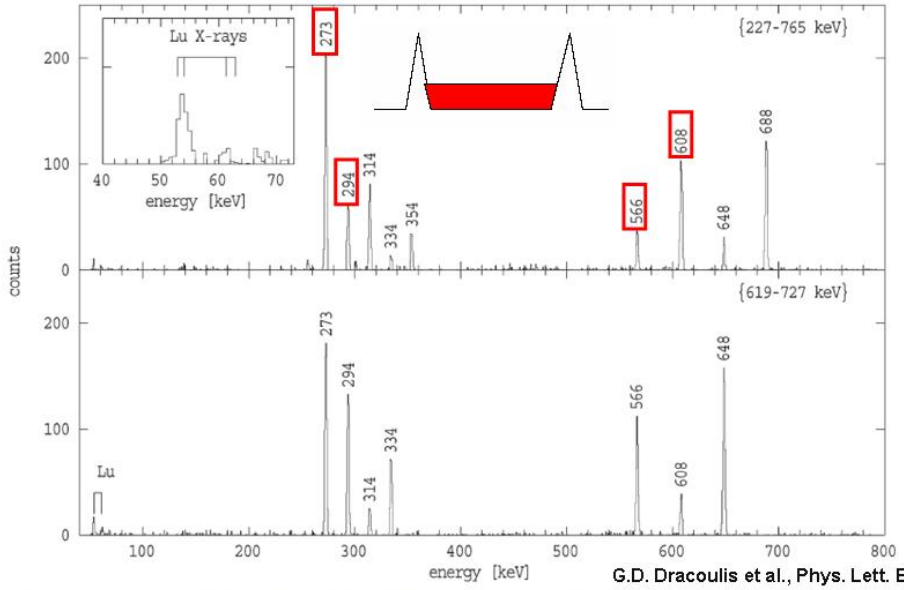


- assumed that refractory elements, such as Hf, are suppressed from a thermal ion source
- measured $T_{1/2}$=76 min +16 -5, that is much longer than the adopted value of 51.4 min 5

two component fit gives $T_{1/2}$=**6 min +3 -2**;
adopted $T_{1/2}$=**7 min 2** for the 39/2- isomer

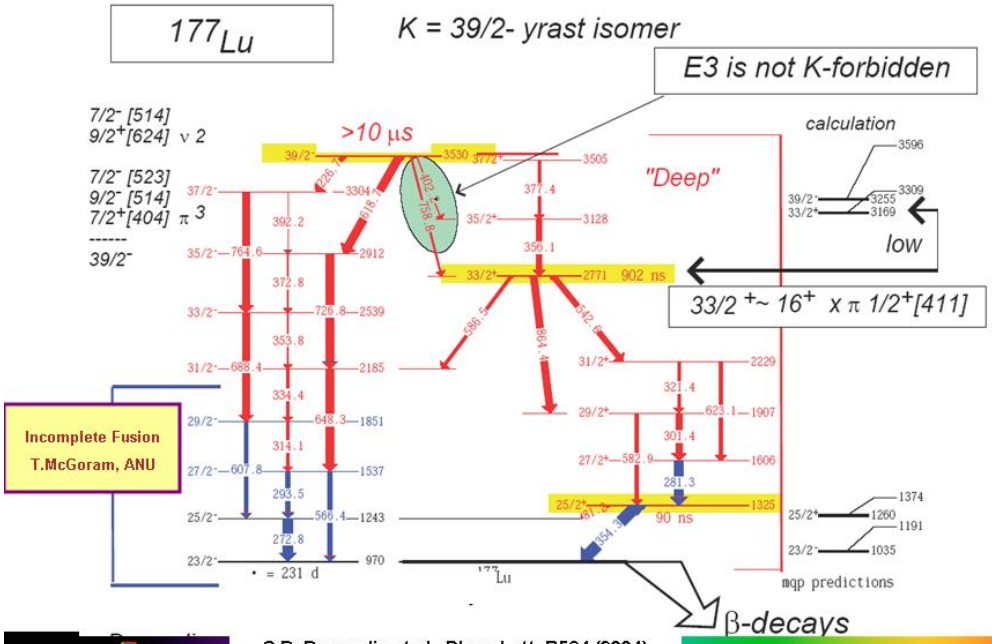
New structures in ^{177}Lu

^{176}Lu target and ^{136}Xe @ 820 MeV with Gammasphere



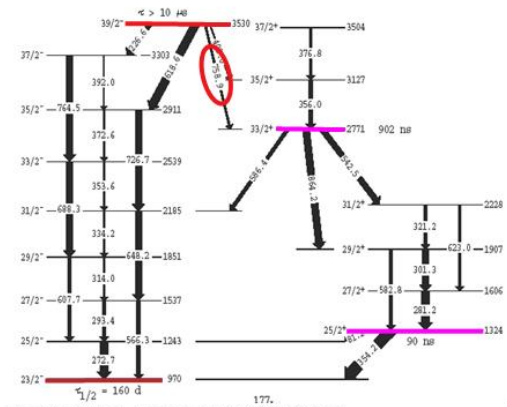
G.D. Dracoulis et al., Phys. Lett. B584 (2004)

K^{π} = 39/2- isomer in ^{177}Lu

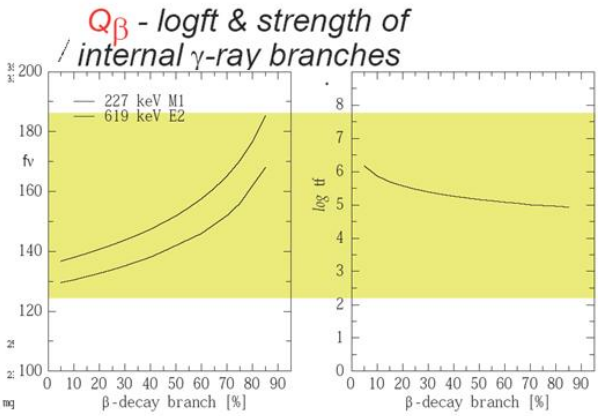


G.D. Dracoulis et al., Phys. Lett. B584 (2004)

Is this the claimed β- decaying isomer?



Dracoulis et al Phys Lett B 584(2004)22



- Ex=3.5 MeV (3.9 MeV)
- unambiguous γ–ray decay signature (no such gammas in the spectrum)
- unprecedented transition strength for the 759 keV, non K-forbidden, E3 transition (10^9! times retarded compared to W.u. if $T_{1/2}$=7 min); f_ν is also huge!
- 89 and 1003 keV γ rays were not seen

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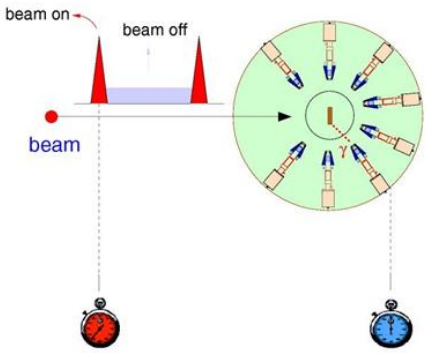
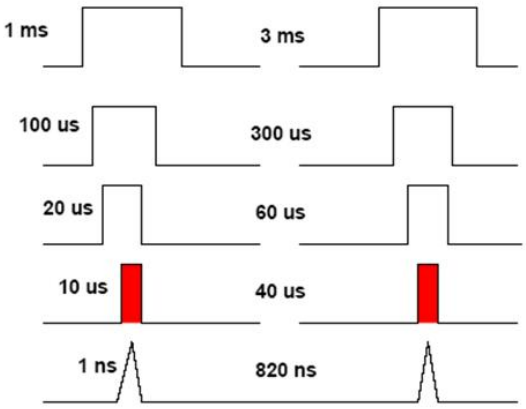
Lifetime of 39/2- isomer

gsfma149/November 2004

136Xe @ 820 MeV

^{176}Yb, ^{175}Lu and ^{176}Lu





present: τ ~ 7 μs ~ 10^{-5} s

compared to τ =10 min ~ 6x10^2 s

S.D. Al-Garni et al., Phys. Rev. C69 (2004) 02430

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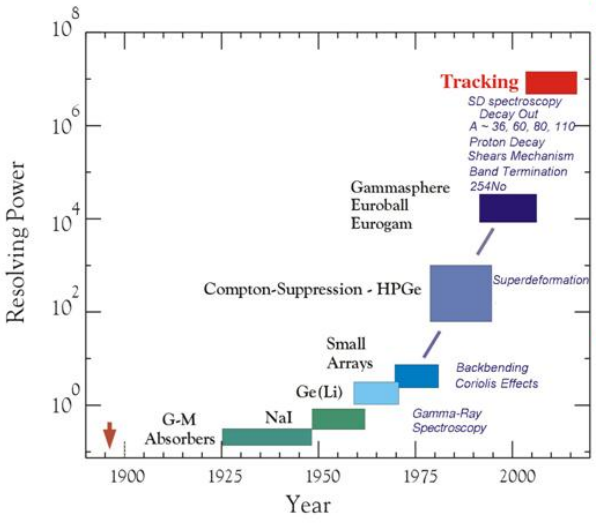
The future of γ–ray spectroscopy

- Historical perspective
- Principle of gamma-ray tracking
- Physics opportunities
- Technical challenges
- Status of project

Gamma-ray Detector Development

Crucial to Nuclear Physics Research



- Advances in detector technology have resulted in new discoveries
- Innovations have improved detector performance
  - Energy resolution
  - Efficiency
  - Peak-to-total ratio
  - Position resolution
  - Directional information
  - Polarization
  - Auxiliary detectors
- Tracking is feasible, will provide new opportunities and meet the challenges of new facilities

$$R \sim \left[\frac{P}{T} \times \varepsilon \times \frac{E_{spacing}}{\Delta E} \right]^n$$

Why gamma-ray arrays?

❑ High energy resolution	ΔE_γ=2.5 keV @1.3 MeV
❑ Large P/T ratio	~60%
❑ Large photopeak efficiency	10% @ 1.3 MeV
❑ Good timing resolution	<10 ns
❑ Wide energy range	~30 keV – 20 MeV
❑ Large solid angle	~ 4π
❑ High granularity	high fold coincidences
❑ High resolving power	ability to isolate γ-ray cascades

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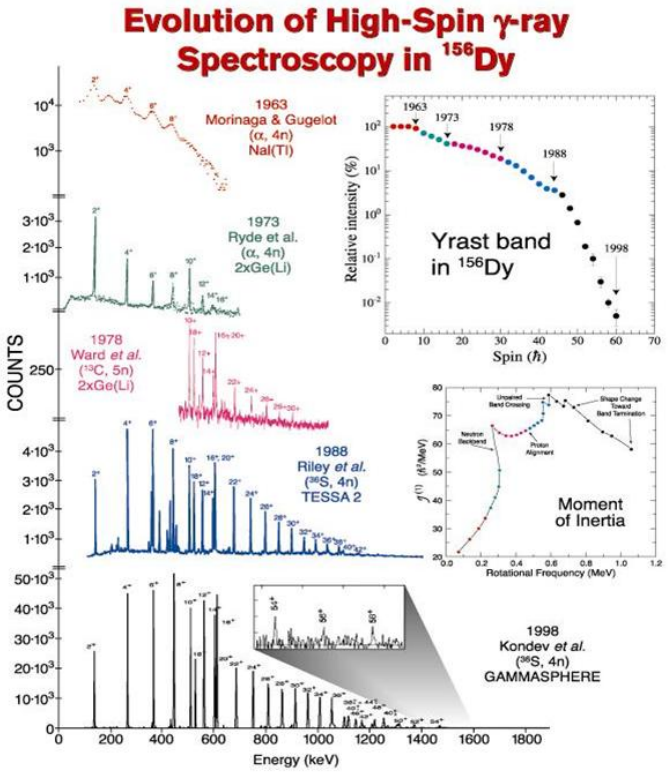
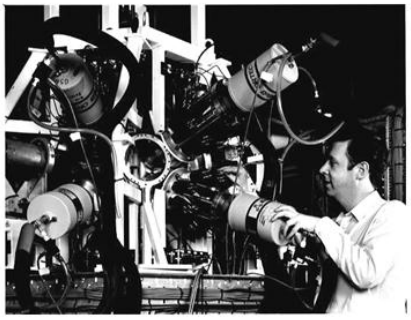
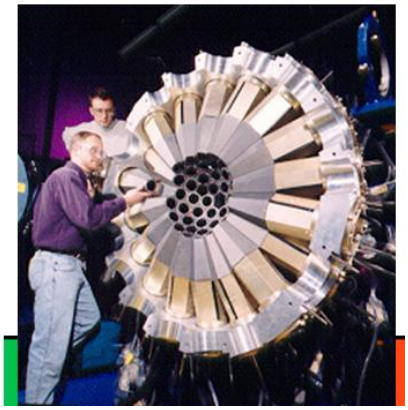
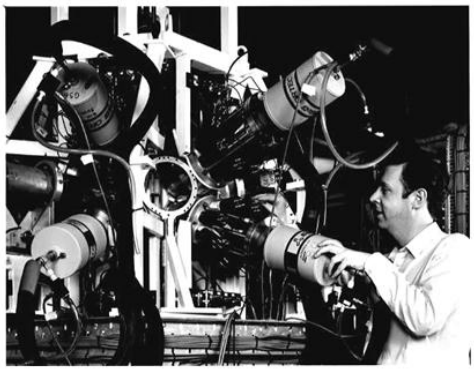






Historical Perspective

~1980 states to spin ~30
naked Ge arrays

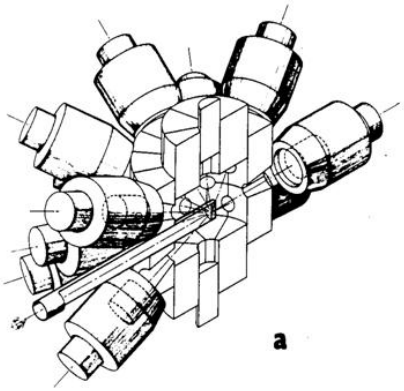


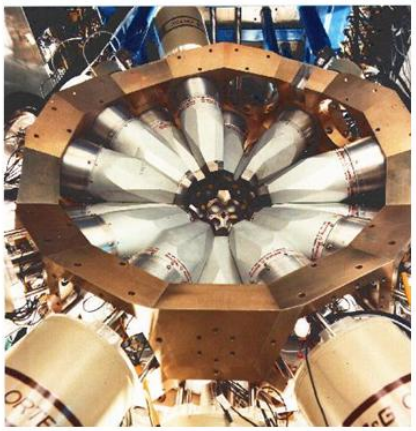
~1980-1982 TESSA
Escape suppressed array at NBI

1983 TESSA to Daresbury
Heavier ion beams
6 ESS using NaI(Tl)
Channel selection included, 50 element inner BGO ball

I ~ 1% sensitivity

Historical Perspective – era of large arrays



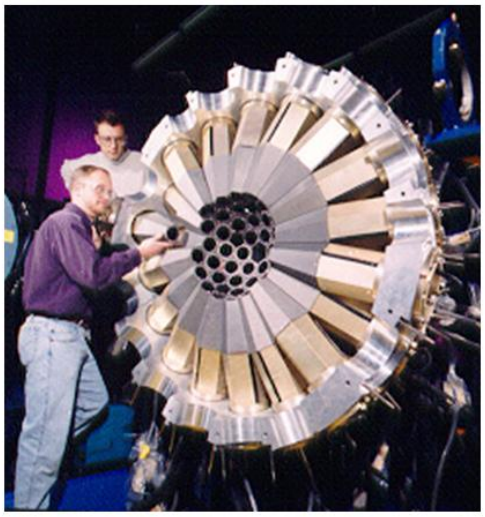


~1987
BGO replaces NaI(Tl)
HERA, TESSA3

I ~ 0.1% sensitivity

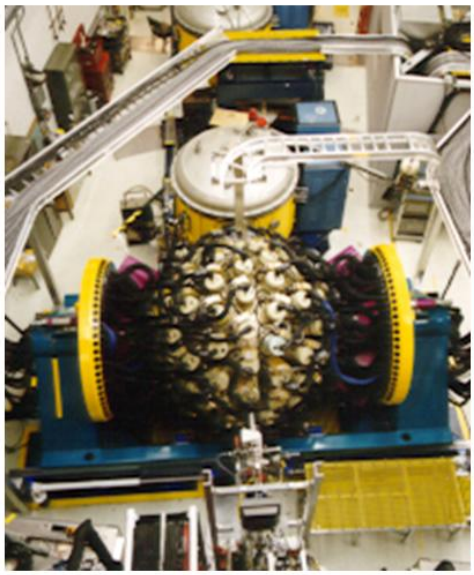
~1995
Large γ-ray arrays
Eurogam, Gammasphere, Euroball's, GASP
I ~ 0.001% sensitivity

Gammasphere spectrometer



- Spectrometer with high detection sensitivity to nuclear electromagnetic radiation due to high resolution, granularity and efficiency
- Consists of a spherical shell of 110 large volume HpGe detectors, each enclosed in a BGO shield
- Funded by US, DOE

Gammasphere operation



- **From 1993 to 1997 GS was constructed and sited at the 88-inch cyclotron, LBNL**
  - **130 experiments**
  - **super deformation**
- **From 1998 to 2000 GS operated at ATLAS, ANL**
  - **101 experiments**
  - **nuclei far from stability**
- **From March 2000 to January 2002 at LBNL**
- **Since March 2002 untill now, GS is back at ANL**

How we do research with Gammasphere …

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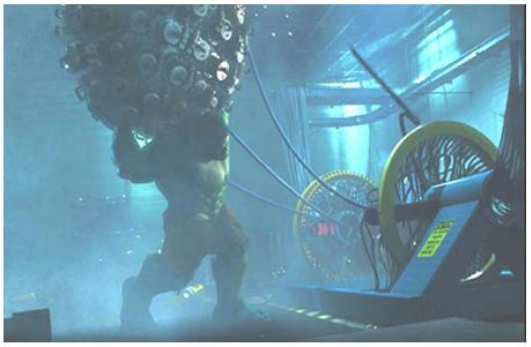
"Gammasphere in Action … "

Universal Studio Picture



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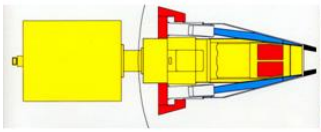
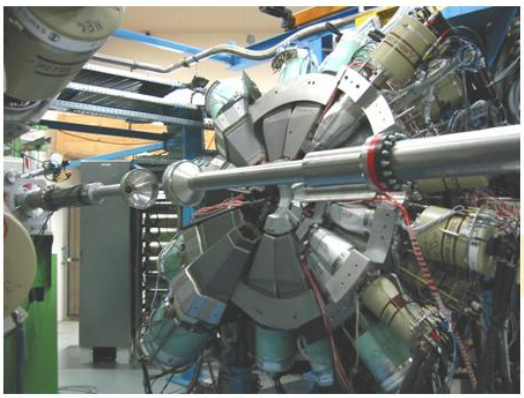
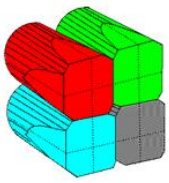
Euroball

European collaboration
France, Denmark, Germany, Italy, Sweden and UK



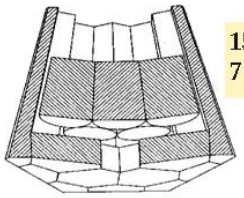
30 large single crystal Ge detectors





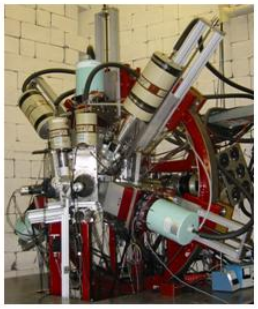
26 Clover Ge detectors
4 crystals per cryostat

239 Ge crystals
Suppression shields
Total peak efficiency ~9.4%
Intensity limit ~ 10^{-5}

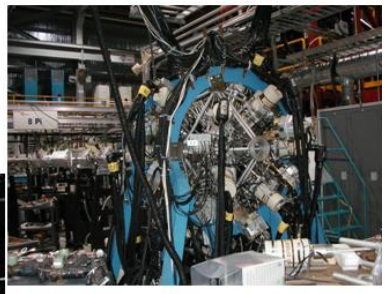


15 Cluster Ge detectors
7 encapsulated Ge crystals per cluster

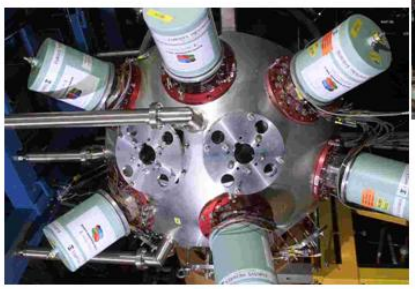
Gamma-ray arrays in USA and Canada



FSU array, USA



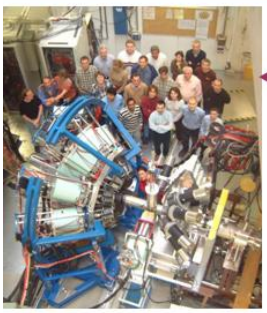
Yrast Ball, Yale University
10 Clover
17 Ge



CLARION, ORNL

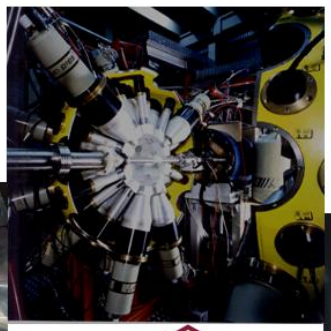
8π, TRIUMF
~40 Ge detectors

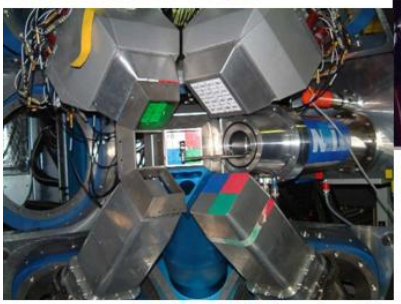
Gamma-ray arrays in Europe



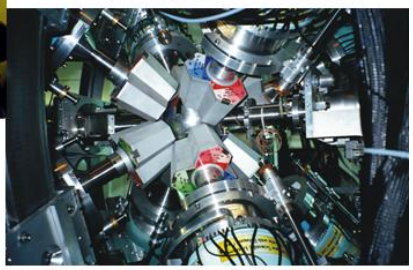
RISING, GSI

JUROGAM, JYFL





GASP, INFN



EXOGAM, Ganil

MINIBALL, RexIsolde

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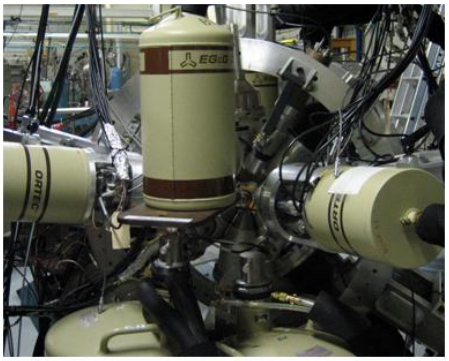
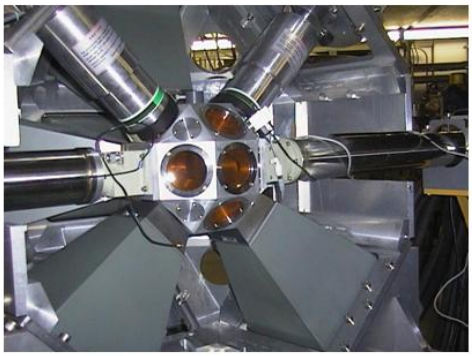
37

Australia, Asia and Africa



CAESAR, Australia



Afrodite, South Africa

Smaller arrays operate in India, China and Japan

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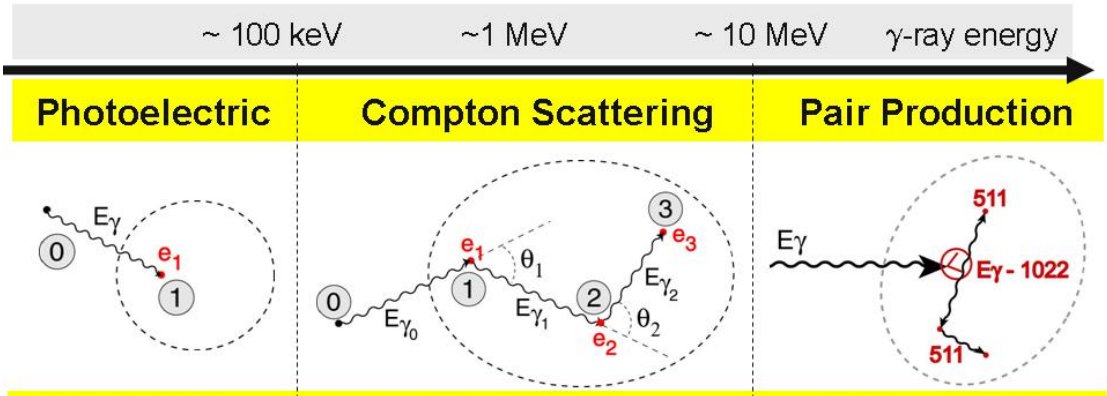
38

Interaction of gamma rays with matter

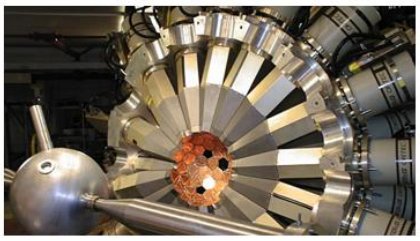


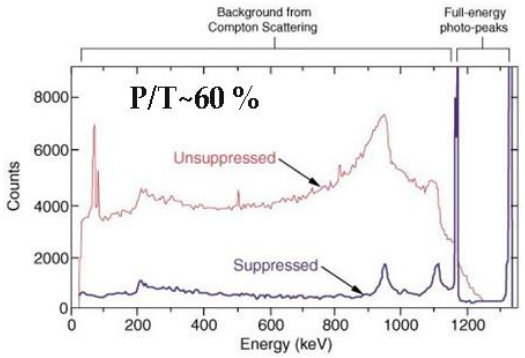
Probability of interaction depth

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)}$$

$E_{1st} = E_\gamma - 2\ mc^2$

Compton suppression – improving P/T

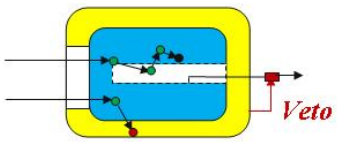




$$R \sim \left[\frac{P}{T} \times \varepsilon \times \frac{E_{spacing}}{\Delta E}\right]^n$$

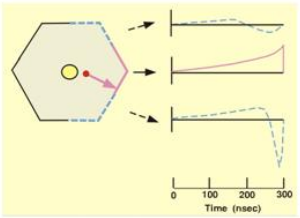
Gamma-ray tracking concepts

- **Compton Suppressed Ge**

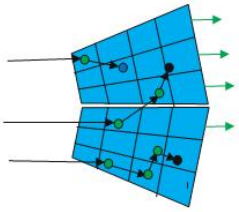


$N_{det} = 100$
Peak efficiency = 8-10%
Efficiency limited

Pulse shape analysis in segments ➔ 3D position

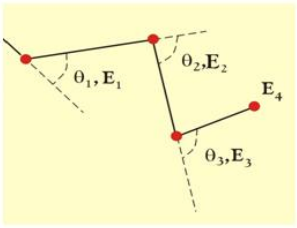


- **Gamma-Ray Tracking**



$N_{det} = 100$
Peak efficiency = 60 %
Segmentation

Tracking of photon interaction points ➔ energy, position



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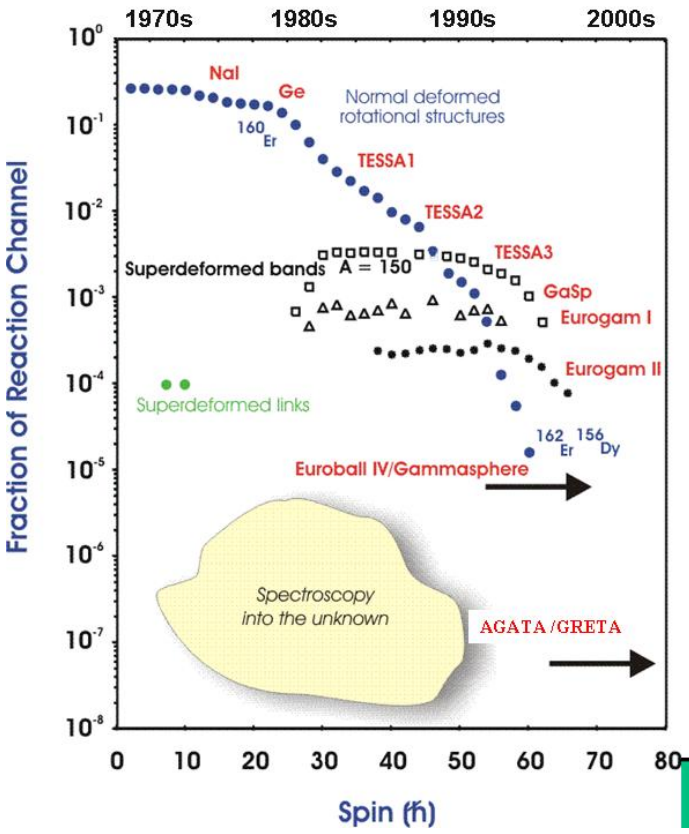
41

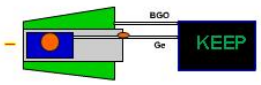


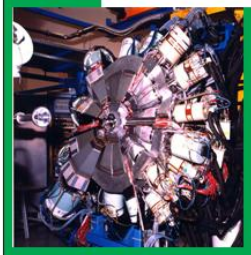
GRETINA

AGATA
ADVANCED GAMMA TRACKING ARRAY

42

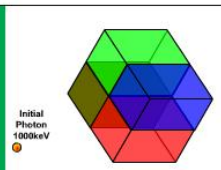
Large Gamma Arrays based on Compton Suppressed Spectrometers

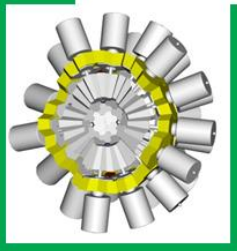


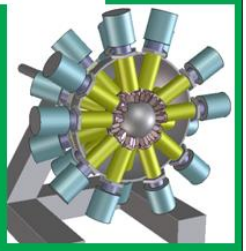


EUROBALL GAMMASPHERE

Tracking Arrays based on Position Sensitive Ge Detectors







AGATA GRETA

$\varepsilon \sim 10 - 5\ \%$ (M_γ=1 — M_γ=30)

$\varepsilon \sim 60 - 40\ \%$ (M_γ=1 — M_γ=30)

Exogam, Miniball, SeGa: optimized for Doppler correction at low γ-multiplicitiy → ε up to 20%

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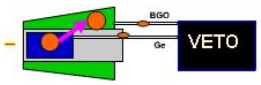
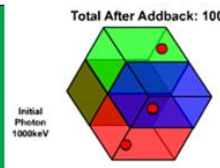
1

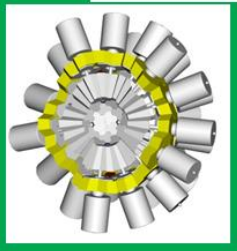
Large Gamma Arrays based on Compton Suppressed Spectrometers



EUROBALL GAMMASPHERE

Tracking Arrays based on Position Sensitive Ge Detectors





AGATA GRETA

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Exogam, Miniball, SeGa: optimized for Doppler correction at low γ-multiplicitiy → ε up to 20%

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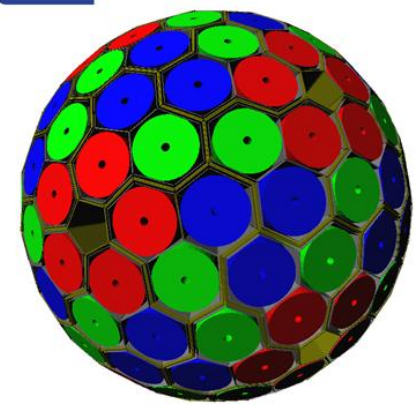
1

GRETA/GRETINA

- Resolving power: 10^7 vs. 10^4
  - Cross sections down to ~1 nb
    - *Most exotic nuclei*
    - *Heavy elements (e.g. ^{253,254}No)*
    - *Drip-line physics*
    - *High level densities (e.g. chaos)*
- Efficiency (high energy) (23% vs. 0.5% at E_γ=15 MeV)
  - Shape of GDR
  - Studies of hypernuclei
- Efficiency (slow beams) (50% vs. 8% at E_γ=1.3 MeV)
  - Fusion evaporation reactions
- Efficiency (fast beams) (50% vs. 0.5% at E_γ=1.3 MeV)
  - Fast-beam spectroscopy with low rates -> RIA
- Angular resolution (0.2° vs. 8°)
  - N-rich exotic beams
    - *Coulomb excitation*
  - Fragmentation-beam spectroscopy
    - *Halos*
    - *Evolution of shell structure*
    - *Transfer reactions*
- Count rate per crystal (100 kHz vs. 10 kHz)
  - More efficient use of available beam intensity
- Linear polarization
- Background rejection by direction

AGATA (Advanced GAmma Tracking Array)

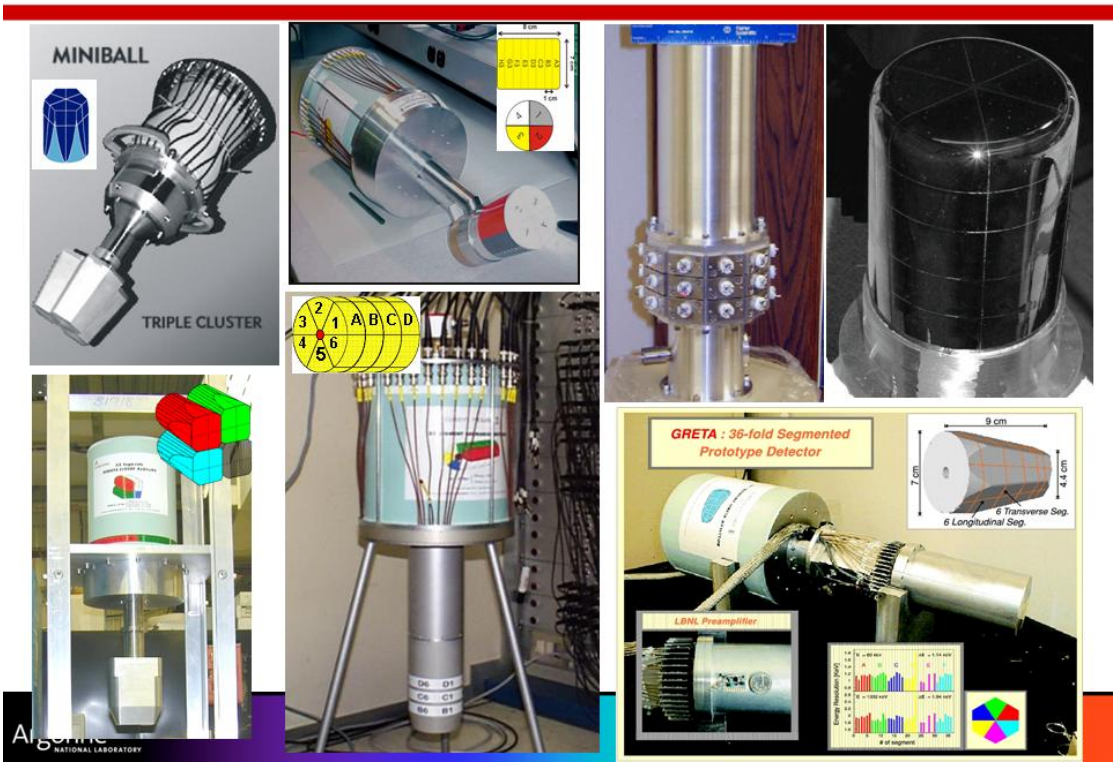


Main features of AGATA

Efficiency:	40% (M_γ=1)	25% (M_γ=30)
today's arrays	~10% (gain ~4)	5% (gain ~1000)
Peak/Total:	55% (M_γ=1)	45% (M_γ=30)
today	~55%	40%
Angular Resolution:	~1° →	
FWHM (1 MeV, v/c=50%)	~ 6 keV !!!	
today	~40 keV	
Rates:	3 MHz (M_γ=1)	300 kHz (M_γ=30)
today	1 MHz	20 kHz

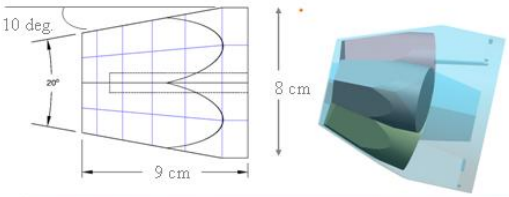
- 180 large volume 36-fold segmented Ge crystals in 60 triple-clusters
- Digital electronics and sophisticated Pulse Shape Analysis algorithms
- Operation of Ge detectors in position sensitive mode → γ-ray tracking

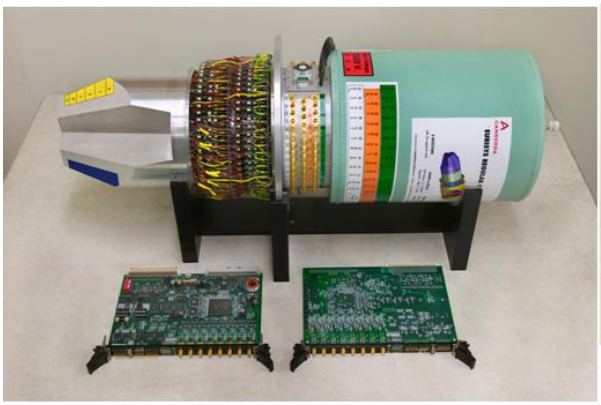
Highly segmented Ge detectors

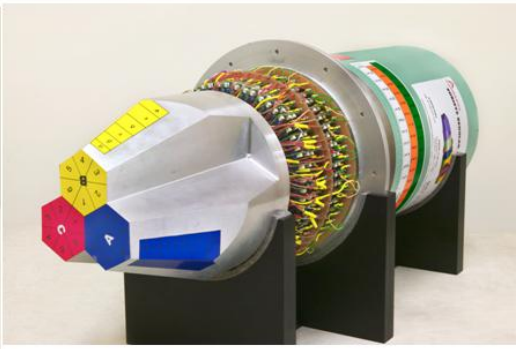


GRETINA detectors

- **Tapered hexagon shape**
- **Highly segmented 6 × 6 = 36**
- **Close packing of 3 crystals**
- **111 channels of signal**

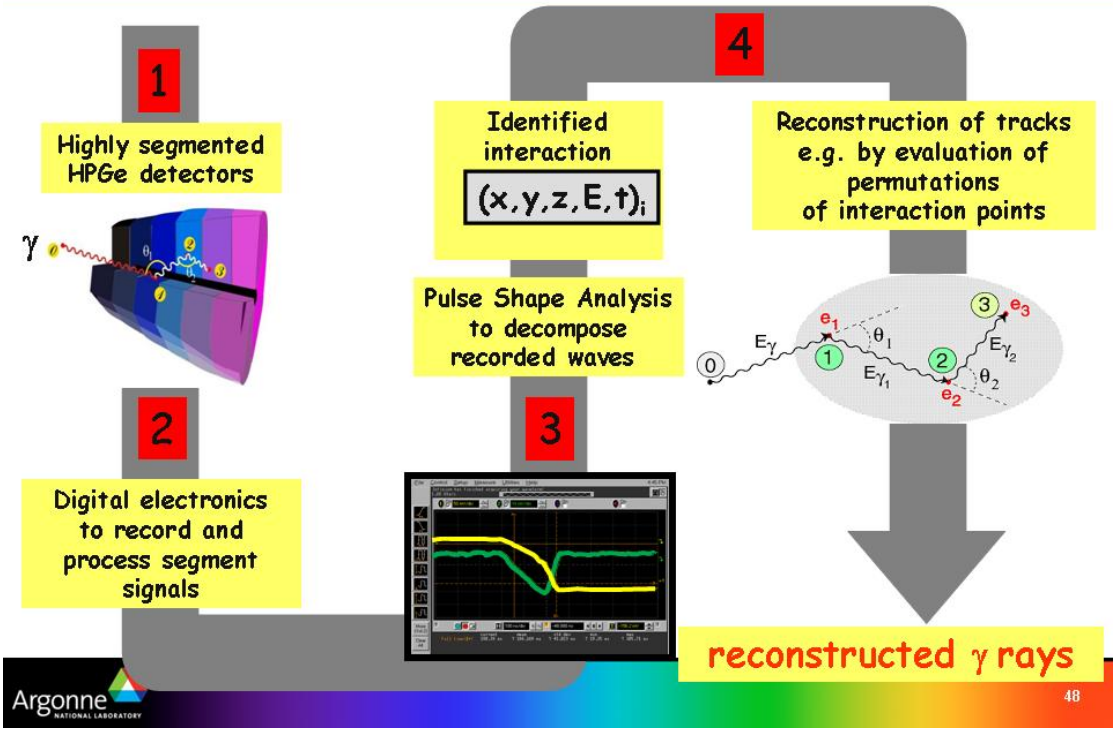




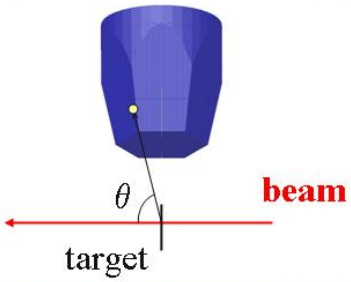


Received June 4, 2004

Main components of γ–ray tracking



In-beam test



Experiment

- LBNL 88" Cyclotron
- Prototype II detector
- $^{82}Se + {}^{12}C$ @ 385 MeV
- ^{90}Zr nuclei ($\beta \sim 8.9\%$)
- 2055 keV ($10^+ \rightarrow 8^+$) in ^{90}Zr
- Detector at 4 cm and 90°
- Three 8-channels LBNL signal Digitizer modules (24 ch.)

Analysis

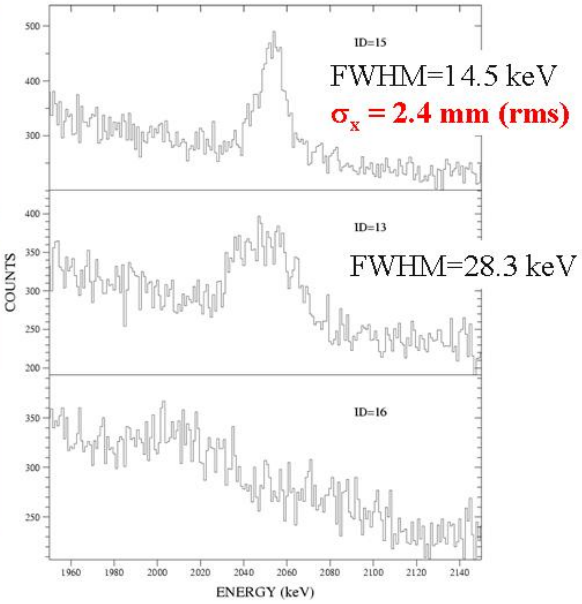
- Event building
- Calibration : cross talk
- Signal decomposition
- Doppler correction

In-beam test results

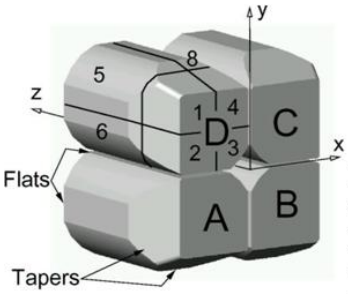
Doppler corrected using first hit position determined by signal decomposition

Corrected using center of segment only

No correction



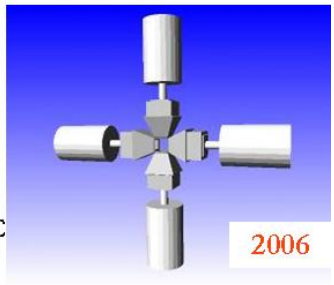
TIGRESS TRIUMF, CANADA

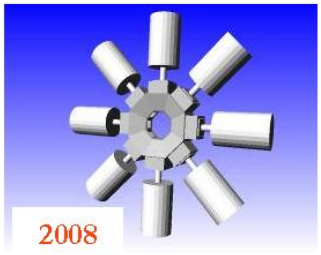


ISAC II

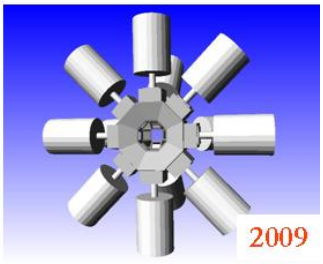
Nuclear Structure:

Evolution of Nuclear Shell Structure
Pairing Correlation far from Stability
Mirror Nuclei and Isospin Symmetry
Coulomb Excitation with Bragg/PPAC
Fusion Evaporation reactions with
CsI(Tl) and neutron detector arrays

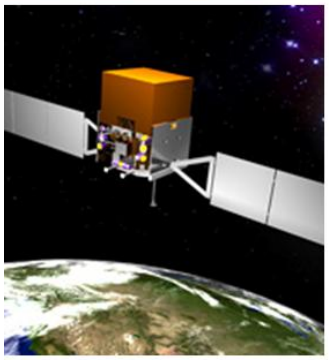


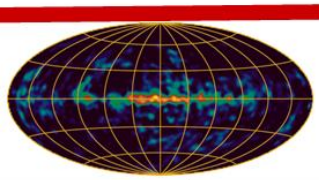


Nuclear Astrophysics:
structure studies of astrophysically important states
Transfer reactions with EMMA/Si Array



Gamma-ray lines of the Cosmos





Science Objective	Isotopes and Lines (MeV)
Understand Type Ia SN explosion mechanism and dynamics	^{56}Ni (0.158, ***0.812***, …) ^{56}Co (***0.847, 1.238***, …) ^{57}Co (0.122)
Understand core collapse SN Explosion mechanism and dynamics	^{56}Ni (0.158, ***0.812***, …) ^{56}Co (***0.847, 1.238***, …) ^{57}Co (0.122), ^{26}Al (***1.809, 0.511***)
Map the Galaxy in nucleosynthetic radioactivity	^{26}Al (***1.809, 0.511***) ^{60}Fe, ^{60}Co (***1.173, 1.332***) ^{44}Ti (0.068, 0.078, ***1.16***)
Map Galactic positron annihilation radiation	e^+–e^- annihilation (***0.511***, 3 photon continuum) SN Ia ^{56}Co positrons (***0.511***) ^{26}Al and ^{44}Ti positrons (***0.511***)
Understand the dynamics of Galactic Novae	^{13}N, ^{14,15}O, ^{18}F positrons (***0.511***) ^{7}Be (***0.478***), ^{22}Na (***1.275, 0.511***)
Cosmic-ray interactions with the ISM	^{12}C (4.4), ^{16}O (6.1), ^{20}Ne(***1.634***), ^{24}Mg(***1.369***,2.754), ^{28}Si(***1.779***), ^{56}Fe(***0.847,1.238***)
Neutron Star Mass-Radius	p-n (***2.223***)

The Concept

Position sensitive gamma-ray detectors have been under development for many years

- Space Science
- Medical Imaging
- Basic Nuclear Research
- Homeland Security and Verification

Scintillator: **NaI, CsI, LSO**

Semi-conductor: **Si, CdZnTe, CdTe**

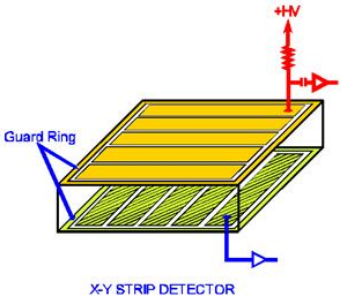
High Purity Germanium: offers the best energy resolution and timing for intermediate (40-2500 keV) radiation. Very large and efficient detectors can now be fabricated

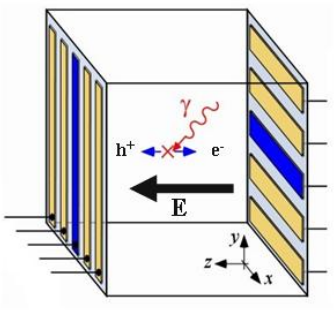
Key Question:

Can reliable, efficient, high resolution *position sensitive* germanium detectors be produced and incorporated into practical devices?

Ge strip Detectors – an excellent choice!

- based on the HpGe planar detector technology
- orthogonal electrodes (strips) that provide position localization of the interactions
- operates like a conventional p-i-n diode
- pulse-shape analysis – depth of the interactions





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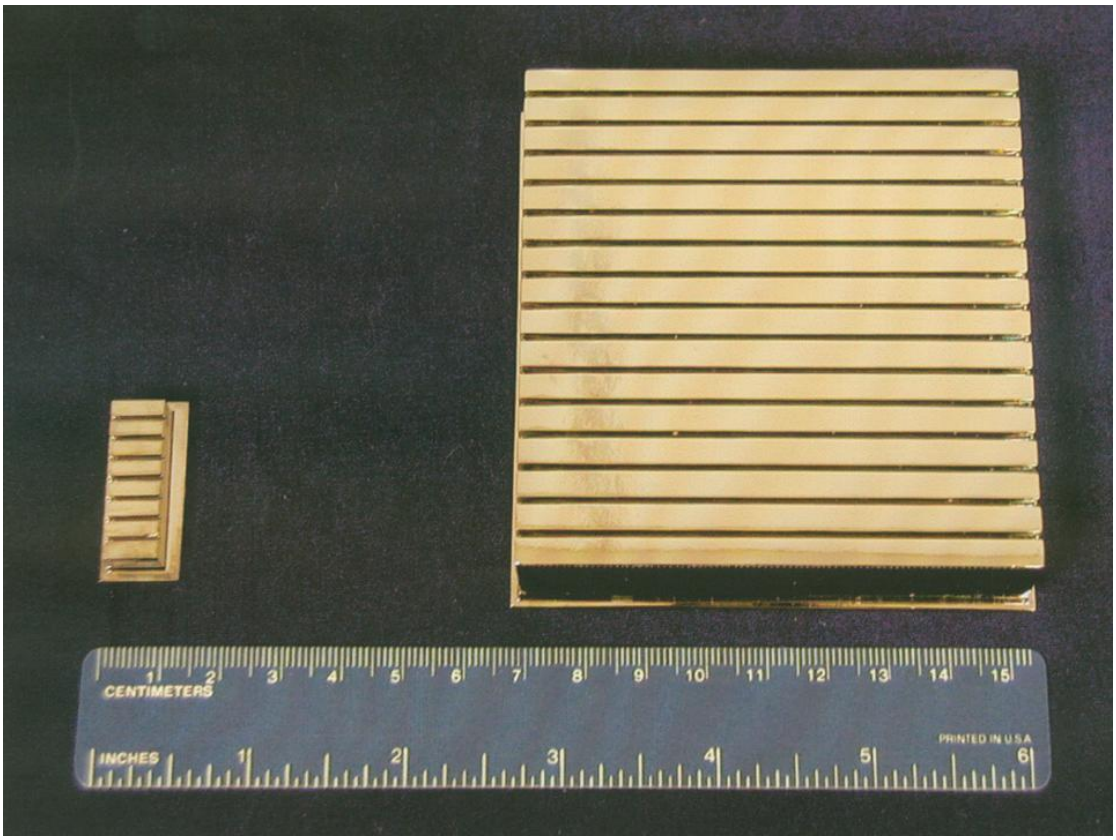
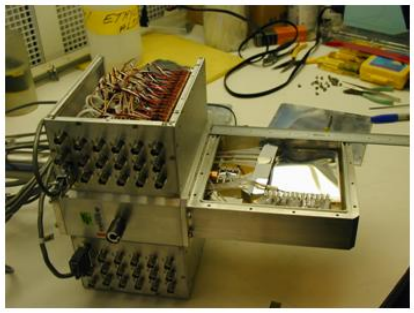
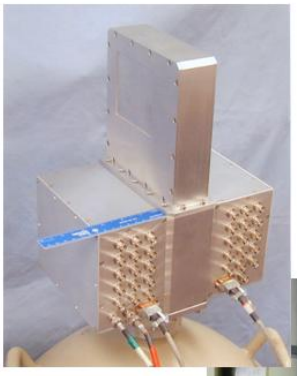


ANL HpGe strip Detector



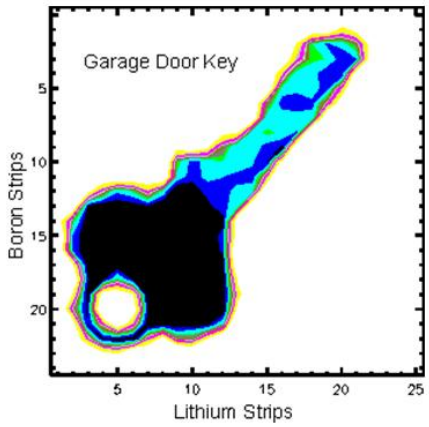


With the premier US germanium detector manufacturer, **Ortec**, we have built

- ***the biggest*** (~90 mm x 90 mm x 20 mm)
- ***the best*** (~1.0 keV at 122 keV, ~2.0 keV at 1.3 MeV)

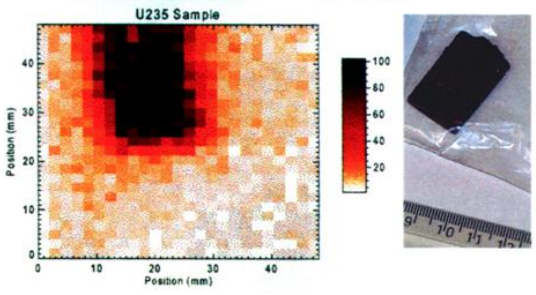
Ge strip detector in the world!

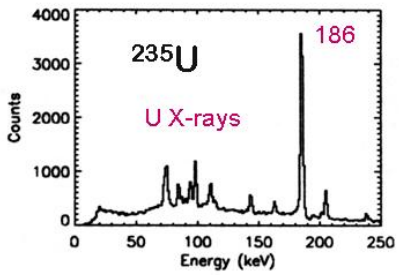
2D imaging capabilities



25 x 25 strip HpGeDSSD
60 keV γ rays from ^{241}Am source

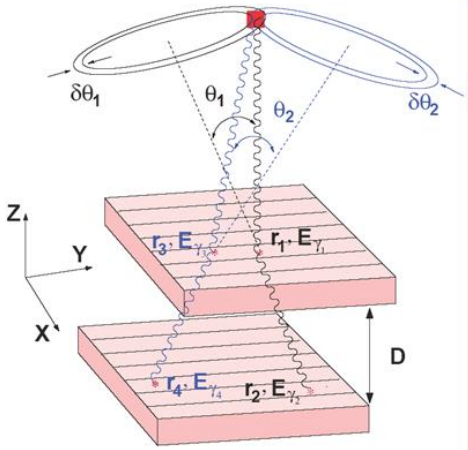
S.E. Inderhees et al., IEEE 43 (1996) 1467





Imaging and characterization

Compton camera



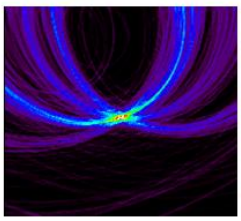
Concept

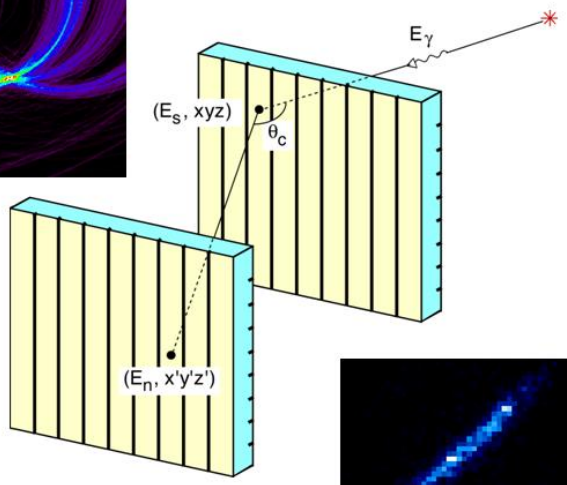
- Gamma-ray Compton scatters in the first detector
- Positions and energies of individual interactions to determine pathway of gamma ray in the detector – *gamma-ray tracking*!
- Energies and positions define cone of incident angles (electron path is not measured)
- Cones are projected on a plane or a sphere (one circle per event) for 2D or into a cube (one cone per event) for 3D imaging

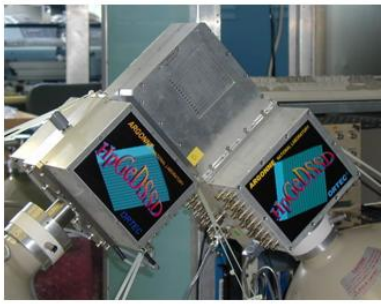
$$\cos\theta_1 = [1 - m_e c^2 ((E_\gamma - E_{\gamma 1}) / E_\gamma E_{\gamma 1})]$$

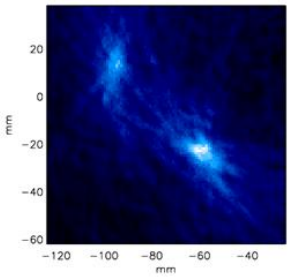
$$E_\gamma = E_{\gamma 1} + E_{\gamma 2}$$

Compton camera

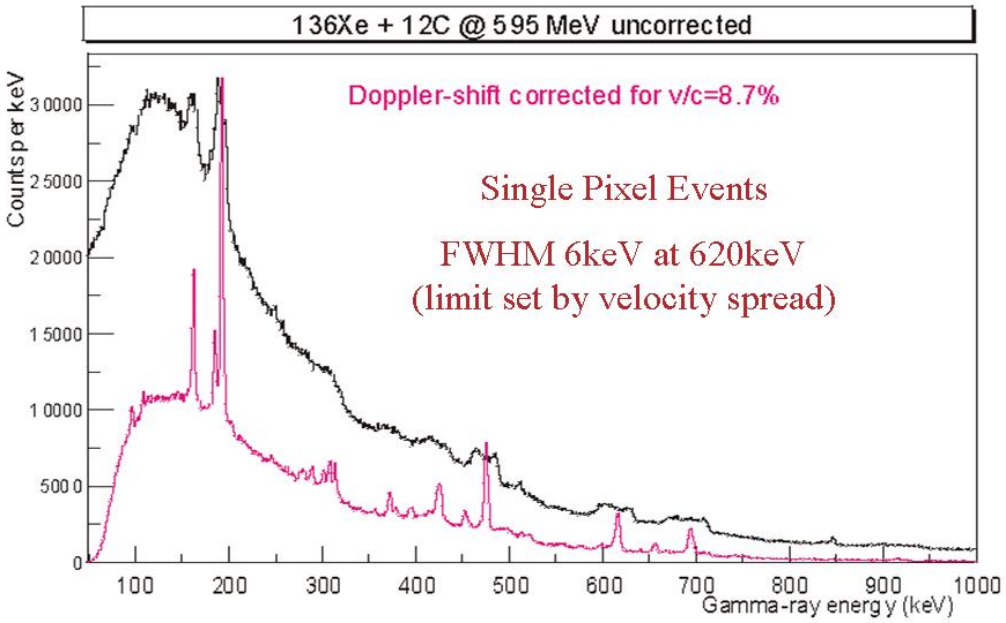




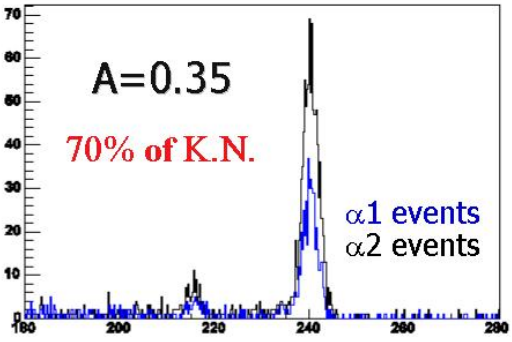




Doppler correction



Polarization in $\alpha-\gamma$ coincidences



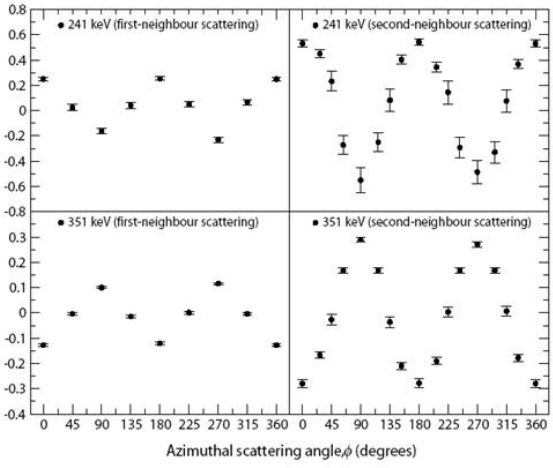
"Second neighbor" analysis has even bigger asymmetry, and almost as much data

16 pixels vs. 4

"Worlds Best" figure of merit

Vertical scatters in HpGeDSSD (Boron Side)

^{228}Th 240-keV (0-2-0) correlation



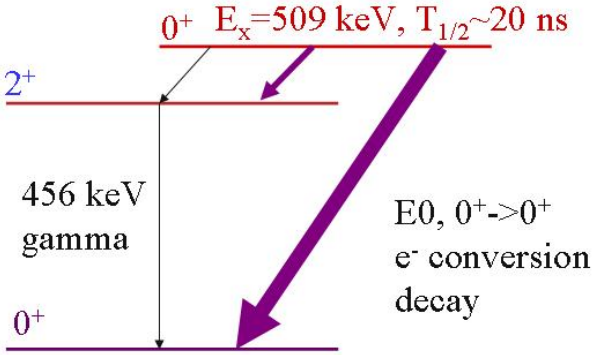
Experimental Nuclear Structure - Additions

F. G. Kondev

Argonne National Laboratory, USA

E-mail: kondev@anl.gov

undressing (to fiddle the decay probability)



$$\Gamma_{tot} = \Gamma_{E0} + \Gamma_{E2,\gamma} + \Gamma_{E2,e-}$$

Fully stripping the nucleus of atomic electrons (in-flight) 'switches off' the electron conversion decay branches - result is that the **bare nuclear isomeric lifetime is increased** compared to 'atomic' value (important in explosive stellar scenarios)

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 56, NUMBER 6 DECEMBER 1997

Evidence for a highly deformed oblate 0^+ state in $^{74}_{36}$Kr

C. Chandler,[1] P. H. Regan,[1] C. J. Pearson,[1] B. Blank,[2] A. M. Bruce,[3] W. N. Catford,[1] N. Curtis,[1] S. Czajkowski,[2] W. Gelletly,[1] R. Grzywacz,[4,5] Z. Janas,[2,4] M. Lewitowicz,[5] C. Marchand,[2] N. A. Orr,[6] R. D. Page,[7] A. Petrovici,[8] A. T. Reed,[7] M. G. Saint-Laurent,[5] S. M. Vincent,[1] R. Wadsworth,[9] D. D. Warner,[10] and J. S. Winfield[5]

^{74}Kr isomer from ^{92}Mo fragmentation at GANIL. 456 keV $2^+ \rightarrow 0^+$ transitions decays **(a) too fast** (500 ns flight time) & **(b) too slow** for measured value of 2^+ state (~25 ps) ?

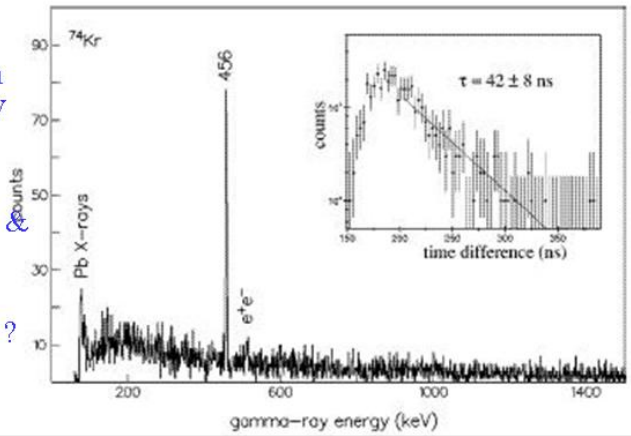
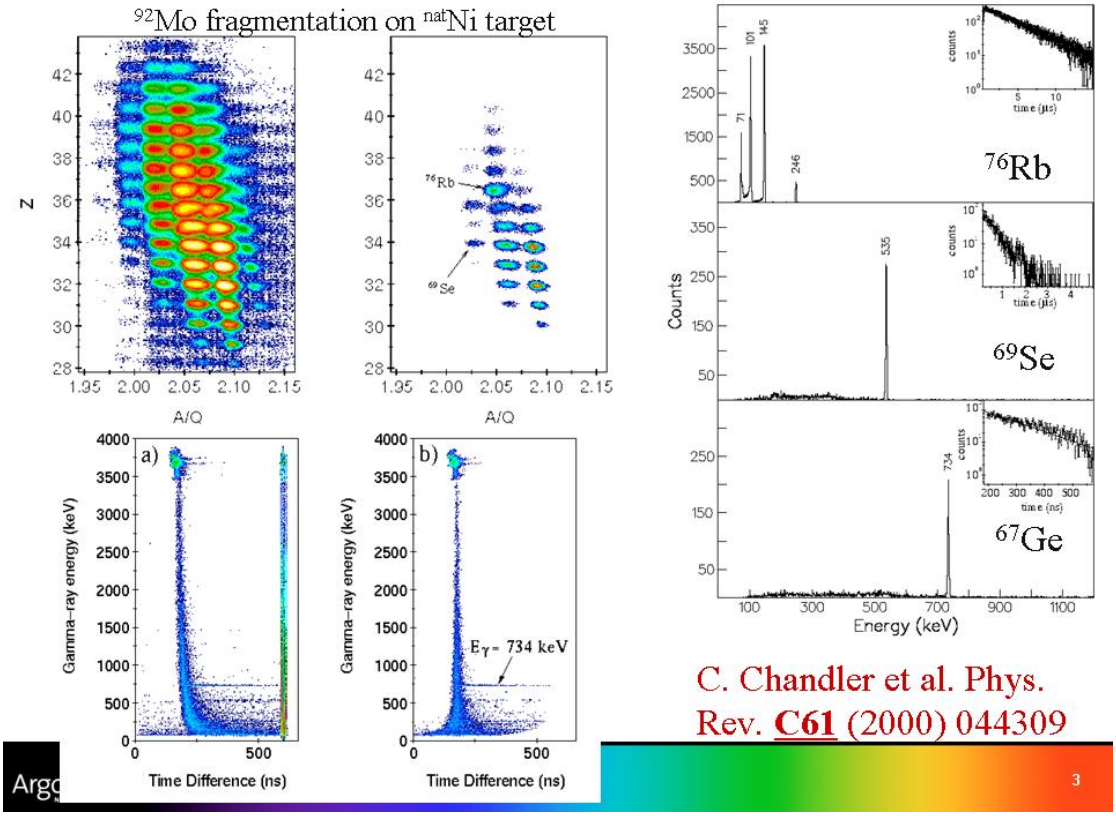


FIG. 1. Gamma-ray and time spectra for ^{74}Kr showing the decay from the proposed O^+ isomer



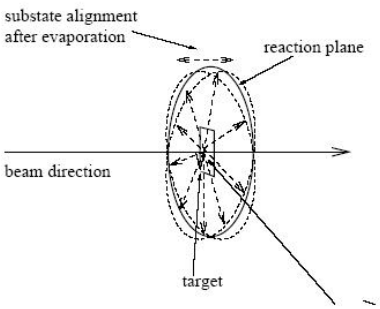
Two level mixing

The gamma rays emitted from nuclear reactions exhibit angular distributions that can be expressed as follow:

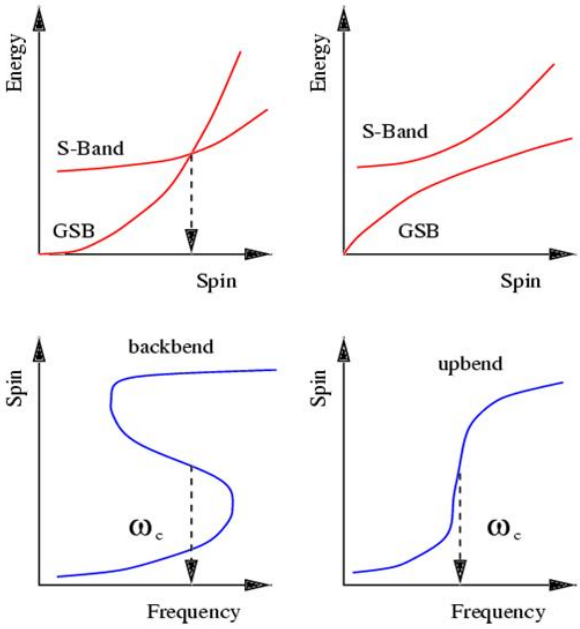
$$W(\theta) = 1 + Q_2 A_{22} P_2(\cos\theta) + Q_4 A_{44} P_4(\cos\theta)$$

Q_2,Q_4: solid angle corrections due to the finite size of the detectors

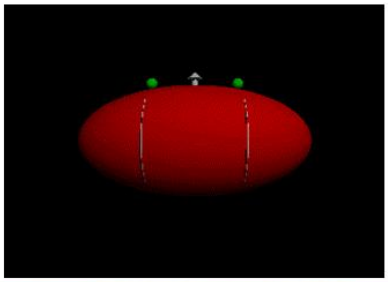
$$A_{22} = \alpha_2 A_2^{\max}; A_{44} = \alpha_4 A_4^{\max}$$



Band Crossings



- Backbending can be interpreted as the crossing of two bands
- The 'G' band (Ground state) is a fully paired configuration
- The 'S' band (Super or Stockholm) contains one broken pair



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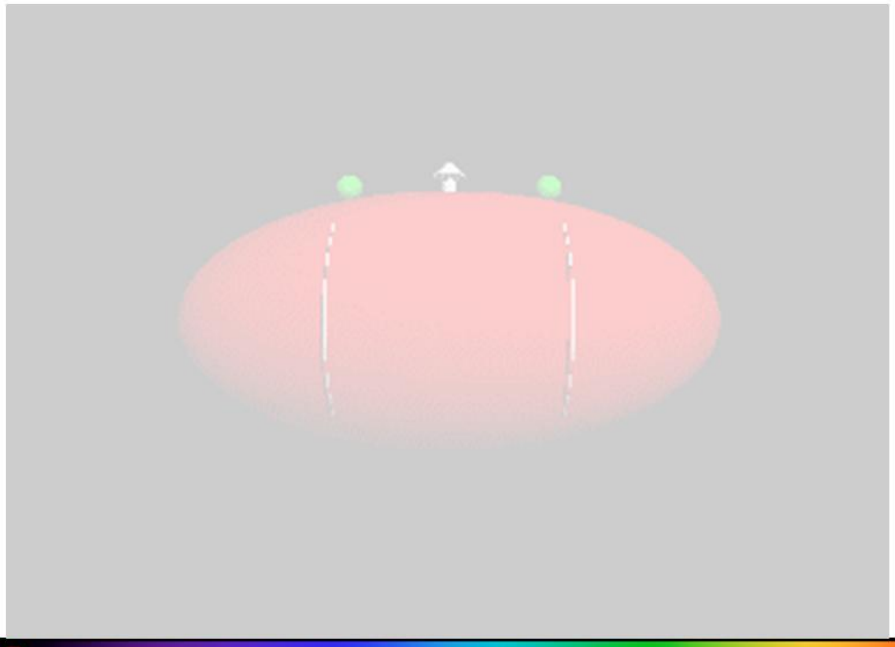
Backbending



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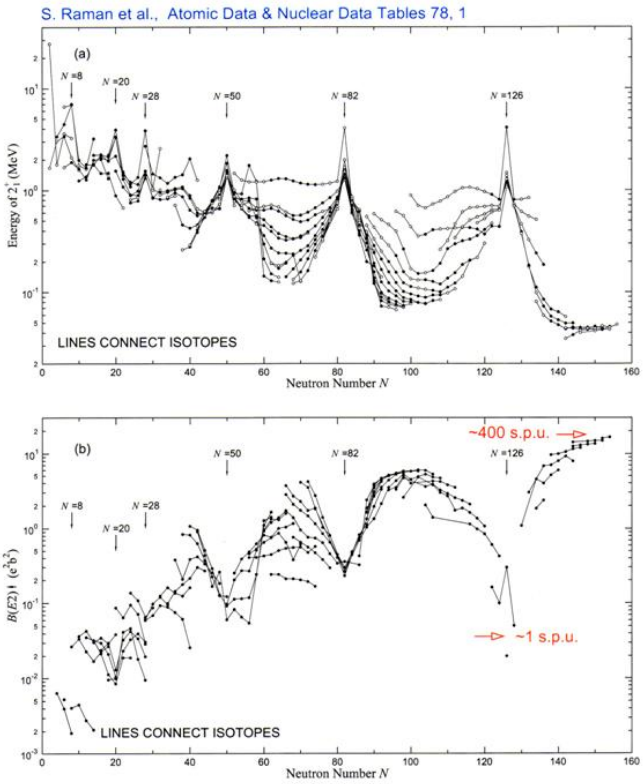
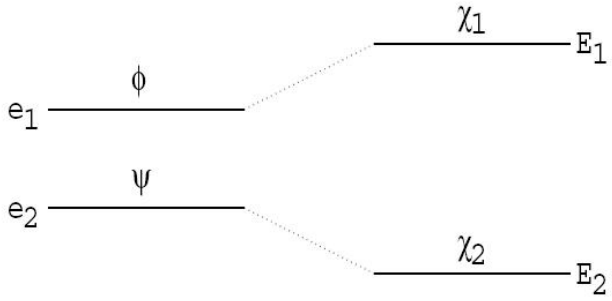
Systematics of B(E2)s

Near stable and proton rich nuclei: there is a fixed relationship between B(E2) and $E2^+$

"GRODZIN'S RULE"

However, this should break down in neutron rich nuclei, and the link between B(E2) and deformation WILL be more complicated





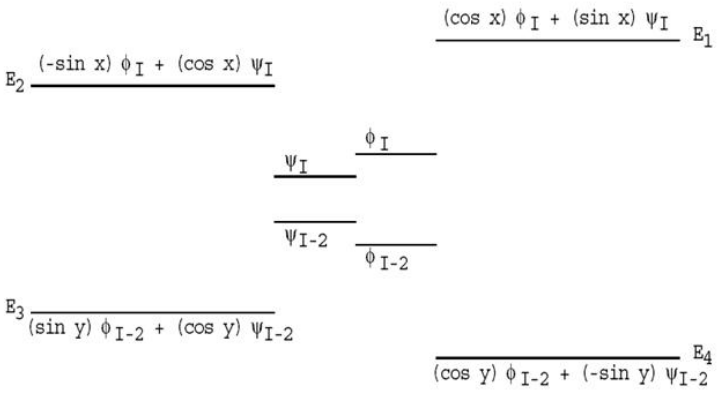
$$\chi_i = a_i\phi + b_i\psi$$

$$(H_0 + H_{int})\,|\chi_i> = E_i|\chi_i>$$

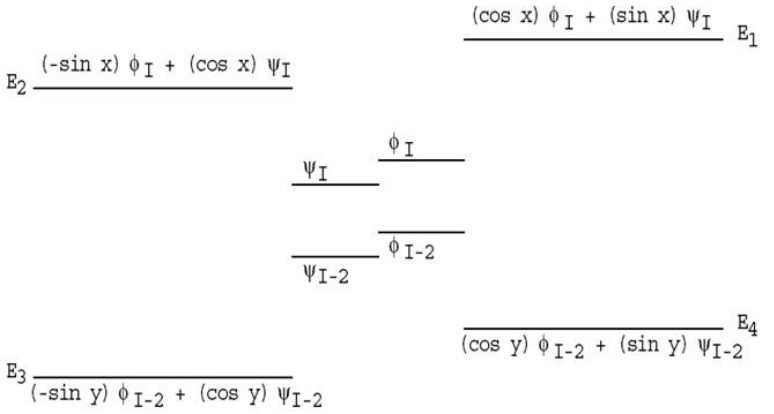
$$\begin{pmatrix} e_1 - E_i & V \\ V & e_2 - E_i \end{pmatrix} \begin{pmatrix} a_i \\ b_i \end{pmatrix} = 0$$

$$\begin{matrix} E_1(+) \\ E_2(-) \end{matrix} = \frac{e_1 + e_2}{2} \pm \frac{\sqrt{(e_1 - e_2)^2 + 4V^2}}{2} \qquad \begin{matrix} e_1(+) \\ e_2(-) \end{matrix} = \frac{E_1 + E_2}{2} \pm \frac{\sqrt{(E_1 - E_2)^2 - 4V^2}}{2}$$

$$\frac{a_i}{b_i} = \frac{V}{E_i - e_1}$$

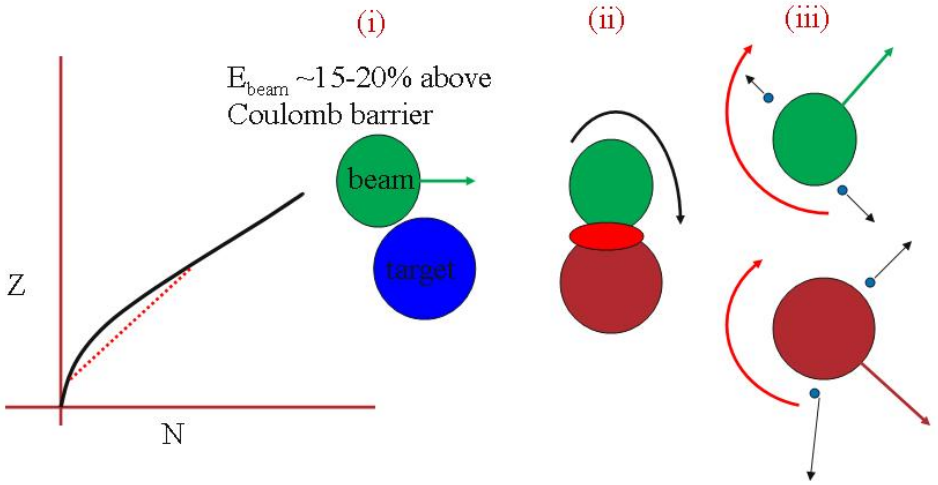

(cos x) ϕ_I + (sin x) ψ_I E_1
E_2 (-sin x) ϕ_I + (cos x) ψ_I
ϕ_I
ψ_I
ψ_{I-2}
ϕ_{I-2}
E_3 (sin y) ϕ_{I-2} + (cos y) ψ_{I-2}
E_4 (cos y) ϕ_{I-2} + (-sin y) ψ_{I-2}

(b)

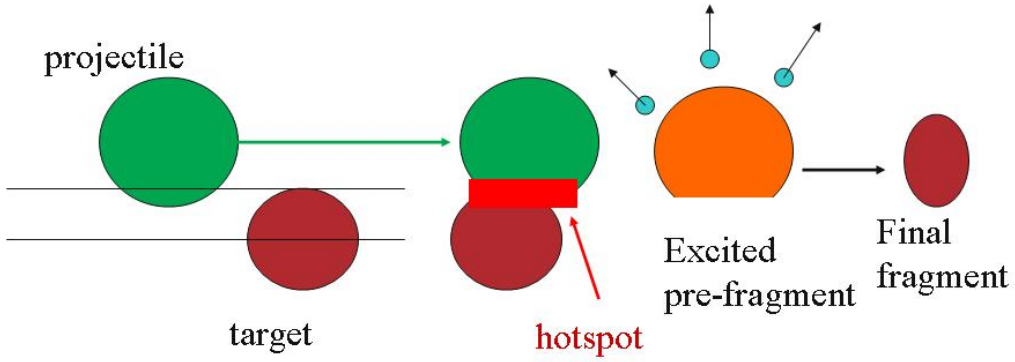

(cos x) ϕ_I + (sin x) ψ_I E_1
E_2 (-sin x) ϕ_I + (cos x) ψ_I
ϕ_I
ψ_I
ϕ_{I-2}
ψ_{I-2}
E_4 (cos y) ϕ_{I-2} + (sin y) ψ_{I-2}
E_3 (-sin y) ϕ_{I-2} + (cos y) ψ_{I-2}

Deep inelastic collisions

Can not use fusion-evaporation reactions to study high-spin states in beta-stable and neutron-rich systems



Projectile Fragmentation Reactions



Energy (velocity) of beam > Fermi velocity inside nucleus ~30 MeV/u
Can 'shear off' different combinations of protons and neutrons
Large variety of exotic nuclear species created, all at forward angles with ~ beam velocity

Nuclear reactions – very schematic!

Near the line of stability

- Gamma-ray induced

  no Coulomb barrier

$$E^* = E_\gamma$$

$$J^* \approx J_{gs} \pm 1$$

- Neutron induced

  low-spin states

  no Coulomb barrier

$$E^* = E_n + S_n$$

$$J^* = J_{gs} \pm 1/2 \quad \text{("capture")}$$

$$J^* = J_{gs} + \beta\sqrt{E_n} \quad \text{("fast")}$$

- Light charged particles,

e.g. p, d, t, α

  Coulomb barrier

  low-spin states

$$Vc = 1.44\frac{Z_b Z_t}{R[fm]}[MeV]$$

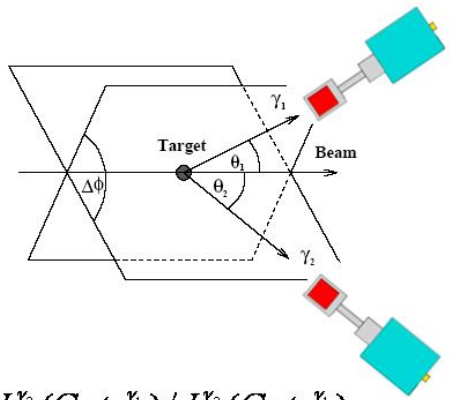
$$E^* = E_{CM} + Q$$

$$J^* = J_{gs} + \beta\sqrt{(E_p - V_c)}$$

DCO ratios

Δϕ is the angle between two planes opened by each detector and the beam axis

$W(\theta_1, \theta_2, \Delta\phi)$ — **probability (intensity) for this specific configuration, e.g. the intensity of transition γ_2, determined in detector 2, gated on the transition γ_1 in detector 1**

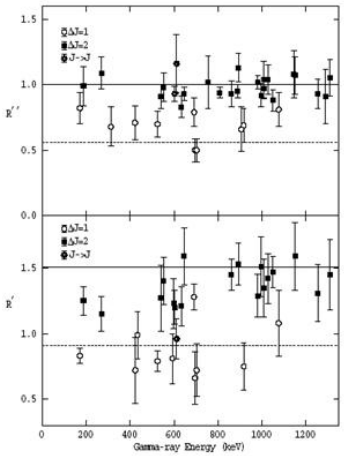


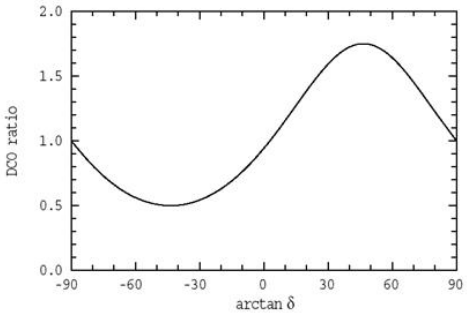
$$R_{DCO} = W(\theta_2, \theta_1, \Delta\phi)/W(\theta_1, \theta_2, \Delta\phi) = I^{\gamma_2}_{\theta_1}(Gate^{\gamma_1}_{\theta_2})/I^{\gamma_2}_{\theta_2}(Gate^{\gamma_1}_{\theta_1})$$

DCO ratios

Δϕ is the angle between two planes opened by each detector and the beam axis

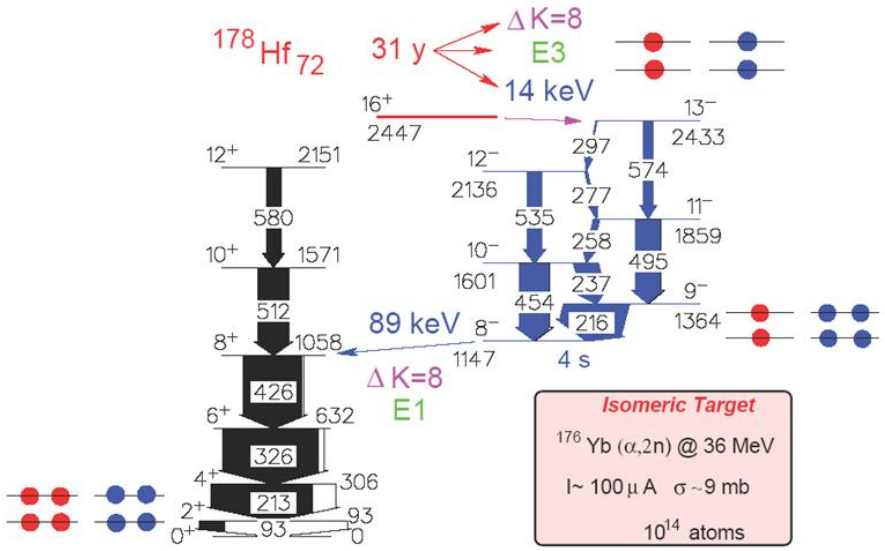
$W(\theta_1,\theta_2,\Delta\phi)$





probability (intensity) for this specific configuration, e.g. the intensity of transition γ_2, determined in detector 2, gated on the transition γ_1 in detector 1

$$R_{DCO} = W(\theta_2,\theta_1,\Delta\phi)/W(\theta_1,\theta_2,\Delta\phi) = I^{\gamma_2}_{\theta_1}(Gate^{\gamma_1}_{\theta_2})/I^{\gamma_2}_{\theta_2}(Gate^{\gamma_1}_{\theta_1})$$



Isomeric Target

^{176}Yb (α,2n) @ 36 MeV

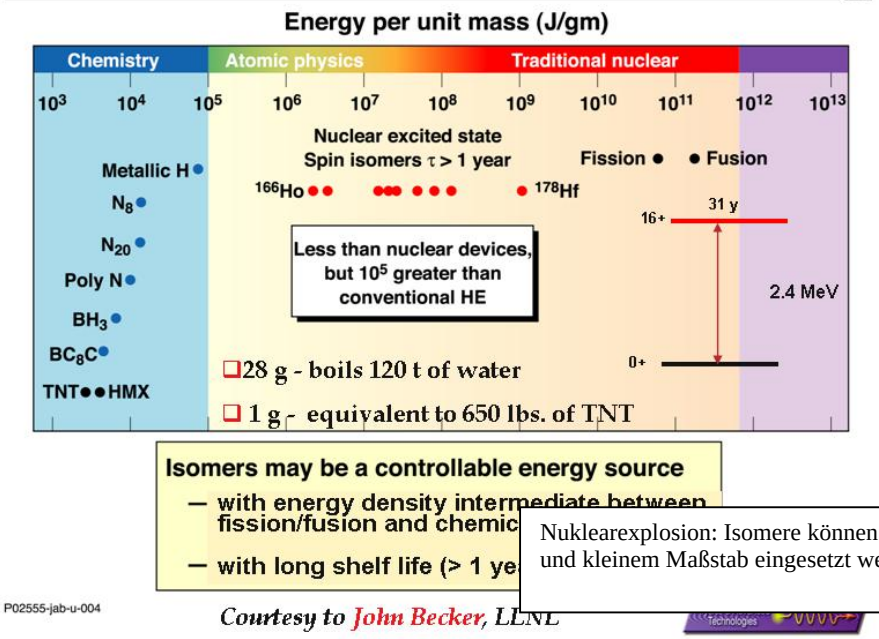
I~ 100 μA σ~9 mb

10^{14} atoms

R.G. Helmer and C.W. Reich , Nucl. Phys. A114 (1968) 649

- Coulumb excitations – Lubikiewicz et al., Z. Phys. A355 (1996) 377
- (d,d') - S. Deylitz et al., Phys. Rev. C53 (1996) 1266
- (γ,n) – S.A. Karamian et al., Z. Phys. A356 (1996) 23
- Q_0 and μ_t – N. Boos et al., Phys. Rev. Lett (1994) 2689

Why should DOE-NE care?
— Unprecedented energy storage opportunities



Isomers may be a controllable energy source

- with energy density intermediate between fission/fusion and chemic
- with long shelf life (> 1 ye

P02555-jab-u-004

Courtesy to John Becker, LLNL

Nuklearexplosion: Isomere können in großem und kleinem Maßstab eingesetzt werden

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Some applications

The World's No.1 Science & Technology News Service

Nuclear-powered drone aircraft on drawing board

19:00 19 February 03

With a nuclear drive a Global Hawk could fly for months without landing (Image: GETTY NEWSERVICE)

New Scientist, 2003

СТАНДАРТ NEWS интернет издание

СВЯТ Понеделник, 25 Август 2003

Bulgarian

Главна АФЕРИ Денят

САЩ разработват лъчева бомба

SPIEGEL ONLINE - 14. August 2003, 15:27

Pentagon-Pläne

Handliches Höllenfeuer

Das US-Militär entwickelt einen neuartigen Nuklearsprengstoff, der schon in kleinsten Mengen ungeheure Vernichtungskräfte entfesseln, zugleich aber auch in Kleinstwaffen eingesetzt werden kann. Experten warnen bereits vor einem neuen globalen Wettrüsten.

Nuklear explosion: Isomere können in großem und kleinem Maßstab eingesetzt werden

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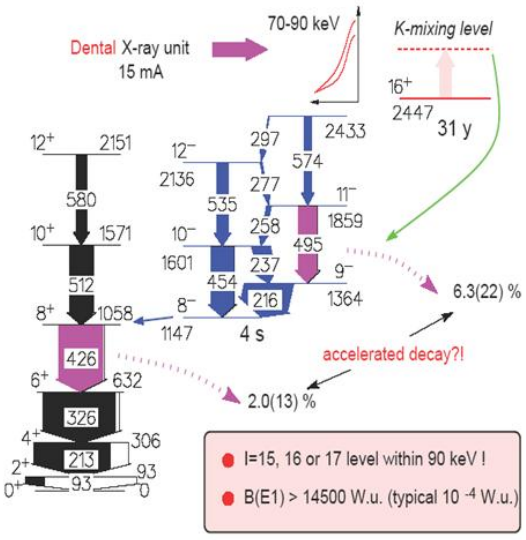
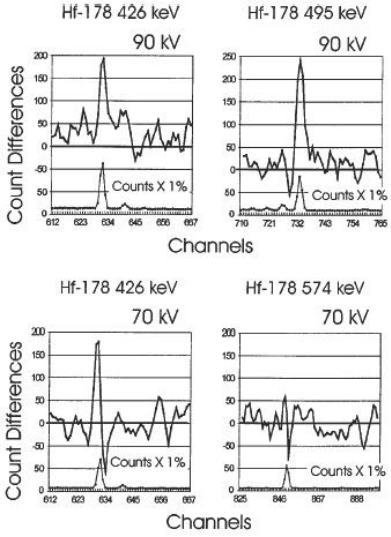
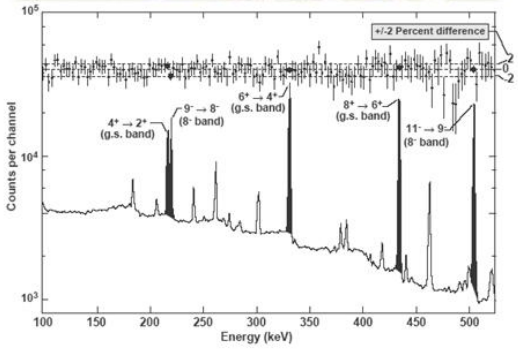
Triggering of ^{178m}Hf using X-rays

Texas/AFRL/SNL Collaboration/Phys. Rev. Lett. 82 (1999) 695

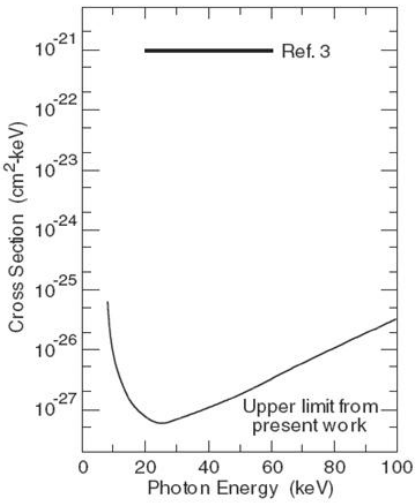




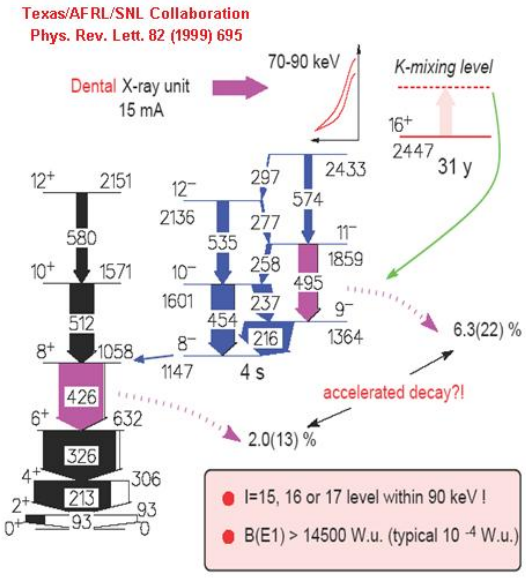
Triggering of ^{178m}Hf using X-rays – cont.

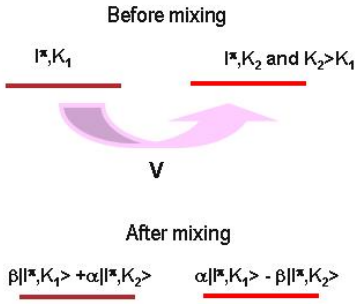


ANL/LANL/LLNL /Phys. Rev. Lett. 87 (2001) 072503



Can K-mixing explain the results of Collins et al?

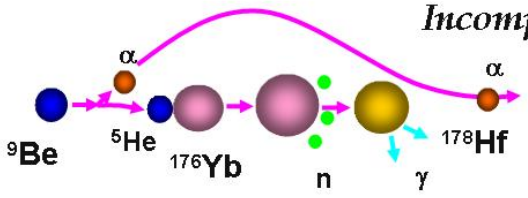


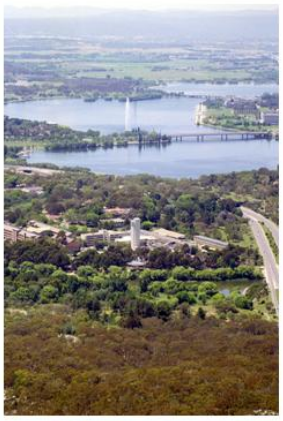


- two levels with the same I^π and <90 keV above the isomer
- must have I = 15, 16 or 17, e.g. high spin
- must have very different K
- V is very small (~ eV!)

^{178}Hf ANU experiment

Incomplete fusion

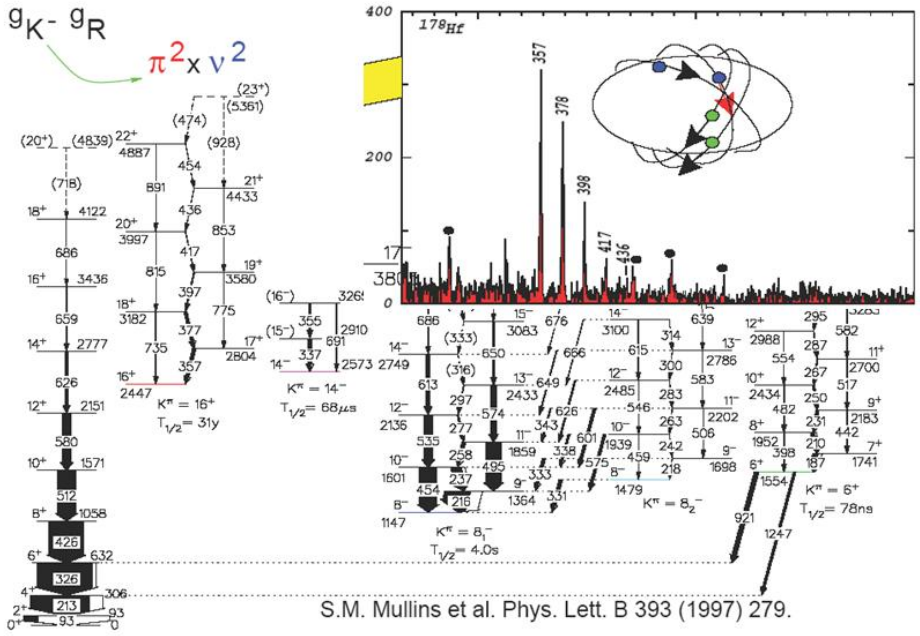




14 - element fast/slow plastic

Compton-suppressed high-resolution Ge

^{178}Hf ANU experiment - cont.



Experimental Nuclear Structure Physics:

Experimental Techniques

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The Australian National University

Experimental techniques to deduce J^{π}

Joint ICTP-IAEA Workshop on
Nuclear Structure and Decay Data Theory and Evaluation
28 April - 9 May 2008

Tibor Kibédi

The Australian National University

Outline:

Lecture I: ***Experimental techniques to deduce J^{π} from***

- ***Internal Conversion Coefficients***
- ***Angular distributions and correlations***
- ***Directional Correlations from Oriented nuclei (DCO)***

Lecture II: **New developments in characterizing nuclei far from stability**

Electromagnetic Decay and Nuclear Structure

Energetics of γ-decay:

E_i J_i^π

E_γ, L, $\Delta\pi$

E_f J_f^π

$E_i = E_f + E_\gamma + T_r$

$0 = p_r + p_\gamma$,

where $T_r = (p_r)^2/2M$; usually $T_r/E_\gamma \sim 10^{-5}$

Angular momentum and parity selection rules; multipolarities

$|J_i - J_f| \leq L \leq J_i + J_f$; $L \neq 0$ $\quad J_i = J_f$

$\Delta\pi$ = no;	E2, E4, E6	M1, M3, M5	E0
$\Delta\pi$ = yes;	E1, E3, E5	M2, M4, M6	

multipolarity known, ΔJ may not be unique, unique Δπ

Mixed multipolarity

$\delta(\pi`L`) = I_\gamma(\pi`L`) / I_\gamma(\pi L)$

	$\Delta\pi = +1$			$\Delta\pi = -1$	
πL	M1	M1	M3	E1	E3
$\pi' L'$	E2	E2	E4	M2	M4
$\pi'' L''$	M3	E0	M5	E3	E5

Electromagnetic decay modes

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- Pair conversion coefficients
- E0 transitions: ΔL=0

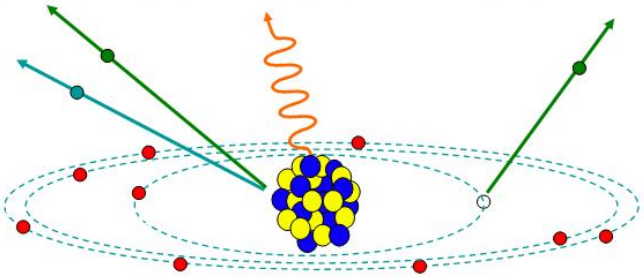
e^- - e^+ pair

- Angular distribution with spins oriented
- Angular correlations
- Polarization effects

γ-ray

- Electron conversion coefficients
- E0 transitions: ΔL=0

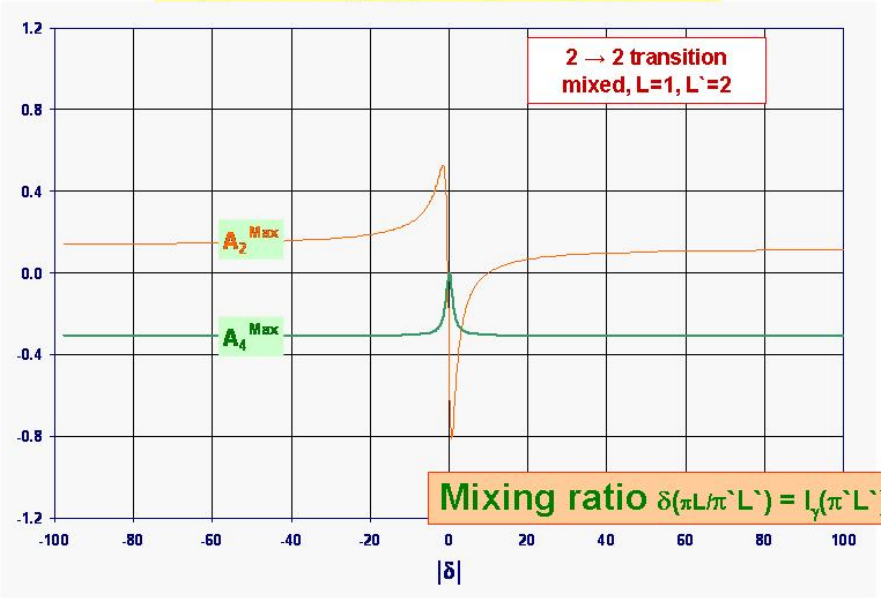
electron conversion



Higher order effects: for example 2 photon emission is very weak

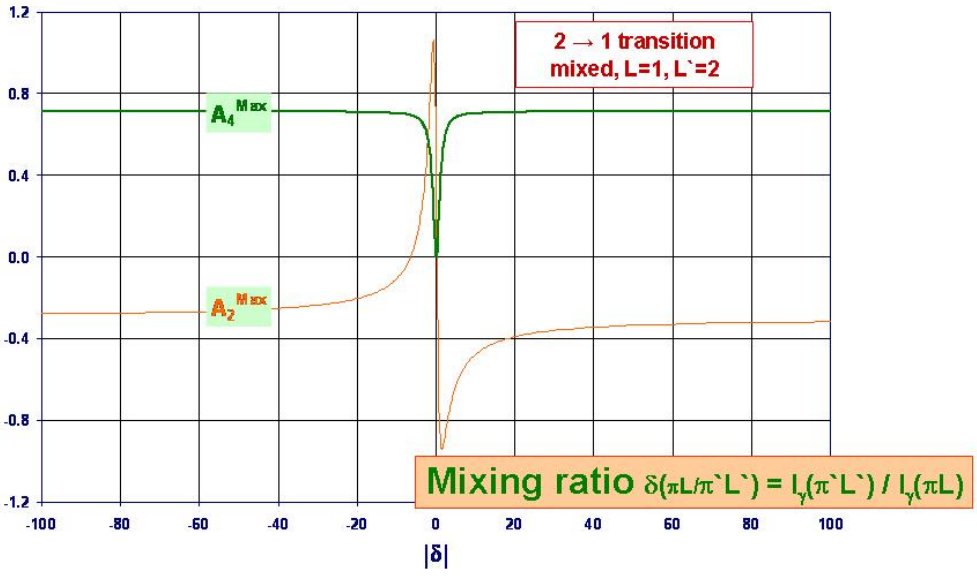
Angular distributions of gamma rays

$$W(\theta) = 1 + A_{22} P_2(\cos\theta) + A_{44} P_4(\cos\theta)$$



Angular distributions of gamma rays

$$W(\theta) = 1 + A_{22} P_2(\cos\theta) + A_{44} P_4(\cos\theta)$$



Angular distributions of gamma rays

$$W(\theta) = 1 + A_{22}P_2(\cos\theta) + A_{44}P_4(\cos\theta)$$

Attenuation due to relaxation of nuclear orientation

$$0 \le A_{kk} \le A_k^{\max}(J_i, J_f, L, L'); k = 2,4\ldots$$

$$A_k^{\max}(J_i, J_f, L, L') = \frac{F_k(LLJ_fJ_i) + 2\delta \times F_k(LL'J_fJ_i) + \delta^2 \times F_k(L'L'J_fJ_i)}{1+\delta^2}$$

for $F_k(LL`J_fJ_i)$ see E. Der Mateosian and A.W. Sunyar, ADNDT 13 (1974) 391

$$A_{kk} = B_k(J_i) \times A_k^{\max}(J_i, J_f, L, L')$$

Nuclear orientation can be achieved

- by interaction of external fields (E,B) with the static moments of the nuclei at low temperatures
- by nuclear reaction

Angular distributions of gamma rays

(n,n) reaction on ^{92}Zr

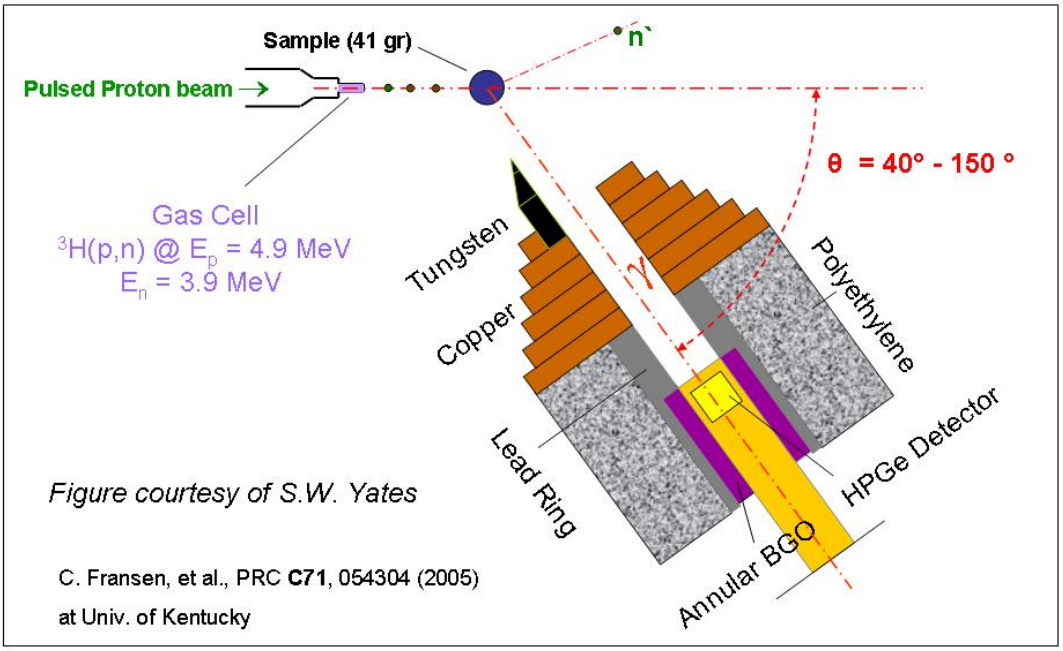


Figure courtesy of S.W. Yates

C. Fransen, et al., PRC **C71**, 054304 (2005)
at Univ. of Kentucky

Angular distributions of gamma rays

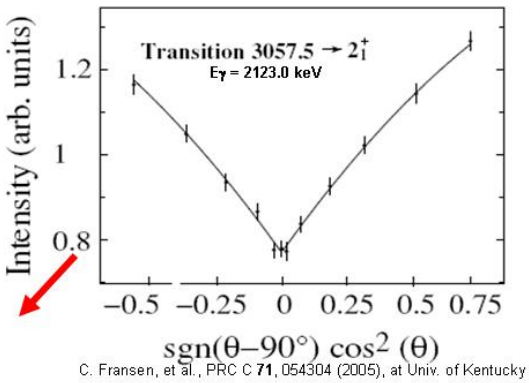
(n,n) reaction on ^{92}Zr

^{92}Zr(n,n`) reaction

12 angles and

12 hours / angle

γ-spectrometer at 1.4 m



C. Fransen, et al., PRC C **71**, 054304 (2005), at Univ. of Kentucky

Fit to data

$$W(\theta) = A_0 + A_{22}P_2(\cos\theta) + A_{44}P_4(\cos\theta)$$

Deduced $A_2 = A_{22}/A_0$

$A_4 = A_{44}/A_0$

Typical values	A2	A4
ΔJ=2 (stretched quadrupole)	+0.3	-0.1
ΔJ=1 (stretched dipole)	-0.2	0
ΔJ=1, D+Q	+0.5 to -0.8	>0

Angular distributions – mixing ratio

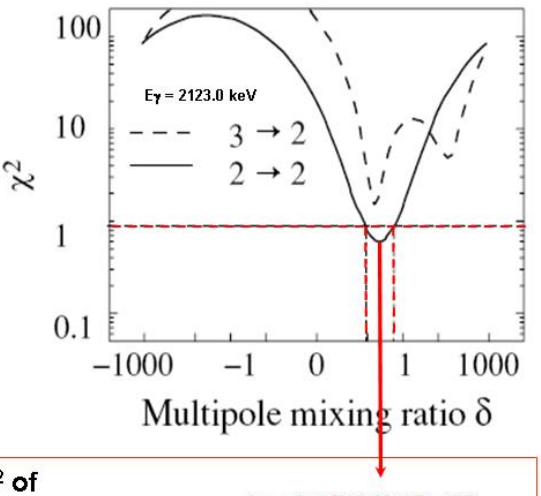
Beam defines symmetry axis

$$W(\theta) = 1 + \Sigma_{k=2,4} B_k(J_i) \times A_k^{\max}(J_i, J_f, L, \delta)$$

where $B_k(J)$ is the statistical tensor

$$B_k(J_i) = \sum_{m=-J_i}^{+J_i} (-1)^{J_i+m} \sqrt{(2k+1)(2J_i+1)} \times \begin{pmatrix} J_i & J_i & k \\ -m & m & 0 \end{pmatrix} \times \frac{Exp(-m^2/2\sigma^2)}{\sum_{m=-1}^{J_i} Exp(-m^2/2\sigma^2)}$$

Approximation with Gaussian distribution



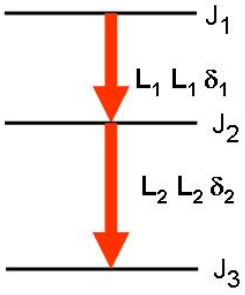
Mixing ratio, δ deduced from χ^2 of

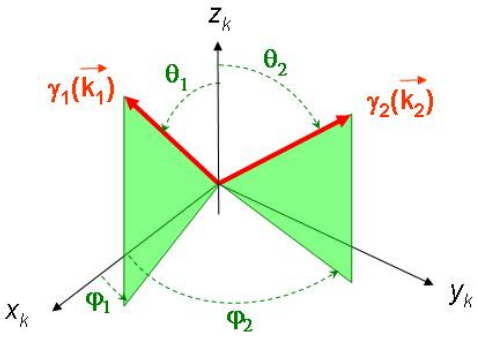
$\frac{W_{exp}(\theta)}{W_{calc}(\theta)}$ as a function of δ

δ = 0.69(16) (D+Q)

But no information on Electric or Magnetic character: E1+M2 or M1+E2

Directional Correlations from Oriented nuclei (DCO)





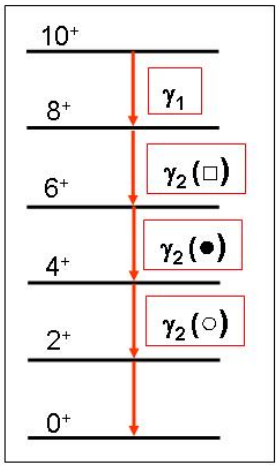
For a $J_1 \rightarrow J_2 \rightarrow J_3$ cascade *(see A.E. Stuchbery, Nucl. Phys. **A723** (2003) 69)*

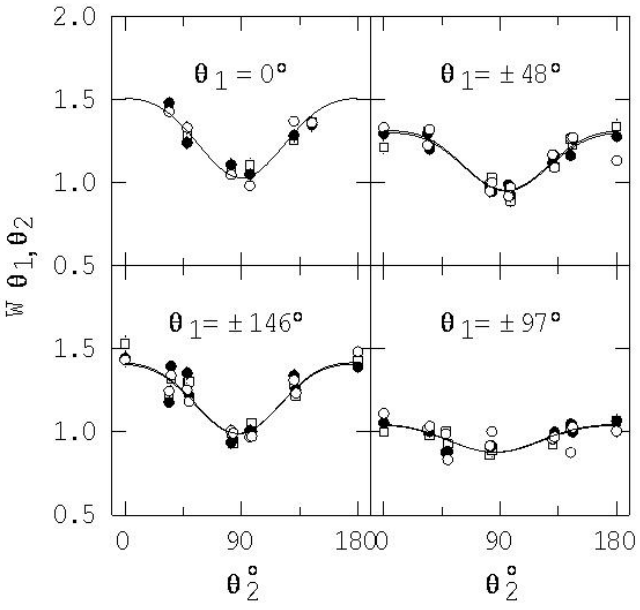
$$W(\theta_1,\varphi_1,\theta_2,\varphi_2) = \sum_{k,q,k_1,q_1,k_2,q_2} \rho_{k_1 q_1}(J_1)(-1)^{k_1+q_1}\sqrt{(2k+1)(2k_1+1)}\begin{pmatrix} k_1 & k & k_2 \\ -q_1 & q & q_2 \end{pmatrix}$$
$$\times A_k^{k_2 k_1}(\delta_{\gamma 12} LL' J_2 J_1) Q_k(E_{\gamma 12}) D^{k*}_{q0}(\varphi_1,\theta_1,0)$$
$$\times A_{k_2}(\delta_{\gamma 23} LL' J_3 J_2) Q_{k_2}(E_{\gamma 23}) D^{k_2*}_{q_2 0}(\varphi_2,\theta_2,0)$$

Directional Correlations from Oriented nuclei (DCO) example

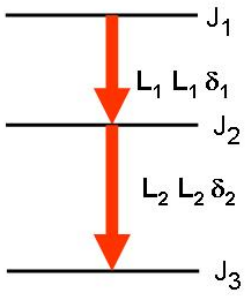
^{184}Pt from ^{nat}Gd + ^{29}Si @ 145 MeV CAESAR array (ANU)

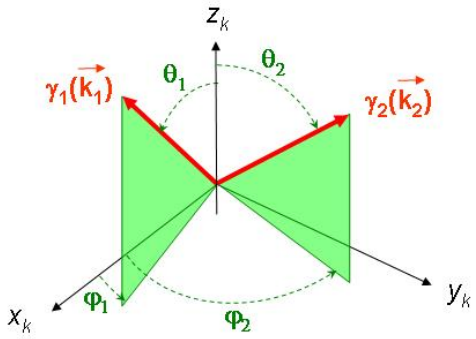
*M.P. Robinson et al., Phys. Lett **B530** (2002) 74*





Directional Correlations from Oriented nuclei
DCO ratio





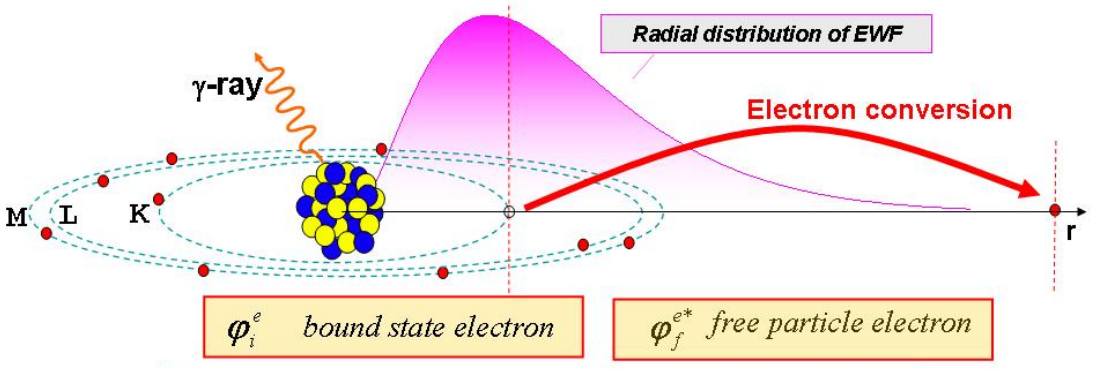
By ignoring φ dependence we get

$$DCO = \frac{W(\theta_1,\gamma_1,\theta_2,\gamma_2)}{W(\theta_1,\gamma_2,\theta_2,\gamma_1)} \approx \frac{W(\theta_1,\gamma_1)\times W(\theta_2,\gamma_2)}{W(\theta_1,\gamma_2)\times W(\theta_2,\gamma_1)}$$

For stretched transitions

	DCO
$L_1 = L_2$	1
L_1=1 and L_2=2	~2

Conversion electrons (CE)



Energetics of CE-decay (I = K, L, M,….)

$E_i = E_f + E_{ce,i} + E_{BE,i} + T_r$

γ- and CE-decays are independent; transition probability

$\lambda_T = \lambda_\gamma + \lambda_{CE} = \lambda_\gamma + \lambda_K + \lambda_L + \lambda_M$……

Conversion coefficient

$\alpha_i = \lambda_{CE,i} / \lambda_\gamma$

Physics of conversion coefficients

$$\alpha_K \equiv \frac{\lambda_{e,K}}{\lambda_\gamma}$$

$$\lambda_e = \frac{2\pi}{\mathrm{h}} |m_{fi}|^2 \frac{d\rho}{dE}$$ *Fermi's golden rule*

Density of the final electron state (continuum)

$$m_{fi} = \psi_f^{N*} \; \varphi_f^{e*} \; F_{\ell,m} \; \psi_i^N \; \varphi_i^e$$

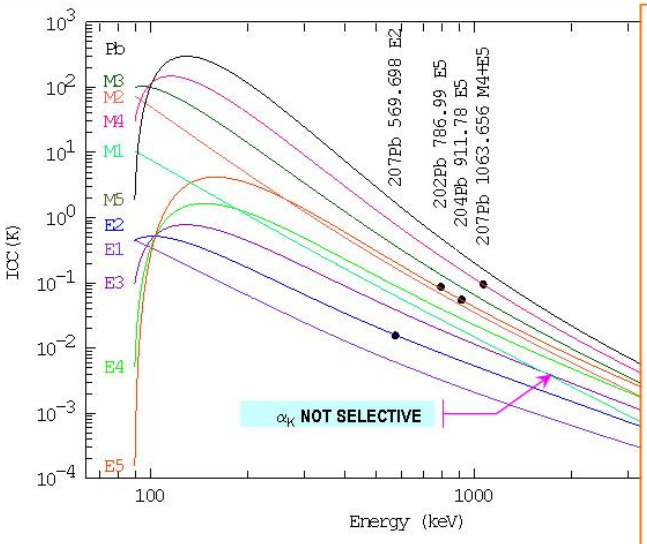
Nuclear | **Electron** | *Multipolar source*

Same for γ and CE

φ_i^e *bound state electron*

φ_f^{e*} *free particle electron*

Sensitivity to transition multipolarity



α_i depends on
1) Transition energy (Eγ)
2) Atomic number (Z)
3) Multipole order (L; angular momentum carried away)
4) Electric (Eλ) or magnetic (Mλ) character
5) Shell or subshell electron is ejected
6) Atomic screening
7) Nuclear structure effects (penetration)

NOTE (3) and (4) often referred to as multipolarity (πL)

Mixed multipolarity and E0 transitions

$$\delta^2 = \frac{I_\gamma(E2)}{I_\gamma(M1)} \qquad \alpha^{M1/E2} = \frac{\alpha_{M1} + \delta^2 \alpha_{E2}}{1+\delta^2}$$

Mixing ratio can be deduced in some cases

$$\delta^2 = \frac{\alpha_{M1} - \alpha^{exp}}{\alpha^{exp} - \alpha_{E2}}$$

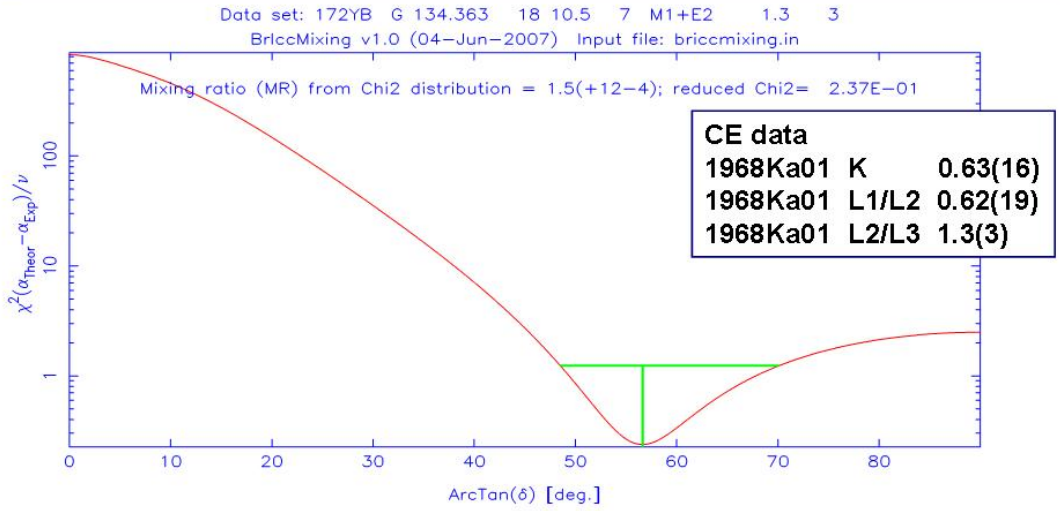
E0 transitions – pure penetration effect; no γ rays (I_γ=0)

$$\alpha = \frac{I_{CE}}{I_\gamma} = \infty$$

- Pure E0 transition: $0^+ \rightarrow 0^+$ or $0^- \rightarrow 0^-$
- J → J (J≠0) transitions can be mixed E0+E2+M1

$$\alpha = \frac{I_{CE}(E0) + I_{CE}(E2) + I_{CE}(M1)}{I_\gamma(E2) + I_\gamma(M1)}$$

134.363(18) keV M1 + E2 transition in ^{172}Yb
χ^2(MR) hypersurface

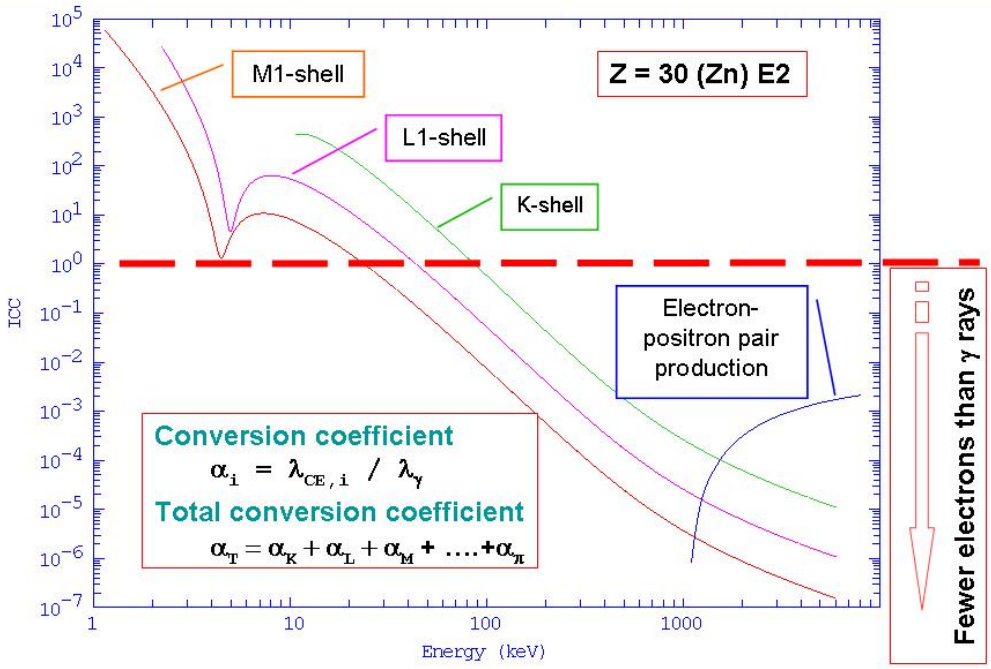


MR=1.3(3) (ENSDF)

MR=1.52(24) (Bricc mixing from Chi-squared fit)

MR=1.5(+12-4) (Bricc mixing from X^2(MR) hypersurface)

More on conversion coefficients



Measuring conversion coefficients - methods

- NPG: normalization of relative CE ($I_{CE,i}$) and γ (I_γ) intensities via intensities of one (or more) transitions with known α

$$\alpha_i = \frac{I_{CE,i}}{I_\gamma} \times \left[\frac{I^*_\gamma}{I^*_{CE}} \times \alpha^* \right]_{KNOWN}$$

- CEL: Coulomb excitation and lifetime measurement

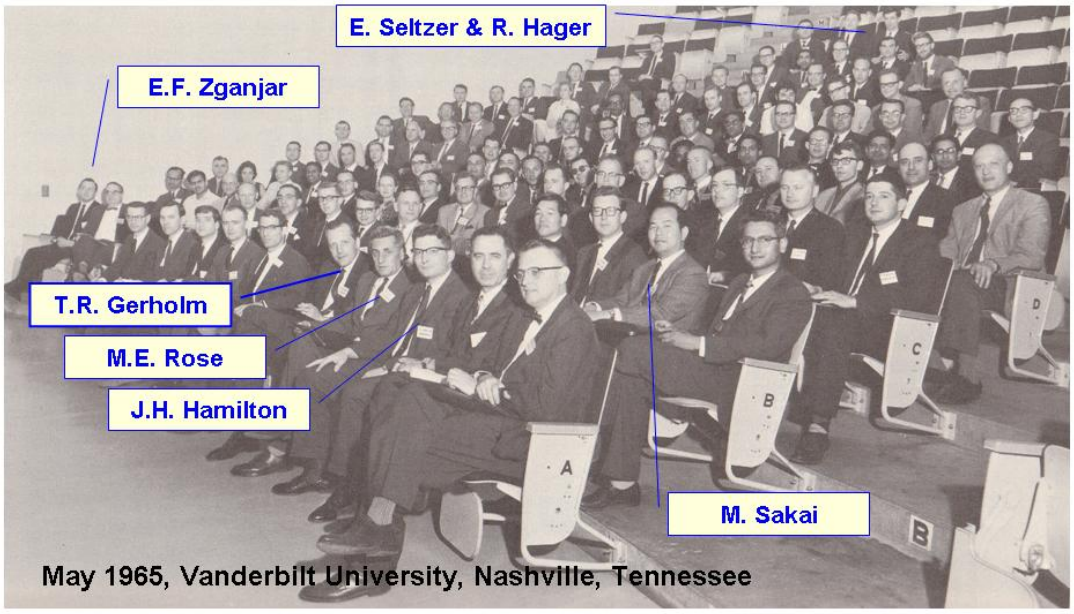
$$\alpha_T = \frac{2.829 \times 10^{11} \times E_\gamma^{-5}(keV)}{B(E2)\uparrow(e^2b^2) \times T_{1/2}(ns)} - 1$$

- XPG: intensity ratio of K X-rays to γ rays with K-fluorescent yield, ω_K

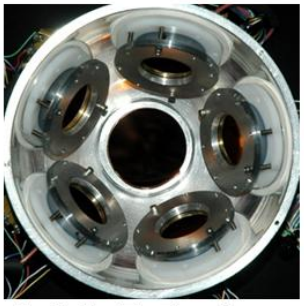
$$\alpha_K = \frac{I_{KX}}{I_\gamma} \times \frac{1}{\omega_K}$$

And many more, see Hamilton`s book

Internal conversion process – the pioneers



Conversion electron spectroscopy with PACES

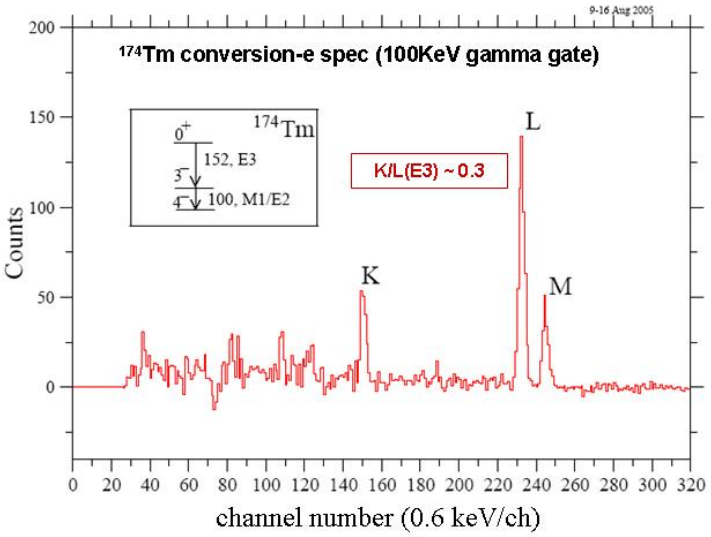


Built by E. Zganjar, LSU

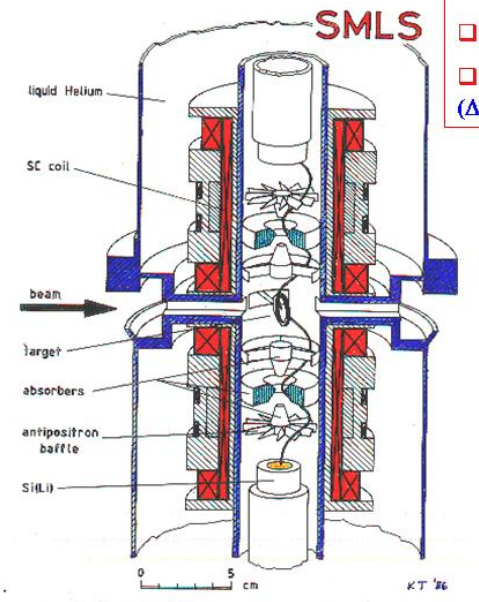
Figure courtesy of P.M. Walker (Surrey) and P. Garrett (Guelph)

Based on new data, favoured interpretation is that isomer is not a high-K, but $K^{\pi}=0^{+}$

Electrons are vital!



Magnetic spectrometers



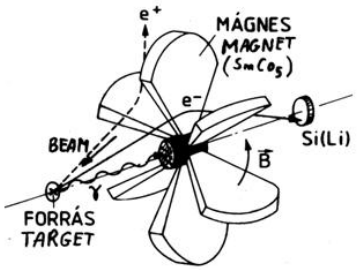
Superconducting solenoid

- **Broad-range mode – 100 keV up to a few MeV**
- **Lens mode – finite transmitted momentum bandwidth (Δp/p~15-25%) – high peak-to-background ratio**

Mini-orange (looks like a peeled orange)

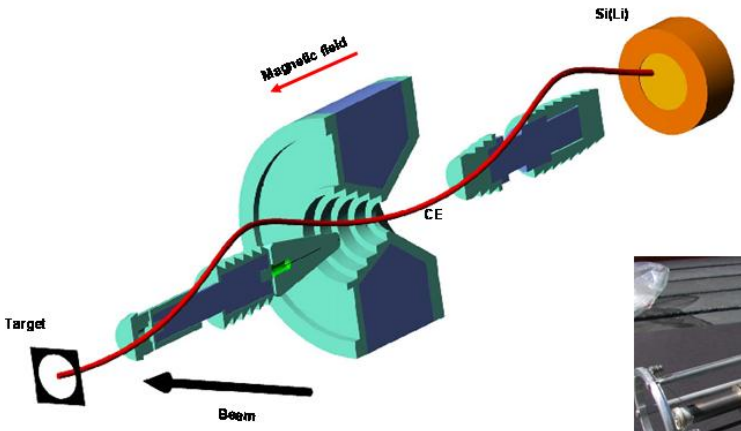
- **transmission > 20%**
- **small size and portability, but poorer quality**

ATOMKI, Debrecen



Super-e Lens (ANU)

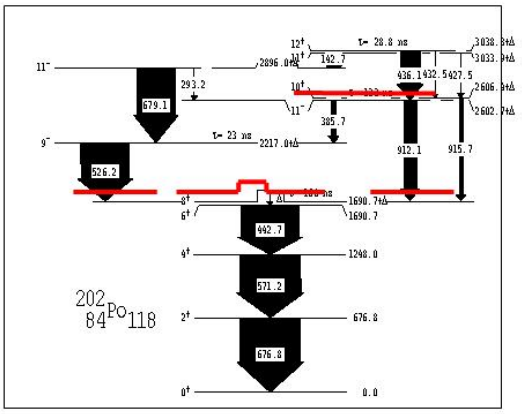
The Australian National University

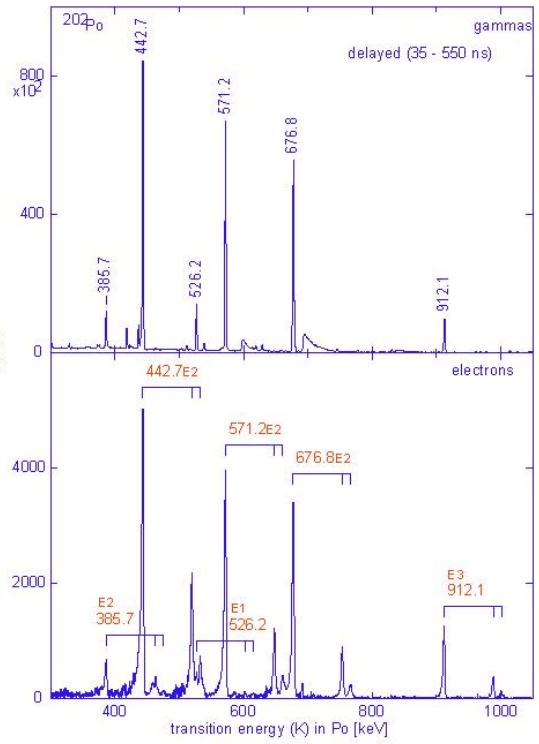


Super-e Lens (ANU)

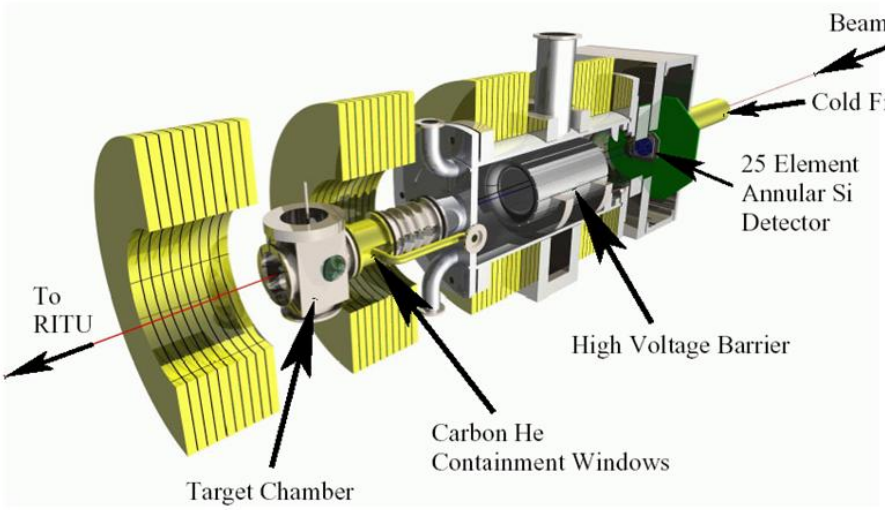
$^{194}Pt(^{12}C,4n)^{202}Po$ @ 76 MeV

Pulsed beams (~1 ns) with 1.7 μs separation



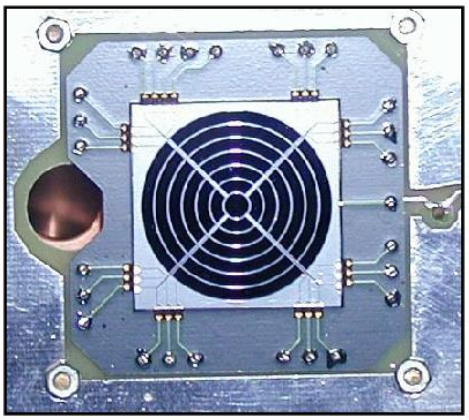


SACRED Electron Spectrometer (Liverpool-JYFL)



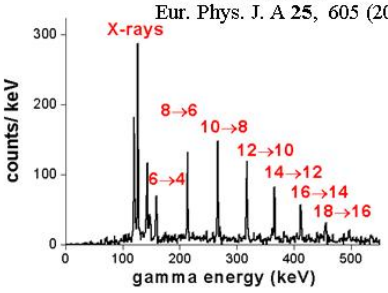
H. Kankaanpää et al., NIM A534 (2004) 503
see also P.A. Butler et al., NIM A381 (1996) 433

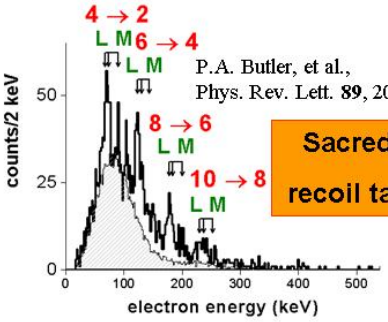
SACRED array example



$^{208}Pb(^{48}Ca,2n)^{254}No$

S. Eeckhaudt, et al.,
Eur. Phys. J. A **25**, 605 (2005)

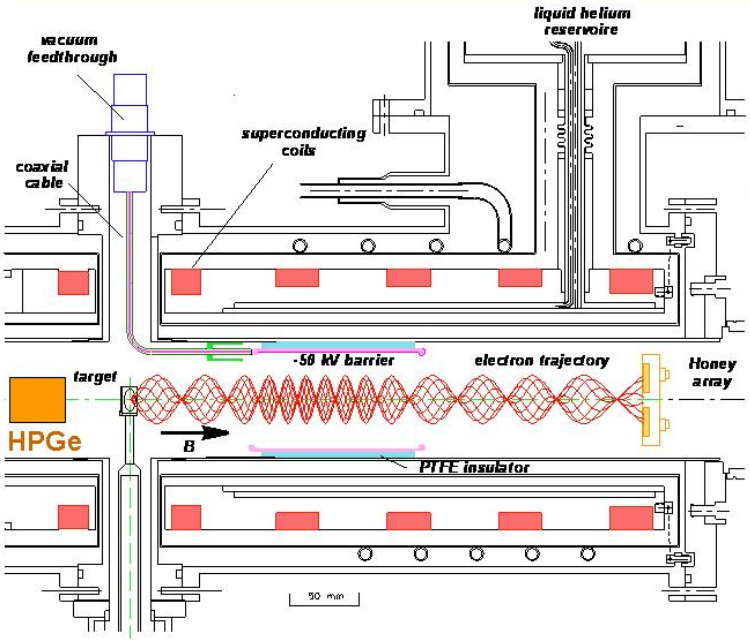




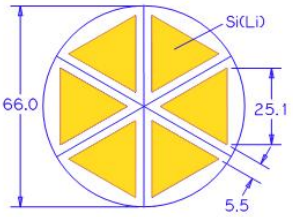
P.A. Butler, et al.,
Phys. Rev. Lett. **89**, 202501 (2002)

Sacred + RITU recoil tagged CE

Super-e Honey (ANU)



Electrons from atomic collisions are the major difficulty in low energy CE spectroscopy using ion induced reactions



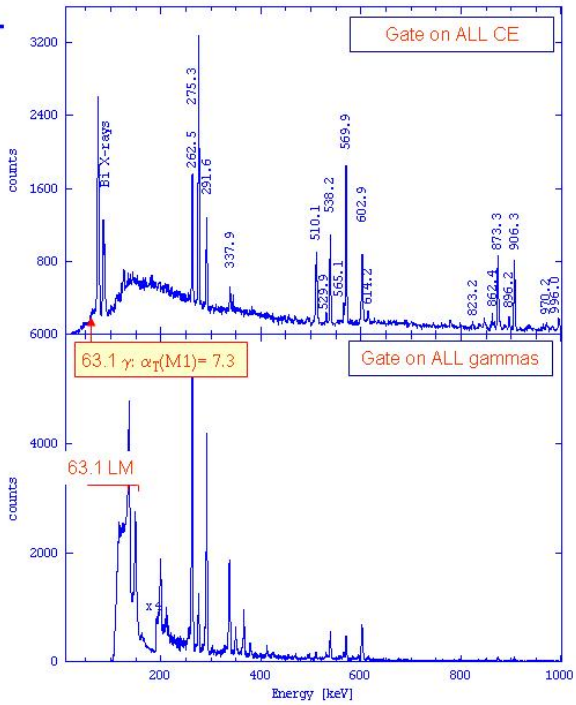
Super-e Honey (ANU)
eeγ coincidences

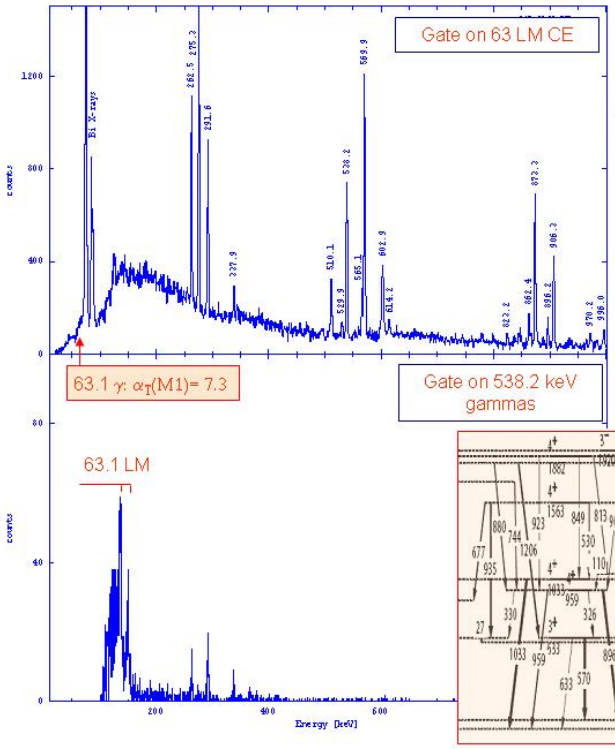
E_γ = 63.1 keV transition not visible in the gamma spectrum

$\alpha_T(M1)$ = 7.3!

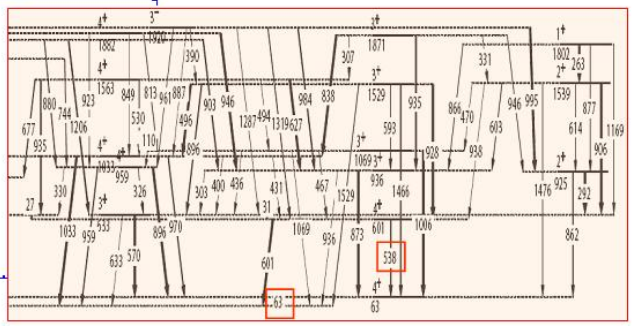
K-shell conversion not allowed
BE_K = 90.5 keV

$^{208}Pb(p,n)^{208}Bi$ @ 9 MeV
K.H. Maier et al,
Phys. Rev. **C 76**, 064304 (2007)





Super-e Honey (ANU)
eeγ coincidences

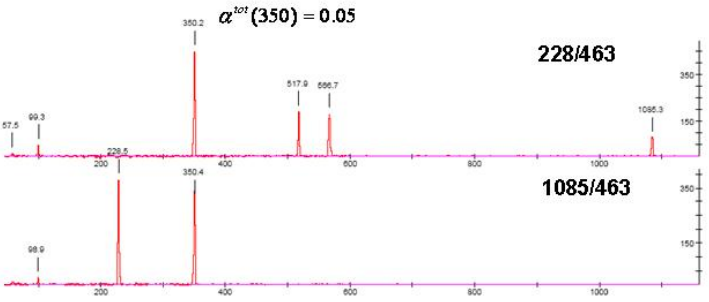


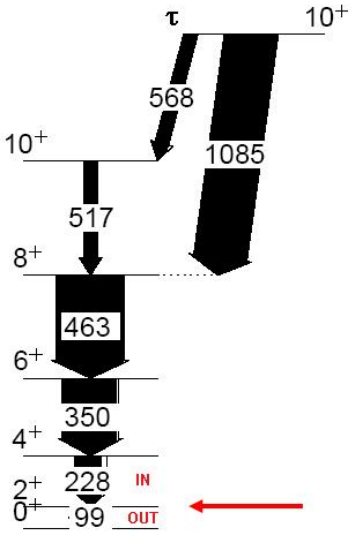
ICC from total intensity balances – example 1

Out-of-beam (or decay) coincidence data

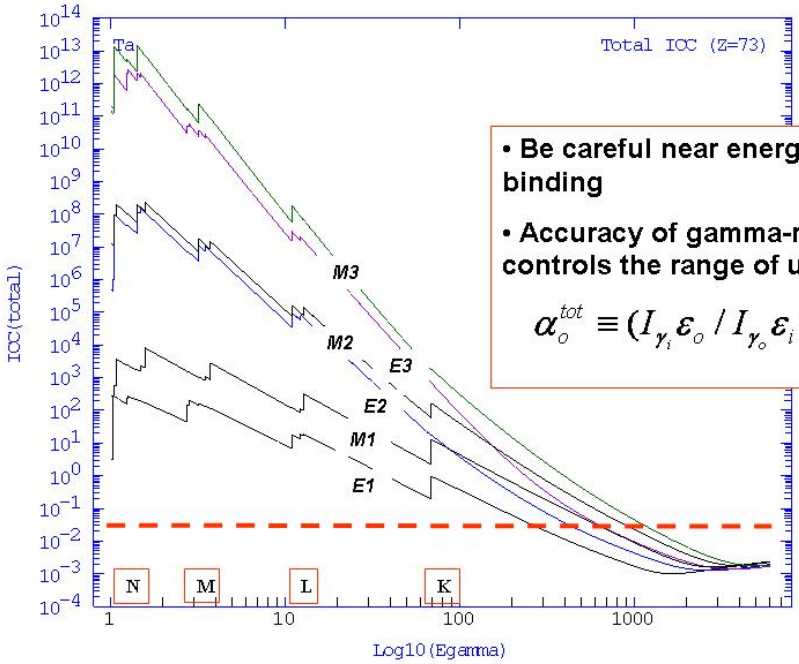
$$I_{\gamma_i}^{tot} = I_{\gamma_i} \times (1 + \alpha_i^{tot}) \equiv I_{\gamma_o}^{tot} = I_{\gamma_o} \times (1 + \alpha_o^{tot})$$

$$\alpha_o^{tot} \equiv (I_{\gamma_i} \varepsilon_o / I_{\gamma_o} \varepsilon_i) \times (1 + \alpha_i^{tot}) - 1$$





ICC from total intensity balances – when to use



- Be careful near energies close to shell binding
- Accuracy of gamma-ray measurements controls the range of use

$$\alpha_o^{tot} \equiv (I_{\gamma_i} \varepsilon_o / I_{\gamma_o} \varepsilon_i) \times (1 + \alpha_i^{tot}) - 1$$

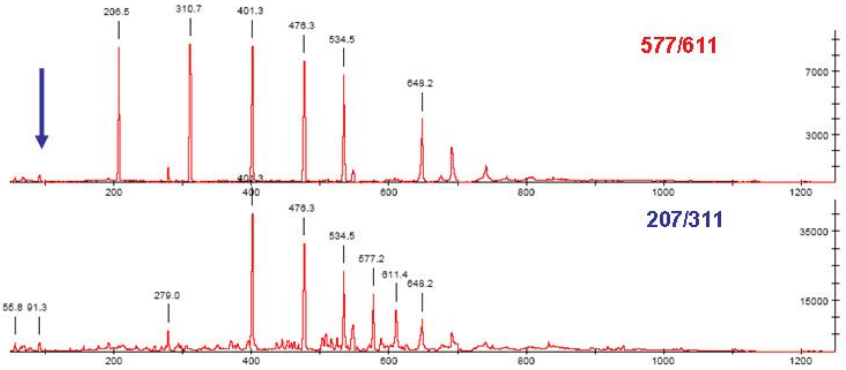
$\delta I_\gamma / I_\gamma \sim 10\%$

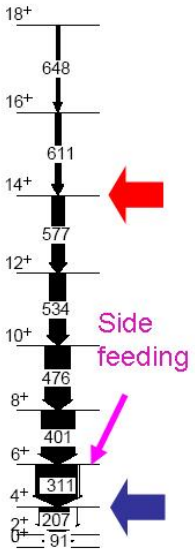
ICC from total intensity balances – example 2

In-beam: only when gating from "above"

$$I_{\gamma_i}^{tot} = I_{\gamma_i} \times (1 + \alpha_i^{tot}) \equiv I_{\gamma_o}^{tot} = I_{\gamma_o} \times (1 + \alpha_o^{tot})$$

$$I_{\gamma_i}^{tot} = I_{\gamma_o}^{tot} + I_{sf}$$



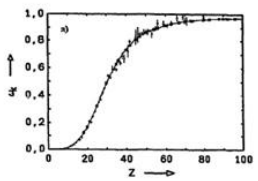


ICC from X- and γ-ray intensities

The Australian National University

Vacancies in the atomic shell give rise to rearrangements in the shells which are accompanied by the emission of

- X-rays
- Auger electrons



K x-rays:

K_α (K-L shells)

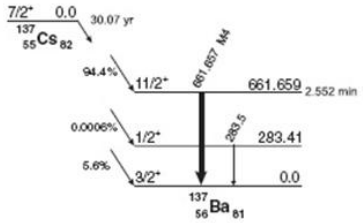
Kb (K-M, K-MN, etc. shells)

$$I_{KX} = I_K \times \omega_K$$

B Schönfeld and h. Janssen, Nucl. Instr. and Meth. in Phys. Res. A 369 (1996) 527.

ICC from X- and γ-ray intensities

The Australian National University

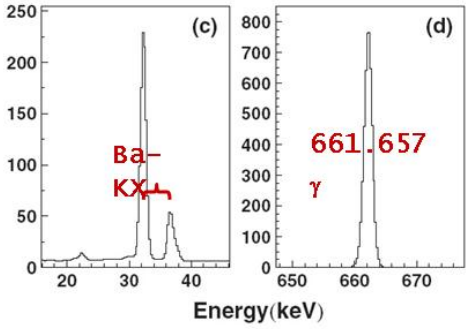


N. Nica, et al. Phys. Rev. C75 (2007) 024308

Singles gamma measurement

- No other photon and/or contaminates
- Well calibrated spectrometer
- Correct treatment of the photon attenuation, scattering, etc.
- Knowledge of the fluorescence yield

$$\alpha_K \omega_K = \frac{N_{KX}}{N_\gamma} \times \frac{\varepsilon_\gamma}{\varepsilon_{KX}}$$



Acknowledgements

G.D. Dracoulis , G.J. Lane, P. Nieminen, H. Maier (*ANU*)

F.G. Kondev (*ANL*)

P.E. Garrett (*University of Guelph and TRIUMF)*

S.W. Yates (University of Kentucky)

Experimental Nuclear Structure Physics:

New Developments in Characterizing Nuclei far from Stability

T. Kibédi

Australian National University, Australia

E-mail: Tibor.Kibedi@anu.edu.au

The Australian National University

New developments in characterizing nuclei far from stability

Joint ICTP-IAEA Workshop on
Nuclear Structure and Decay Data Theory and Evaluation
28 April - 9 May 2008

Tibor Kibédi

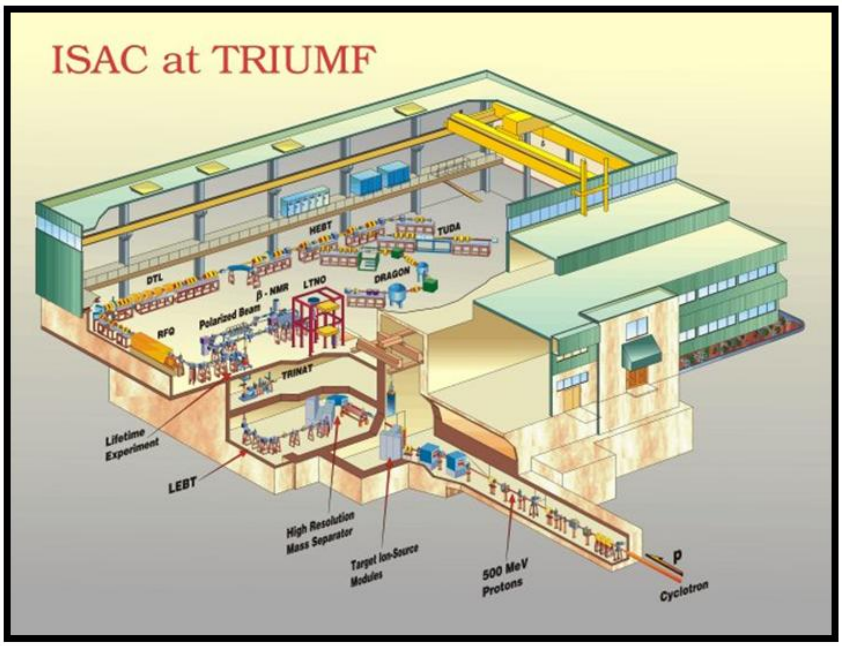
The Australian National University

Outline:

TRIUMF-ISAC

- **Heavy Element Spectroscopy at JYFL**
- **New compact recoil separator at the ANU**
- **Future – radioactive beam facilities**

The Australian National University



8π spectrometer

8π spectrometer at ISAC

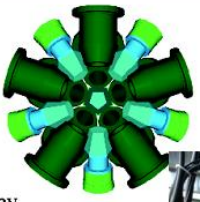
20 Compton-suppressed HPGe detectors

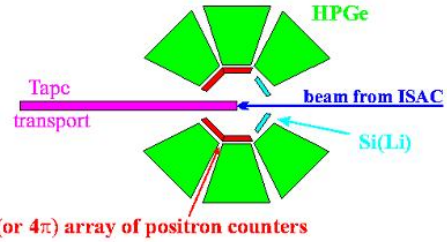
And 10 BaF_2 detectors for γ-ray detection

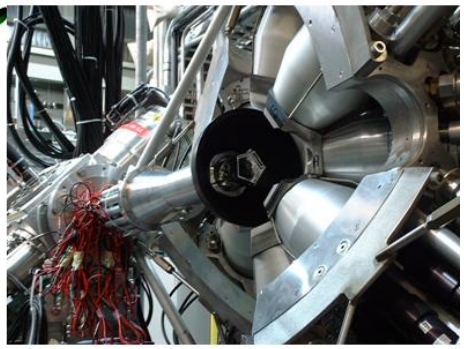
20 plastic scintillators for β detection

5 Si(Li) detectors for conversion electron spectroscopy

Fast, in-vacuum tape transport system





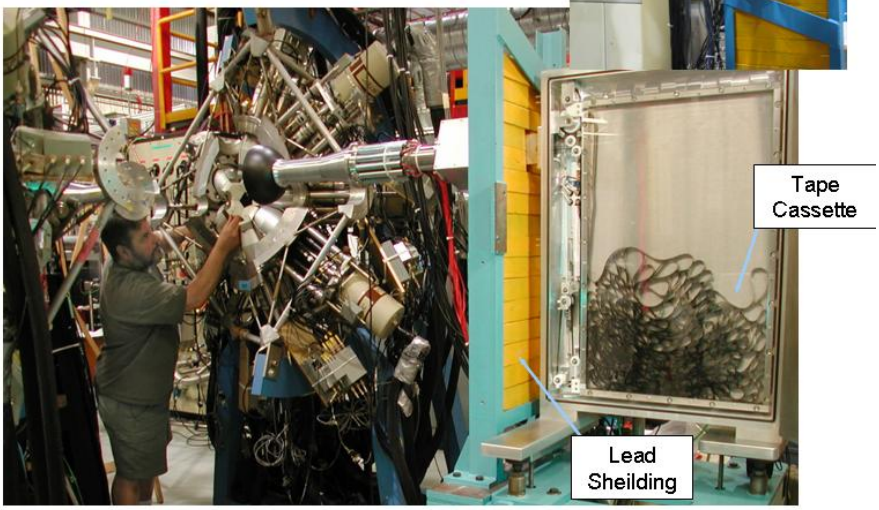


Trigger rate of ~30 kHz; data transfer 5 MB/s

The 8π spectrometer is a unique device for this type of study. Simultaneous collection of γ-singles, γγ coincidences, β tagging, conversion electrons, and lifetime measurements

Moving tape collector for transport of activity

- Beam implanted on to a moving tape
- Allows for movement of long-lived activity out of focus of spectrometer
- Beam collection time variable (down to ~ 10 ms)
- Tape speeds, dwell times, etc., variable



Built by

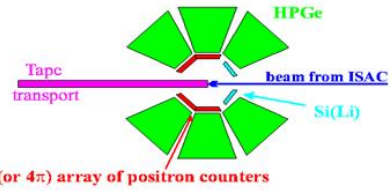
E. Zganjar, LSU

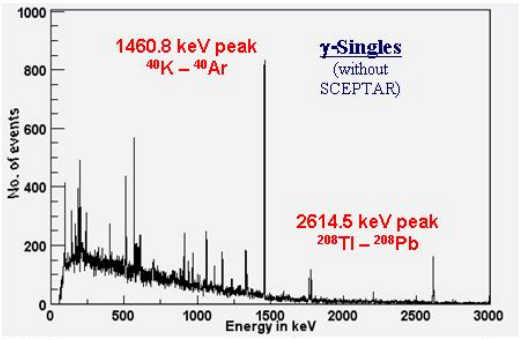
^{32}Na decay

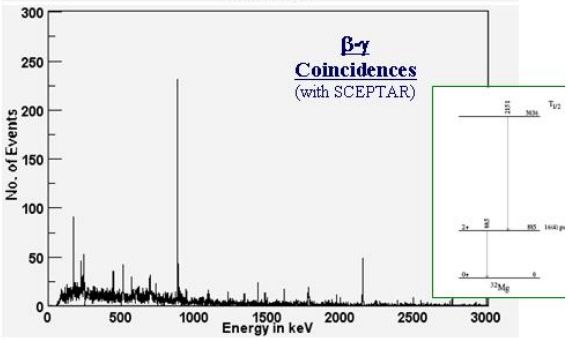
^{32}Na decay investigated as a means to study the excited nuclear states of ^{32}Mg (Z=12, N=20)

- **Investigate the breakdown of shell closures far from stability**
- **β-γ coincidences measured with 8π and SCEPTAR**
- **Reduce background and allow weak ^{32}Na decay spectrum to be measured (^{32}Na beam rate at ~2 ions/s)**
- **Beam production with Ta target insufficient for detailed study, but expect boost of 2-3 orders of magnitude with actinide target**

C. M. Mattoon, et al., Phys. Rev. C75, 017302 (2007)

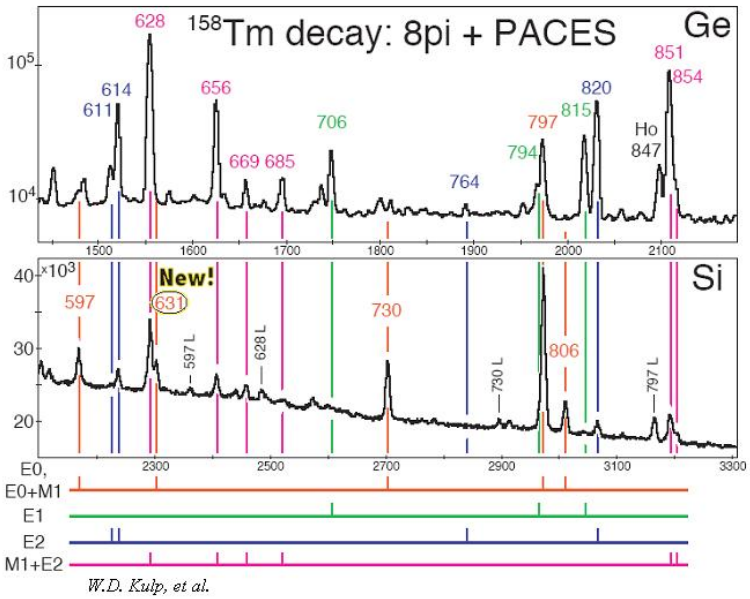


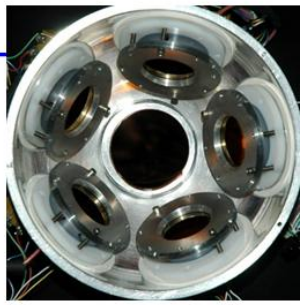




Preliminary experiment on ^{158}Er

The Australian National University

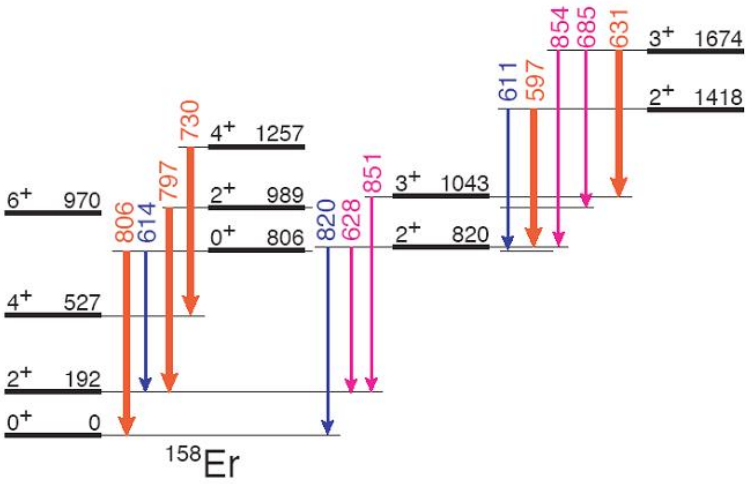




Data are for 1/3 of the sample, 1 detector

Enhanced E0 transitions observed

E0 transitions: mixing between co-existing shapes of different deformation



RITU

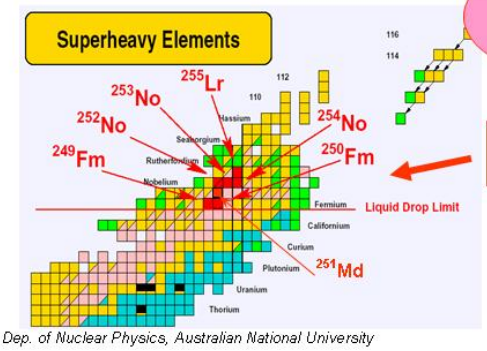
Next predicted closed shells

Nilsson/Woods Saxon:
Z = … 50, 82, *114*
N =… 50, 82, 126, *184*

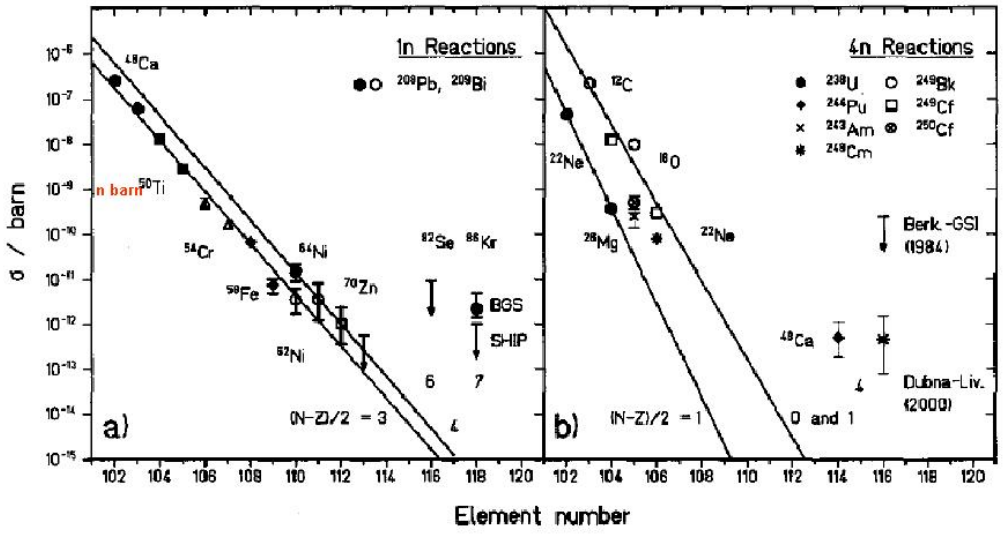
Skyrme-Hartree-Fock:
Z = … 50, 82, *126*
N = … 50, 82, 126, *184*

Relativistic mean-field:
Z = … 50, 82, *120*
N = … 50, 82, 126, *172*

Not accessible yet

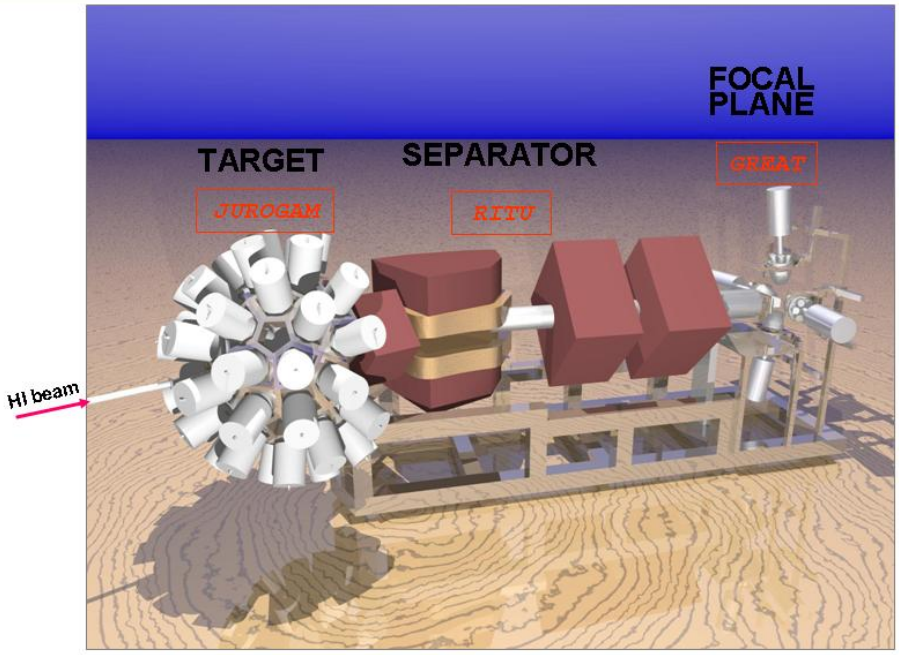


New spectroscopic data can be used to improve predictions



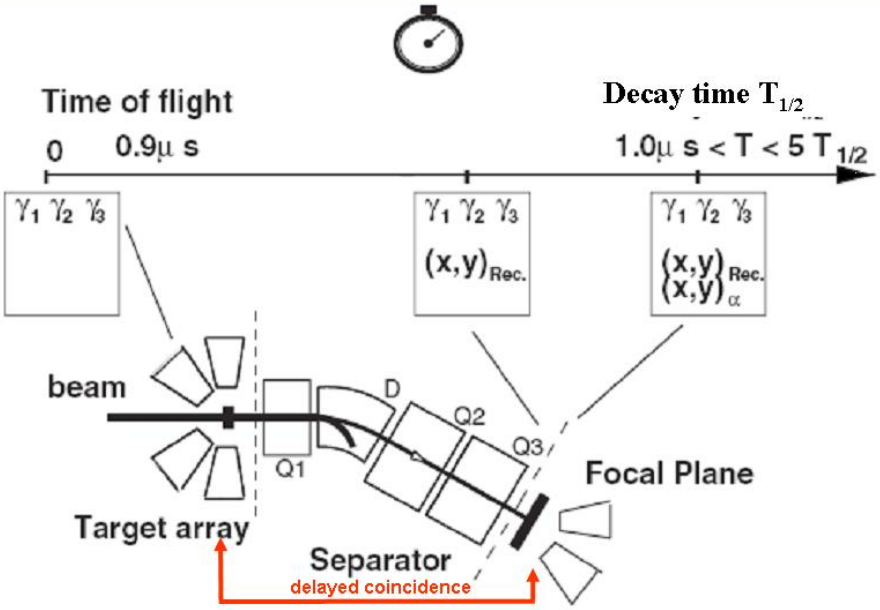
S. Hofmann / Prog. Part. Nucl. Phys. 46 (2001) 293.

RITU + JUROGAM + GREAT



Recoil Decay Tagging (RDT)

The Australian National University



R-D Herzberg, J. Phys. G 30 (2004) R123.

JuroGam

43 Phase I and GASP-type detectors – Ex. EUROBALL and UK-France loan pool

Efficiency ~ 4.2% @ 1.3 MeV

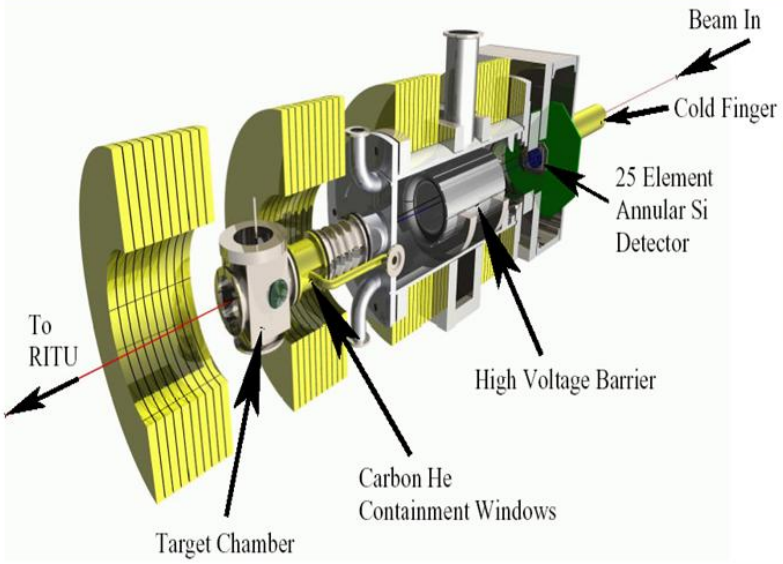
TDR data acquisition system – data rate ~ 5 MB/s @ 10 kHz

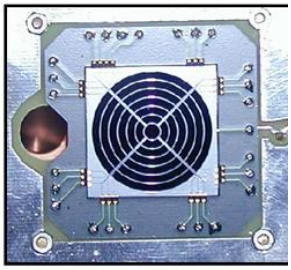
Software BGO suppression

Auto fill system built by University of York, part of GREAT Project

Online/offline sorting – Grain developed by P. Rahkila

ANU *SACRED Electron Spectrometer*





THE UNIVERSITY of LIVERPOOL

UNIVERSITY OF JYVÄSKYLÄ

*H. Kankaanpää, et al., Nucl. Instrum. Meth. Phys. Res .**A534** (2004) 503*
*see also P.A. Butler, et al., Nucl. Instrum. Meth. Phys. Res. **A381** (1996) 433*

SACRED

Z = 102

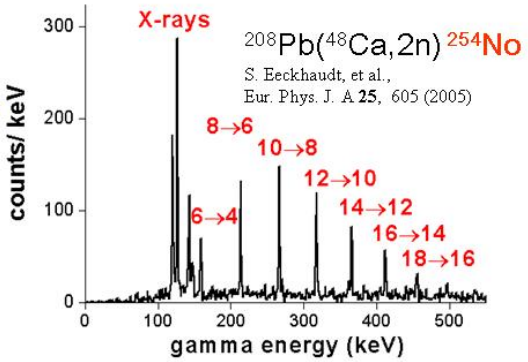
BE_K = 149.2 keV!

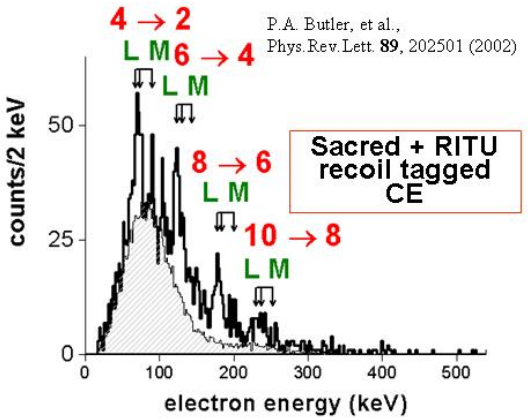
Lowest transitions are fully converted

	E_γ (keV)	α_K(E2)	α_L(E2)	α_T(E2)
$2^+ \rightarrow 0^+$(*)	44(1)	N/A	1100	1540
$4^+ \rightarrow 2^+$(*)	102(1)	N/A	20.6	28.8
$6^+ \rightarrow 4^+$	159.5(2)	0.108	2.74	3.93
$8^+ \rightarrow 6^+$	214.1(1)	0.122	0.772	1.20

(*) transition not seen; from extrapolation using the Harris formulae

Figure courtesy of P. Greenlees





Collective nuclear properties

Dynamic Moments of Inertia

$$\mathcal{J}^{(2)} = \frac{4\hbar^2}{E_\gamma(I) - E_\gamma(I-2)}$$

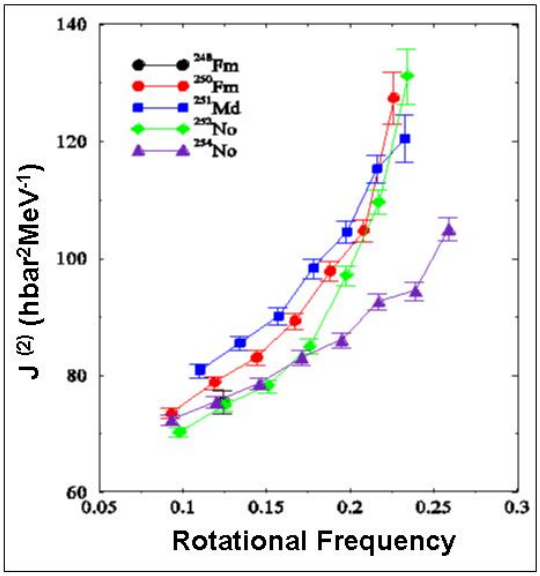
^{250}Fm
Experiment: J.E. Bastin et al.,
Phys. Rev. C73 (2006) 024308

$B\uparrow(E2;2^+ \rightarrow 0^+) = 17.9(23)\quad e^2b^2$

β_2 = 0.28(2)

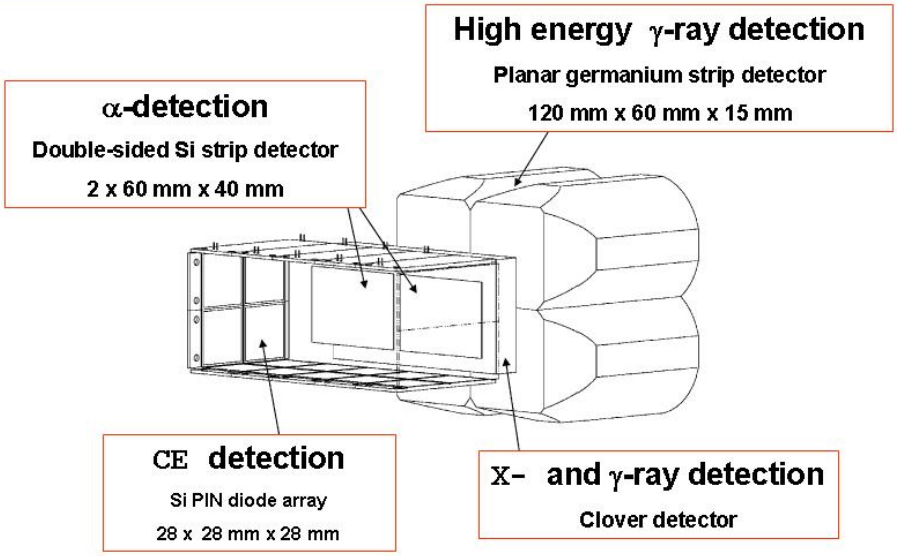
Raman, et al.,
Atomic Data and Nuclear Data Tables **78,** 1–128 (2001)
GLOBAL FIT to data:

$B\uparrow(E2;2^+ \rightarrow 0^+) = 14.7(31)\quad e^2b^2$



Courtesy of P. Greenlees

GREAT Spectrometer



Total Data Readout (TDR) Acquisiton System

R.D. Page, et al.,
Nucl. Instrum.Meth.Phys.Res. ***B 204*** *(2003) 634.*

New compact recoil separator at ANU

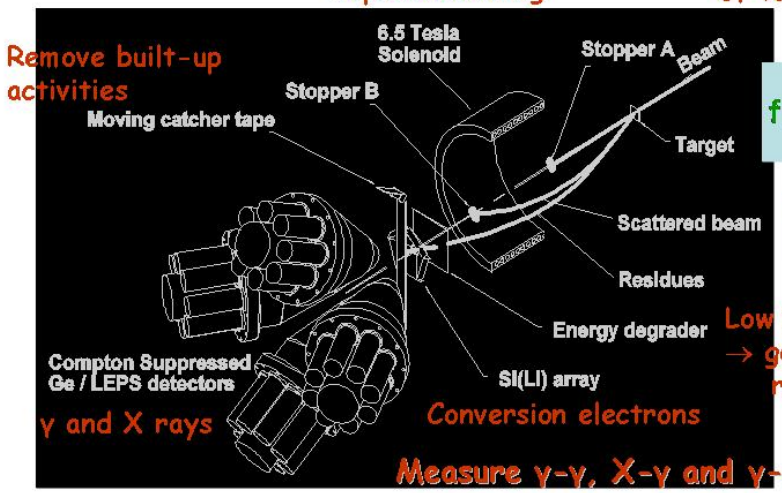
Australian Research Council Discovery Grant and
ANU Major Equipment Grant

with G.J. Lane, G.D. Dracoulis, P. Nieminen, D.J. Hinde and N. Dasgupta

System design

Gas-filled, superconducting

Gas window in front of target



Remove built-up activities

$$f = \frac{2\pi m_p v_z \cos(\theta_{lab})}{qB_z}$$

q : average charge state in gas

Low implantation depth → good electron resolution

Measure γ-γ, X-γ and γ-e coincidences

* No recoil detector in use during experiments, possibly a removable array of solar cell detectors for image size measurements during setup

First experiment in April 2008

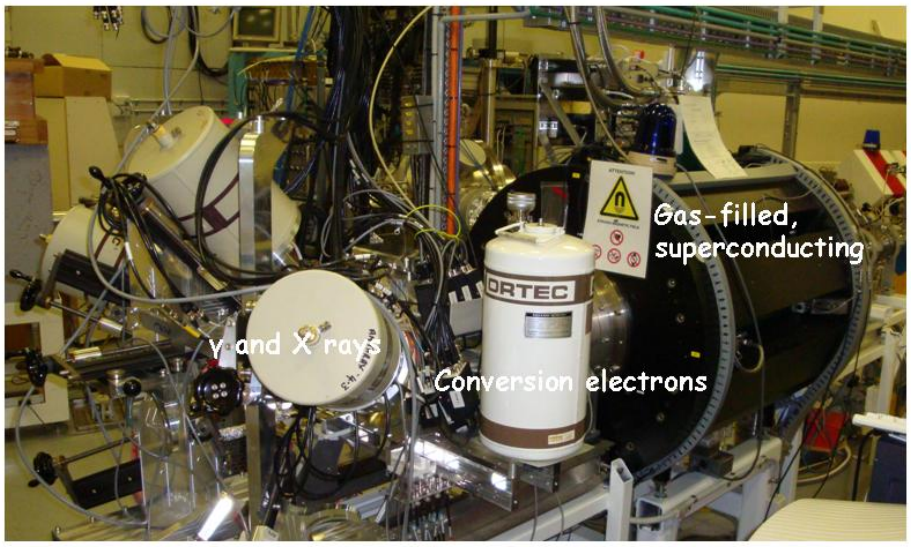
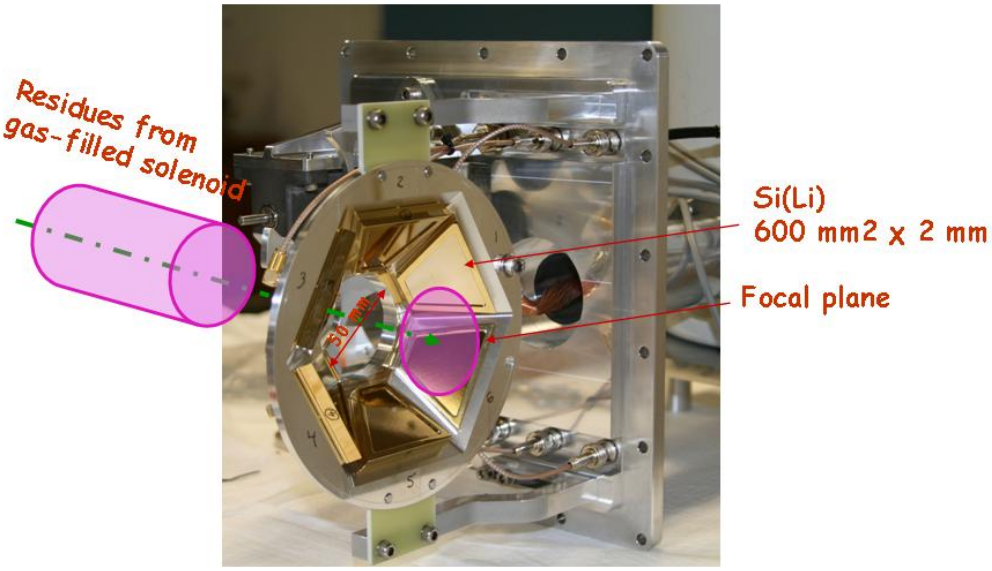


Photo courtesy of P. Nieminen

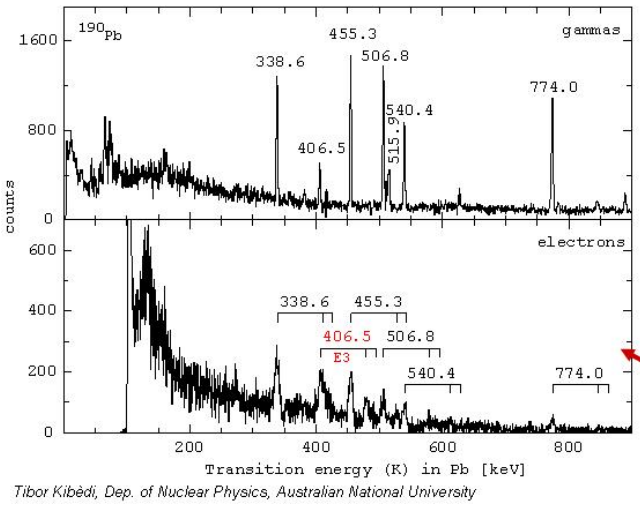
Hexa-e Si(Li) array for conversion electron spectroscopy

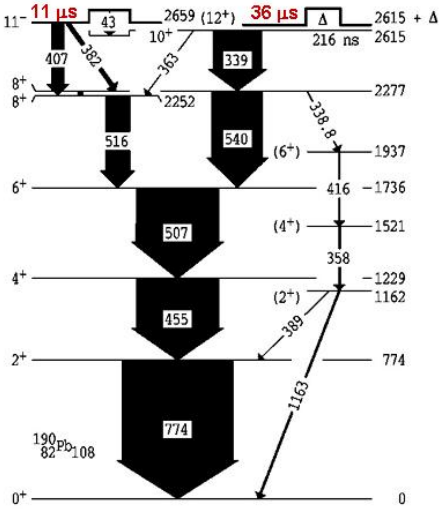


Isomers in ^{190}Pb

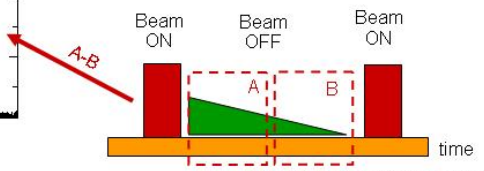
$^{166}Er(^{28}Si,4n)^{190}Pb$ @140 MeV; 500 $\mu g/cm^2$ target

6.5 Tesla; 1 Torr He + N_2 gas





G.D. Dracoulis, et al., Phys. Rev. **C63** (2001) 061302



6.

Statistical Analyses

Evaluation of Discrepant Data I

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IAEA Workshop

Nuclear Structure and Decay Data

Evaluation of Discrepant Data I

Desmond MacMahon

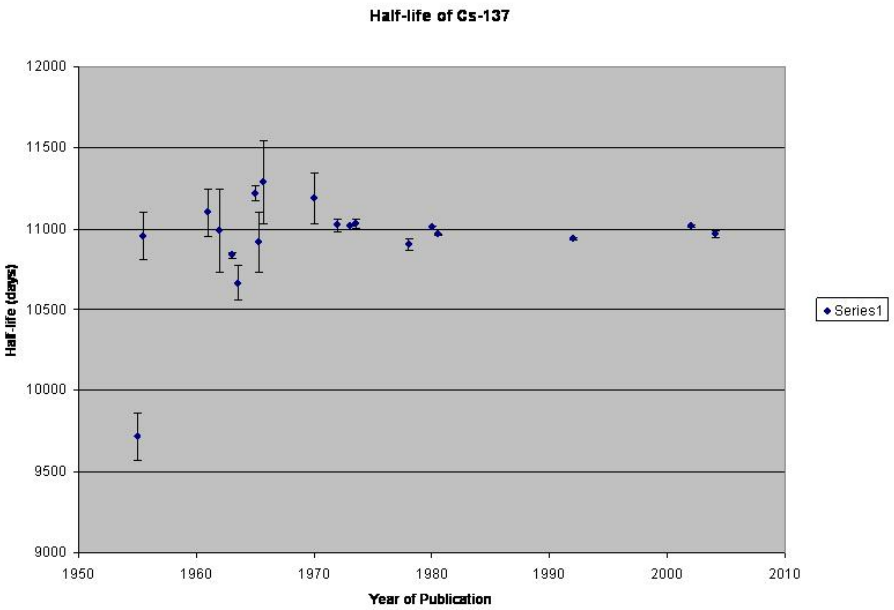
United Kingdom

Evaluation of Discrepant Data

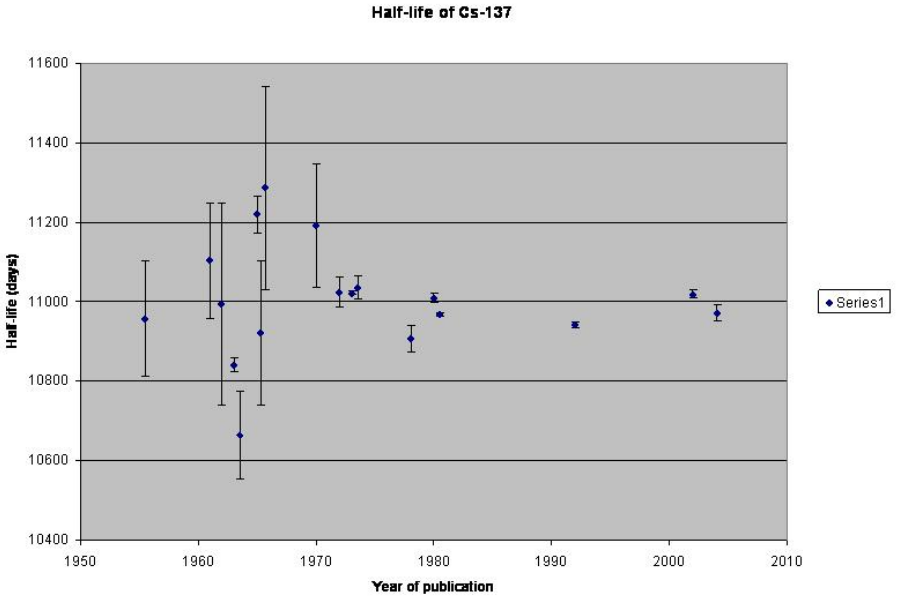
- What is the half-life of ^{137}Cs?
- What is its uncertainty?
- Look at the published data from experimental measurements:

Measured half-lives of Cs-137

Authors		Measured half-lives	
		in days	
		$t_{1/2}$	σ
Wiles & Tomlinson (1955a)		9715	146
Brown et al. (1955)		10957	146
Farrar et al. (1961)		11103	146
Fleishman et al. (1962)		10994	256
Gorbics et al. (1963)		10840	18
Rider et al. (1963)		10665	110
Lewis et al. (1965)		11220	47
Flynn et al. (1965)		10921	183
Flynn et al. (1965)		11286	256
Harbottle (1970)		11191	157
Emery et al. (1972)		11023	37
Dietz & Pachucki (1973)		11020.8	4.1
Corbett (1973)		11034	29
Gries & Steyn (1978)		10906	33
Houtermans et al. (1980)		11009	11
Martin & Taylor (1980)		10967.8	4.5
Gostely (1992)		10940.8	6.9
Unterweger (2002)		11018.3	9.5
Schrader (2004)		10970	20



ICTP May 2008



Evaluation of Discrepant Data

- The measured data range from 9715 days to 11286 days.
- What value are we going to use for practical applications?
- The simplest procedure is to take the unweighted mean: x
- If x_i, for i = 1 to N, are the individual values of the half-life, then the unweighted mean, x_u, and standard deviation, σ_u, are given by:

The Unweighted Mean

$$x_u = \frac{\sum x_i}{N}$$

$$\sigma_u = \sqrt{\frac{\sum (x_i - x_u)^2}{N(N-1)}}$$

The Unweighted Mean

- This gives the result: 10936 ± 75 days
- However, the unweighted mean is influenced by outliers in the data, in particular the first, low value of 9715 days
- Secondly, the unweighted mean takes no account of the fact that different authors made measurements of different precision, so we have lost some of the information content of the listed data

The Weighted Mean

- We can take into account the authors' quoted uncertainties, σ_i (i = 1 to N), by weighting each value, using weights w_i, to give the weighted mean, x_w

$$w_i = \frac{1}{\sigma_i^2}$$

$$x_w = \frac{\sum x_i w_i}{\sum w_i}$$

The Weighted Mean

- The standard deviation of the weighted mean, σ_w, is given by:

$$\sigma_w = \sqrt{\frac{1}{\sum w_i}}$$

- And for the half-life of Cs-137 the result is 10988 ± 3 days

The Weighted Mean

- This result has a small uncertainty, but how do we know how reliable this value is?
- How do we know that all the data are consistent?
- We can look at the deviations of the individual data from the mean, compared to their individual uncertainties
- We can define a quantity 'chi-squared'

$$\chi_i^2 = \frac{(x_i - x_w)^2}{\sigma_i^2}$$

The Weighted Mean

- We can also define a 'total chi-squared'

$$\chi^2 = \sum_i \chi_i^2$$

- In an ideal consistent data set, the 'total chi-squared' should be equal to the number of degrees of freedom, i.e. to the number of data points minus one

The Weighted Mean

- So, we can define a 'reduced chi-squared':

$$\chi^2_R = \frac{\chi^2}{N-1}$$

- which should be close to unity for a consistent data set.

The Weighted Mean

- For the Cs-137 data which we have considered, the 'reduced chi-squared' is 18.6, indicating significant inconsistencies in the data
- Let us look at the data again
- Can we identify the more discrepant data?

Measured half-lives of Cs-137

Authors		Measured half-lives	
		in days	
		$t_{1/2}$	σ
Wiles & Tomlinson (1955a)		9715	146
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Unterweger (2002)		11018.3	9.5
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The Weighted Mean

- The highlighted values are the more discrepant ones
- Which means that their values are far from the mean and their uncertainties are small
- Clearly, in cases such as the Cs-137 half-life, the uncertainty, σ_W, ascribed to the weighted mean, is much too small
- One way of taking into account the inconsistencies is to multiply the uncertainty of the weighted mean by the Birge ratio:

The Weighted Mean

- The Birge Ratio

$$\sqrt{\frac{\chi^2}{N-1}} = \sqrt{\chi_R^2}$$

- In the case of Cs-137, this would increase the uncertainty of the weighted mean from 3 days to 13 days, which would be more realistic

The Limitation of Relative Statistical Weights (LRSW)

- This procedure has been adopted by the IAEA in the Coordinated Research Project on X- and gamma-ray standards
- A Relative Statistical Weight is defined as $\frac{w_i}{\sum w_i}$
- If the most precise value in a data set (the value with the smallest uncertainty) has a relative weight greater than 0.5, the uncertainty of this value is increased until its relative weight has dropped to 0.5

The Limitation of Relative Statistical Weights (LRSW)

- This avoids any single value having too much influence in determining the weighted mean
- (In the case of Cs-137, there is no such value)
- The LRSW procedure then compares the unweighted mean with the new weighted mean. If they overlap, i.e.

$$\left|x_u - x_w\right| \leq \sigma_u + \sigma_w$$

then the weighted mean is the adopted value.

The Limitation of Relative Statistical Weights (LRSW)

- If the weighted mean and the unweighted mean do not overlap in the above sense, the data are inconsistent, and the unweighted mean is adopted

- Whichever mean is adopted, the uncertainty is increased, if necessary, to cover the most precise value in the data set

The Limitation of Relative Statistical Weights (LRSW)

- In the case of Cs-137:
- Unweighted Mean: 10936 ± 75 days
- Weighted Mean: 10988 ± 3 days
- The two means do overlap so the weighted mean is adopted
- The most precise value in the data set is that of Dietz & Pachucki (1973): 11020.8 ± 4.1 days
- The uncertainty in the weighted mean is therefore increased to 33 days: 10988 ± 33 days

The Median

- Individual values in a data set are listed in order of magnitude
- If there is an odd number of values, the middle value is the median
- If there is an even number of values, the median is the average of the two middle values
- The median has the advantage that it is very insensitive to outliers

The Median

- We now need some way of attributing an uncertainty to the median
- For this we first have to determine a quantity 'the median of the absolute deviations' or 'MAD'

$$MAD = med\{|x_i - \tilde{m}|\} \quad for\ i = 1, 2, 3, \ldots N$$

where $\tilde{m}$ is the median value

The Median

- The uncertainty in the median can be expressed as:

$$\frac{1.9 \times MAD}{\sqrt{(N-1)}}$$

The Median

- Consider the Cs-137 half-life data already presented, the median is 10970 ± 23 days
- As with the unweighted mean, the median does not use the uncertainties assigned by the authors, so again some information is lost
- However, the median is much less influenced by outliers than is the unweighted mean

Bootstrap Method

- A Monte Carlo procedure to estimate a best value and uncertainty
- A random sample (with replacement) is selected from the data set and the median of this random sample is determined, $x_{med,j}$
- The sampling is repeated for j = 1, 2, 3, ……..M

Bootstrap Method

- The best estimate is then given by:

$$\hat{x} = \frac{1}{M}\sum_{j=1}^{M} x_{med,j}$$

- With variance:

$$\sigma_{\hat{x}}^2 = \frac{1}{M-1}\sum_{j=1}^{M}\left(x_{med,j} - \hat{x}\right)^2$$

Bootstrap Method

- Note that each sample of the data set, j, may have some values of the data set repeated and other values missing

- As in the case of the simple median, the Bootstrap Method does not make use of the uncertainties quoted with the data

Extended Bootstrap Method

- A procedure has been devised based on the Bootstrap Method, but also making use of the quoted uncertainties

- A Gaussian distribution is assigned to each input value taking into account the associated standard uncertainty

Extended Bootstrap Method

- Random samples are then taken from the probability distribution for each of the input quantities
- About one million Monte Carlo trials are recommended
- The best value and standard deviation are then calculated as shown for the Bootstrap Method

Evaluation of Discrepant Data

So, in summary, we have:

◆ Unweighted Mean:	10936 ± 75 days
◆ Weighted Mean:	10988 ± 3 days
◆ LRSW:	10988 ± 33 days
◆ Median:	10970 ± 23 days
◆ Bootstrap Method	10990 ± 26 days
◆ Extended Bootstrap	10992 ± 19 days

Reference

‘Convergence of techniques for the evaluation of discrepant data’

Desmond MacMahon, Andy Pearce, Peter Harris

Applied Radiation and Isotopes, **60** (2004) 275-281

Statistical Analyses:

Evaluation of Discrepant Data, II

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IAEA Workshop

Nuclear Structure and Decay Data

Evaluation of Discrepant Data II

Desmond MacMahon
United Kingdom

Evaluation of Discrepant Data

- Unweighted Mean: 10936 ± 75 days
- The unweighted mean can be influenced by outliers and has a large uncertainty
- Weighted Mean: 10988 ± 3 days
- The weighted mean has an unrealistically low uncertainty due to the high quoted precision of one or two measurements - value of 'chi-squared' is very high, indicating inconsistencies in the data

Evaluation of Discrepant Data

- LRSW: 10988 ± 33 days
- The Limitation of Relative Statistical Weights has not increased the uncertainty of any value in the case of Cs-137, but has increased the overall uncertainty to include the most precise value
- Median: 10970 ± 23 days
- The median is not influenced by outliers, nor by particularly precise values; on the other hand the median ignores all the uncertainty information supplied with the measurements

Evaluation of Discrepant Data

- Bootstrap Method 10990 ± 26 days
- A more robust procedure than the simple median, but does not use quoted uncertainties

- Extended Bootstrap 10992 ± 19 days
- Extends Bootstrap Method to make use of quoted uncertainty data; leads to a smaller final uncertainty

Evaluation of Discrepant Data

- There are two other statistical procedures which attempt to:

  (i) identify the more discrepant data, and

  (ii) decrease the influence of these data by increasing their uncertainties

- These are known as the Normalised Residuals Technique and the Rajeval Technique

Evaluation of Discrepant Data

- Normalised Residuals Technique
- A normalised residual for each value in a data set is defined as follows:

$$R_i = \sqrt{\frac{w_i W}{(W - w_i)}} \times (x_i - x_w)$$

$$\textit{where} \quad x_w = \frac{\sum x_i w_i}{W}; \quad w_i = \frac{1}{\sigma_i^2}; \quad W = \sum w_i$$

Evaluation of Discrepant Data

- A limiting value, R_0, of the normalised residual for a set of N values is defined as:

$$R_0 = \sqrt{1.8 \ln N + 2.6} \quad for \quad 2 \le N \le 100$$

- If any value in the data set has $|R_i| > R_0$, the weight of the value with the largest R_i is reduced until the normalised residual is reduced to R_0

Evaluation of Discrepant Data

- This procedure is repeated until no normalised residual is greater than R_0
- The weighted mean is then re-calculated with the adjusted weights
- The results of applying this method to the Cs-137 data is shown on the next slide, which shows only those values whose uncertainties have been adjusted

Author	Half-life (days)	Original Uncertainty	R_i $R_0 = 2.8$	Adjusted Uncertainty
Wiles 1955	9715	146	- 8.7	453
Gorbics 1963	10840	18	- 8.3	52
Rider 1963	10665	110	- 2.9	114
Lewis 1965	11220	47	4.9	88
Dietz 1973	11020.8	4.1	10.1	18.4
Martin 1980	10967.8	4.5	- 5.4	8.7
Gostely 1992	10940.8	6.9	- 7.4	16.4
Unterweger 2002	11018.3	9.5	3.3	15.5
New Weighted Mean	**10985**	**10**		

Rajeval Technique

- This technique is similar to the normalised residuals technique - inflates the uncertainties of only the more discrepant data, but uses a different statistical recipe
- Also has a preliminary population test which allows rejection of very discrepant data
- The Rajeval technique makes generally more adjustments than the normalised residuals method, but the outcomes are usually very similar

Rajeval Technique

- Initial Population Test:
- Outliers in the data set are detected by calculating the quantity y_i:

$$y_i = \frac{x_i - x_{ui}}{\sqrt{\sigma_i^2 + \sigma_{ui}^2}}$$

- where x_{ui} is the unweighted mean of the whole data set excluding x_i, and σ_{ui} is the standard deviation associated with x_{ui}

Rajeval Technique

- The critical value of $|y_i|$ at 5 % significance is 1.96
- At this stage only values with $|y_i| > 3 \times 1.96 = 5.88$ are rejected
- Consider the Cs-137 half-life data - only the first value, 9715 ± 146 days, is rejected with a value of $|y_i| = 8.61$

Rajeval Technique

◆ Standardised deviates, Z_i, are calculated in the next stage of the procedure:

$$Z_i = \frac{x_i - x_w}{\sqrt{\sigma_i^2 - \sigma_w^2}} \quad where \quad \sigma_w = \sqrt{\frac{1}{W}}$$

Rajeval Technique

◆ The probability integral for each Zi

$$P(Z) = \int_{-\infty}^{Z} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-t^2}{2}\right) dt$$

is determined.

Rajeval Technique

- The absolute difference between P(Z) and 0.5 is a measure of the 'central deviation' (CD)
- A critical value of the central deviation (cv) can be determined by the expression:

$$cv = \left[(0.5)^{\frac{N}{N-1}} \right] \quad for\ N > 1$$

Rajeval Technique

- If the central deviation (CD) of any value is greater than the critical value (cv), that value is regarded as discrepant, and the uncertainties of the discrepant values are adjusted to

$$\sigma_i' = \sqrt{\sigma_i^2 + \sigma_w^2}$$

Rajeval Technique

- An iteration procedure is adopted in which σ_w is recalculated each time and added in quadrature to the uncertainties of those values with CD > cv
- The iteration process is terminated when all CD < cv
- Consider the Cs-137 half-life data - one value is rejected by the initial population test and 8 of the remaining 18 values have their uncertainties adjusted as on the next slide

Author	Half-life (days)	Original Uncertainty	CD **cv = 0.480**	Adjusted Uncertainty
Gorbics 1963	10840	18	0.500	64
Rider 1963	10665	110	0.498	149
Lewis 1965	11220	47	0.500	121
Dietz 1973	11020.8	4.1	0.500	24
Corbett 1973	11034	29	0.443	31
Houtermans 1980	11009	11	0.473	19
Gostely 1992	10940.8	6.9	0.500	15
Unterweger 2002	11018.3	9.5	0.499	23
New Weighted Mean	**10971**	**4**		

Rajeval Technique

- If the Rajeval Technique table is compared to that for the Normalised Residuals Technique, the differences between them are seen to be:

1. The Rajeval Technique has rejected the Wiles & Tomlinson value
2. The Rajeval Technique makes generally larger adjustments to the uncertainties of discrepant data than does the Normalised Residuals Technique, and has a lower final uncertainty

Evaluation of Discrepant Data

- We now have 8 methods of extracting a half-life from the measured data:

Evaluation Method	Half-life (days)	Uncertainty
Unweighted Mean	10936	75
Weighted Mean	10988	3
LRSW	10988	33
Median	10970	23
Normalised Residuals	10985	10
Rajeval	10971	4
Bootstrap	10990	26
Extended Bootstrap	10992	19

Evaluation of Discrepant Data

- We have already pointed out that the unweighted mean can be influenced by outliers and is, therefore, to be avoided if possible

- The weighted mean can be heavily influenced by discrepant data with small quoted uncertainties, and would only be acceptable where the reduced chi-squared is small, i.e. close to unity - certainly not the case for Cs-137 with a reduced chi-squared of 18.6

Evaluation of Discrepant Data

- The Limitation of Relative Statistical Weights (LRSW), in the case of Cs-137 data, still chooses the weighted mean but inflates the associated uncertainty to cover the most precise value
- Therefore, both the LRSW value and associated uncertainty are heavily influenced by the most precise value of Dietz & Pachucki, which is identified as the most discrepant value in the data set by the Normalised Residuals and Rajeval Techniques.

Evaluation of Discrepant Data

- The median is a more reliable estimator since this value is very insensitive to outliers and to discrepant data.
- However, by not using the experimental uncertainties, this approach is not making use of all the information available
- The Normalised Residuals, Rajeval and Extended Bootstrap techniques have been developed to address the problems of the other techniques and to maximise the use of all the experimental information available

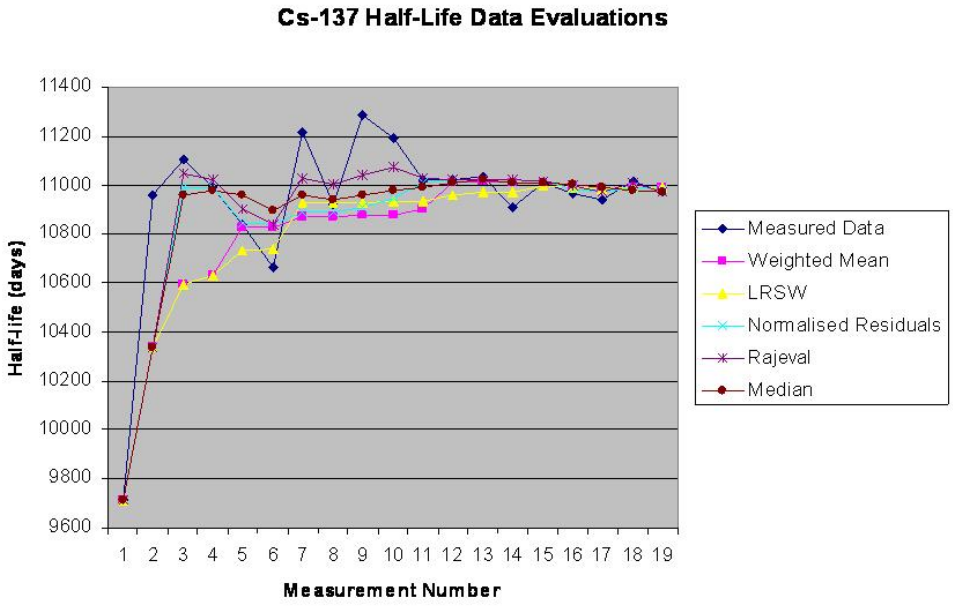
Evaluation of Discrepant Data

- The Normalised Residuals and Rajeval techniques use different statistical techniques to reach the same objective: they identify discrepant data and increase the uncertainties of such data to reduce their influence on the final weighted mean
- Note that all the techniques, excepting only the unweighted mean, lead to Cs-137 half-lives in the range 10970 – 10992 days: a value of 10981 ± 11 days covers the results of all the evaluation techniques and could be adopted as the current best estimate

Evaluation of Discrepant Data

◆ The adopted half-life of Cs-137 is therefore:

10981 ± 11 days

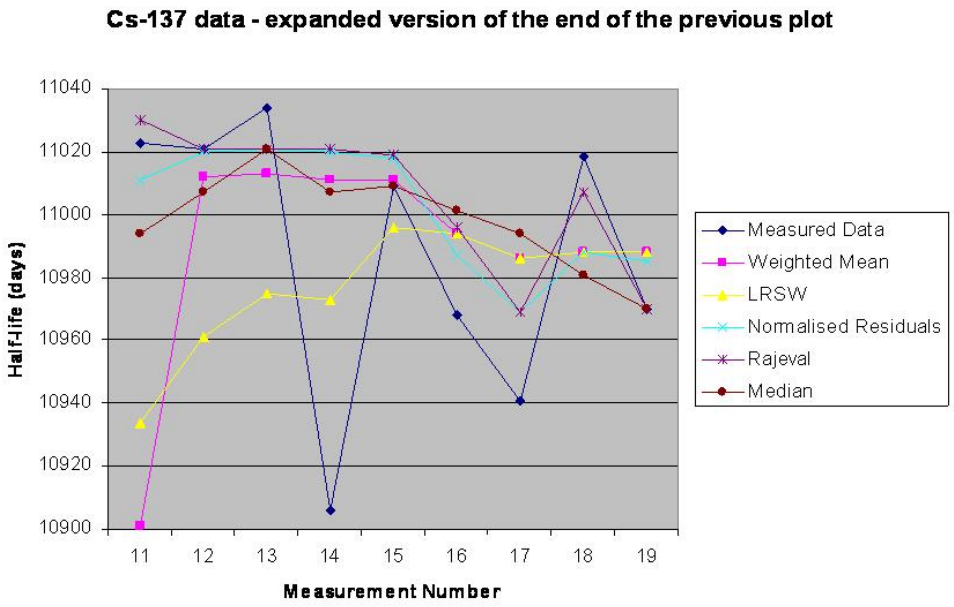


Evaluation of Discrepant Data

- The previous slide shows how the evaluation techniques behave as each new data point is added to the data set
- The left-hand portion of the plot shows that the weighted mean and the LRSW values take much longer to recover from the first, very low and discrepant value than do the other techniques

Evaluation of Discrepant Data

- The next plot shows an expanded version of the second half of the previous plot, showing in more detail how the different techniques behave as the number of data points reaches 19
- Taking into account the 19^{th} point the overall spread in the evaluation techniques is only 18 days or 0.16%


Cs-137 data - expanded version of the end of the previous plot
Half-life (days)
11040
11020
11000
10980
10960
10940
10920
10900
11
12
13
14
15
16
17
18
19
Measurement Number
Measured Data
Weighted Mean
LRSW
Normalised Residuals
Rajeval
Median

Statistical Analyses:

Evaluation of Discrepant Data, III

D. MacMahon

UK

E-mail: desmond.macmahon@npl.co.uk

IAEA Workshop
Nuclear Structure and Decay Data

Evaluation of Discrepant Data III

Desmond MacMahon
United Kingdom

Authors		Measured half-lives	
		days	
		$t_{1/2}$	σ
Wiles & Tomlinson (1955b)		10120	150
Anikina et al. (1958)		10700	580
Flynn et al. (1965)		10230	150
Flynn et al. (1965)		10410	330
Hoppes (1977)		10636	88
Lagoutine et al. (1978)		10282	12
Ramthun (1983)		10588	91
Kochin et al. (1989)		10665	37
Martin et al. (1994)		10561	14
Woods & Lucas (1996)		10495	4
Schrader (2004)		10557	11

Authors		Measured half-lives	
		days	
		$t_{1/2}$	σ
Wiles & Tomlinson (1955b)		10120	150
Anikina et al. (1958)		10700	580
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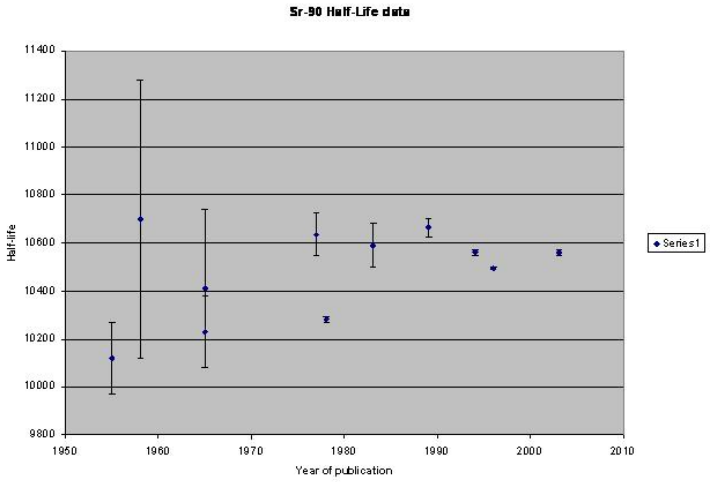
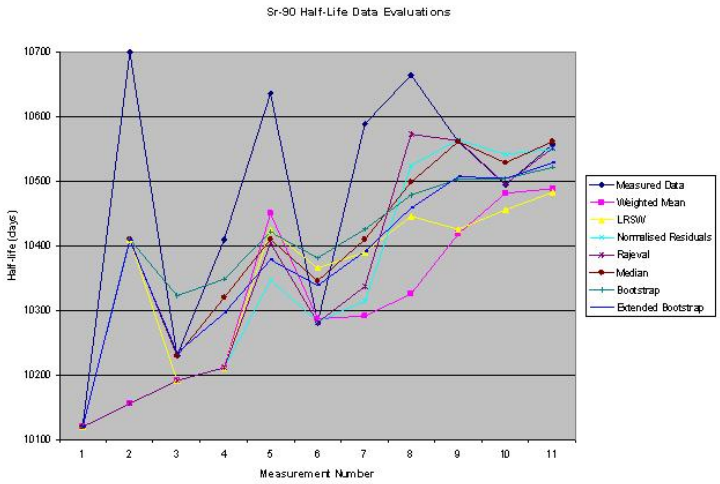
Schrader (2004)		10557	11



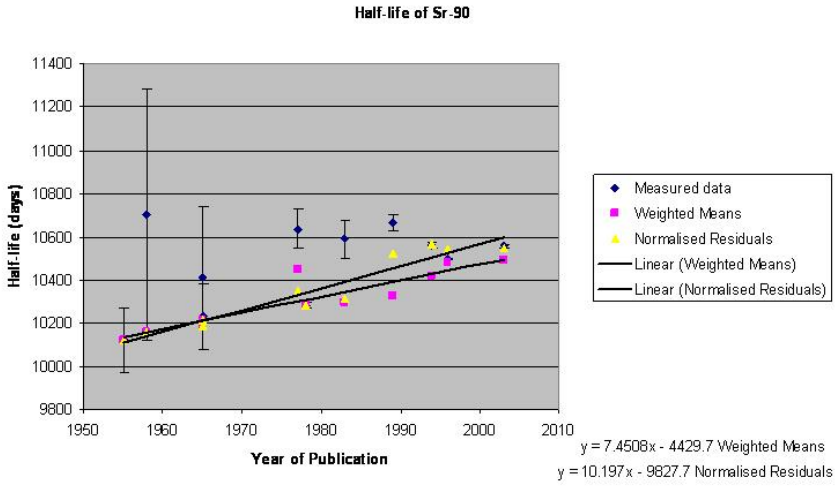
Evaluations of Sr-90 Half-Life Measurements:
reduced chi-squared = 40

Evaluation Technique	Result - days	Uncertainty - days
Weighted Mean	10489	3
LRSW	10483	30
Normalised Residuals	10550	14
Rajeval	10552	10
Median	10561	62
Bootstrap	10521	82
Extended Bootstrap	10528	32

Sr-90 Half-Life Data



Sr-90 Half-Life Data



Sr-90 Half-Life Data

- The previous figure shows that the last four Normalised Residuals results (1989 – 2004) are rather close together. Taking into account their uncertainties (one standard deviation) they are consistent:

  1989 10525(69) days
  1994 10565(23) days
  1996 10542(21) days
  2004 10550(14) days

Sr-90 Half-Life Data

- The final Normalised Residuals result is thus 10550 (14) days
- The Rajeval result is 10552 (10) days
- Therefore, the recommended half-life is : **10551 (14) days**

Mo-99 half-life exercise

			Half-Life of Mo-99		(days)							
				x_i	σ_i	$w_i=1/\sigma_i^2$ x10^{-6}	RSW	Adjusted RSW	Adjusted σ_i	Adjusted weights		NORM Adjusted σ_i
Emery (1972)				2.75083	0.00042							
Houtermans (1980)				2.74771	0.00013							
Unterweger (1992)				2.746829	0.000242							
Schrader (2004)				2.7489	0.0006							
Unweighted Mean $\mu = \Sigma x_i/n$												
Uncertainty = $\Sigma(x_i-\mu)^2/n(n-1)$												
							LRSW =				NORM =	
Weighted Mean = $(\Sigma w_i x_i)/\Sigma w_i$							unc. =				unc. =	
Uncertainty = $1/SQRT(\Sigma w_i)$												

Mo-99 half-life exercise

			Half-Life of Mo-99		(days)							
				x_i	σ_i	$w_i=1/\sigma_i^2$ x10^{-6}	RSW	Adjusted RSW	Adjusted σ_i	Adjusted weights		NORM Adjusted σ_i
Emery (1972)				2.75083	0.00042	5.67						
Houtermans (1980)				2.74771	0.00013	59.17						
Unterweger (1992)				2.746829	0.000242	17.08						
Schrader (2004)				2.7489	0.0006	2.78						
						84.69						
Unweighted Mean $\mu = \Sigma x_i/n$				**2.7486**								
Uncertainty = $\Sigma(x_i-\mu)^2/n(n-1)$				0.0009								
							LRSW =				NORM =	
Weighted Mean = $(\Sigma w_i x_i)/\Sigma w_i$				**2.74778**			unc. =				unc. =	
Uncertainty = $1/SQRT(\Sigma w_i)$				0.00011								

Mo-99 half-life exercise

			Half-Life of Mo-99	(days)							
				x_i	σ_i	$w_i=1/\sigma_i^2$ x10^{-6}	RSW	Adjusted RSW	Adjusted σ_i	Adjusted weights	NORM Adjusted σ_i
Emery (1972)				2.75083	0.00042	5.67	0.067	0.111	0.00042	5.67	0.00144
Houtermans (1980)				2.74771	0.00013	59.17	0.699	0.500	0.00020	25.00	0.00013
Unterweger (1992)				2.746829	0.000242	17.08	0.202	0.335	0.000242	17.08	0.00041
Schrader (2004)				2.7489	0.0006	2.78	0.033	0.054	0.0006	2.78	0.0006
						84.69	1.000	1.000		50.52	
Unweighted Mean $\mu = \Sigma x_i/n$				**2.7486**							
Uncertainty = $\Sigma(x_i-\mu)^2/n(n-1)$				0.0009							
							LRSW =	**2.74783**		NORM =	**2.74770**
Weighted Mean = $(\Sigma w_i x_i)/\Sigma w_i$				**2.74778**			unc. =	0.00014		unc. =	0.00025
Uncertainty = $1/SQRT(\Sigma w_i)$				0.00011							

Statistical Analyses:

Evaluation of ^{56}Co Decay Data

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Evaluation of ^{56}Co Decay Data

Desmond MacMahon

Coral Baglin

IAEA Workshop, Trieste, May 2008

^{56}Co Decay Data

- ^{56}Co decays by positron emission (19.58%) and by electron capture (80.42%) to excited states of ^{56}Fe
- 46 gamma rays with energies up to 3.6 MeV de-exciting 15 excited states in ^{56}Fe have been reported
- This energy range makes ^{56}Co useful as a calibration source in gamma-ray spectrometry

^{56}Co Decay Data

- The Q value for the decay is given by Audi *et al.* as **4566 (20) keV**
- The half-life of ^{56}Co has been evaluated by Woods *et al.* as **77.236 (26) days**
- Main gamma-ray energies are taken from the Helmer and van der Leun evaluation (2000)

^{56}Co Gamma-Ray Emission Probabilities

- Relative gamma-ray emission probabilities for the 46 gamma rays reported by 31 authors between 1965 and 2002 were tabulated
- A problem arose when considering the high energy data
- In many cases detector efficiency curves used measured data up to about 2.5 MeV, and then extrapolated to 3.6 MeV

^{56}Co Gamma-Ray Emission Probabilities

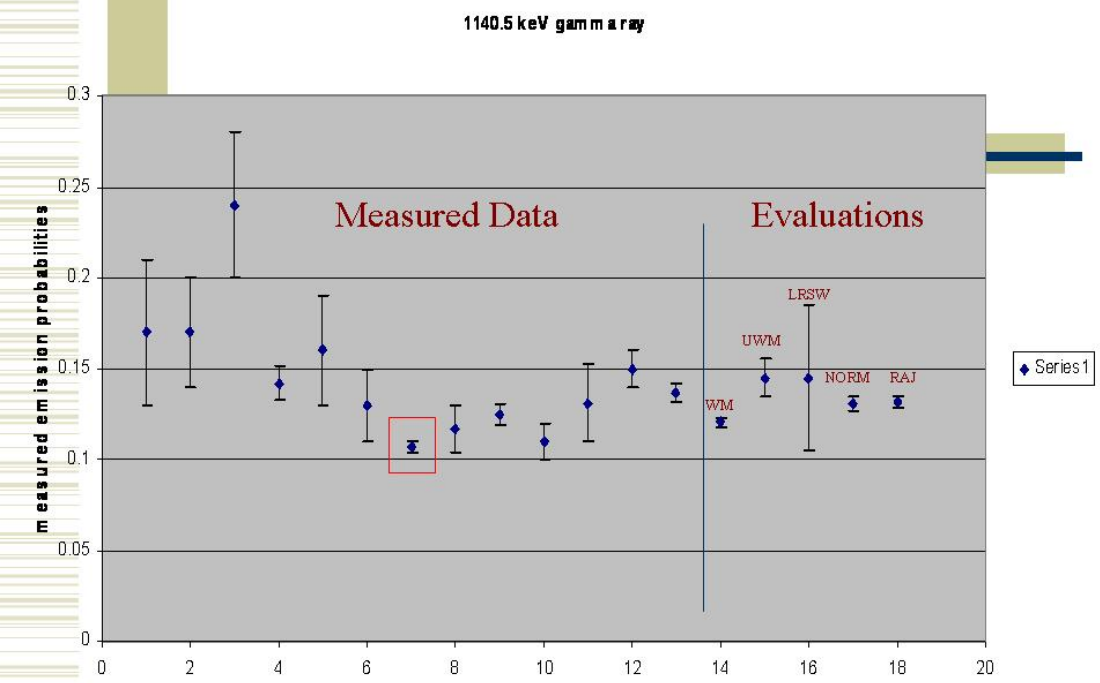
- Experimentally determined efficiency curves above 3 MeV demonstrated clearly that the extrapolated curves introduced errors of up to 6%
- Therefore, of the 31 papers cited, only 8 which had used experimentally determined efficiency curves up to 3.6 MeV were included in the evaluation of data above 3 MeV

^{56}Co Gamma-Ray Emission Probabilities

- The second problem was the significant number of discrepant data
- Of the 46 gamma rays considered, 18 had data sets with a reduced chi-squared ranging from 2.0 to 7.8, indicating significant discrepancies

^{56}Co Gamma-Ray Emission Probabilities

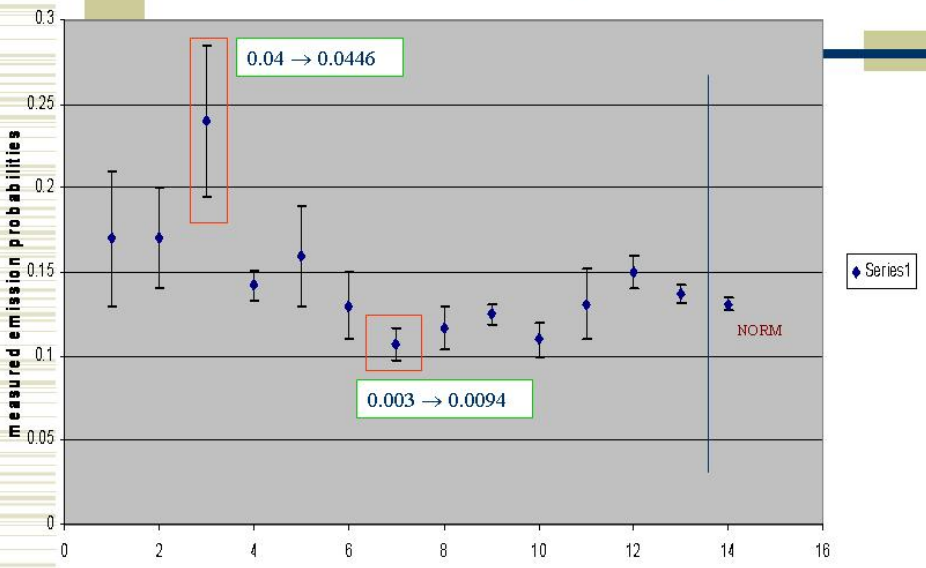
- The following graph shows the data for the 1140.5 keV gamma ray, for which the reduced chi-squared is 5.2
- The discrepancies are clear from the graph

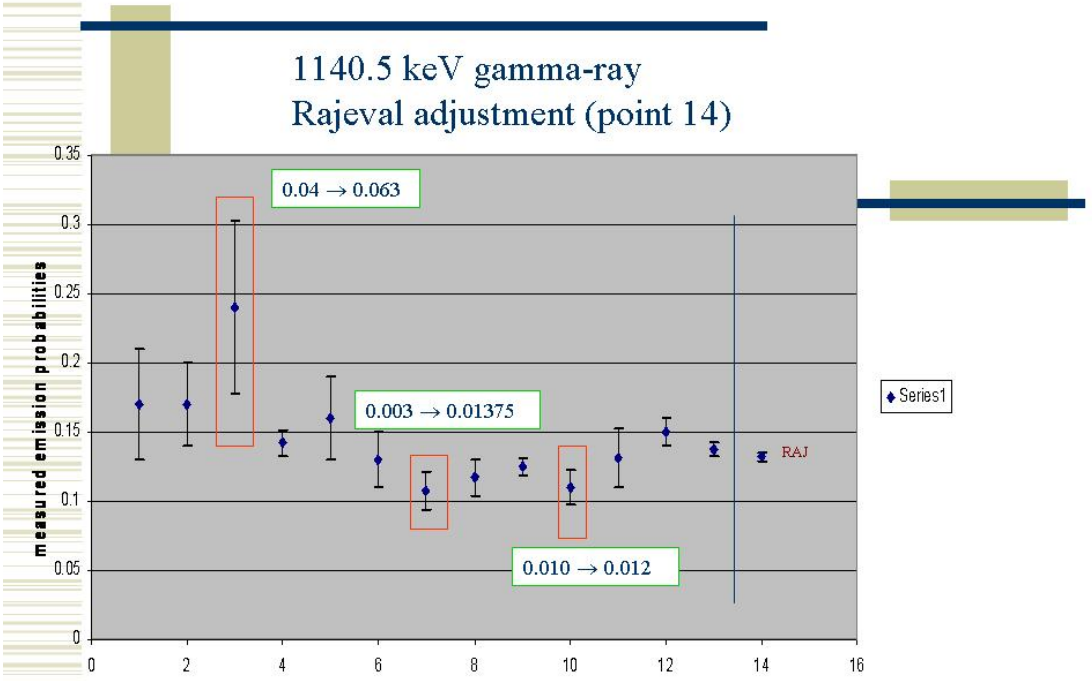


^{56}Co Gamma Ray Emission Probabilities

- On the previous graph points 1 to 13 are the experimental data
- Point 14 is the weighted mean 0.1204(21)
- Point 15 is the unweighted mean 0.145(10)
- Point 16 is the LRSW 0.145 (38)
- Point 17 is the normalised residual 0.131(4)
- Point 18 is the Rajeval value 0.132(4)

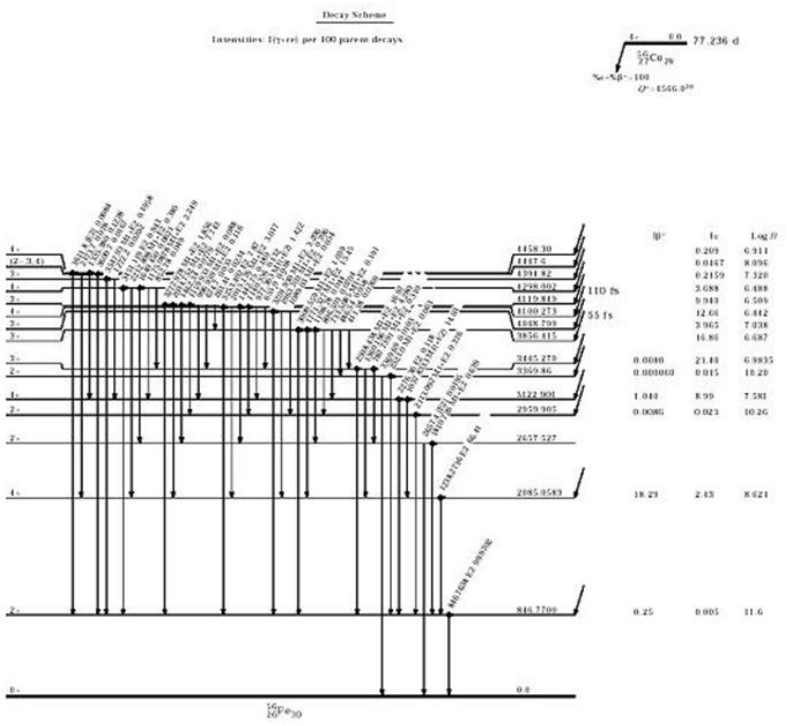
1140.5 keV gamma-ray
Normalised REsiduals adjustment (point 14)





Normalisation

- Evaluated intensities are relative to the strongest 847 keV transition to the ground state
- Normalisation is accomplished by requiring that all transitions to the ground state add up to 100



Normalisation

- Assuming zero electron capture/positron feeding from the 4^+ ^{56}Co parent to the 0^+ ^{56}Fe ground state:

$$\Sigma\left(I\left(\gamma + ce\right) \textit{to the ground state}\right) \quad = \quad 100$$

Normalisation

$$N = \frac{100}{\left[I(847\gamma)(1+\alpha(847\gamma)) + I(2657\gamma) + I(3370\gamma)\right]}$$

$$= \frac{100}{100.0303(9) + 0.0195(20) + 0.0103(8)}$$

$$= 0.999399(23)$$

Evaluated Data

Gamma Energy keV	Relative Iγ	Absolute Pγ
846.772	100	0.999399(23)
1037.840	14.04(5)	0.1403(5)
1238.282	66.45(16)	0.6641(16)
1360.215	4.283(13)	0.04280(13)
1771.351	15.46(4)	0.1545(4)
2034.755	7.746(13)	0.07741(13)
2598.458	16.97(4)	0.1696(4)
3201.962	3.205(13)	0.03203(13)
3253.416	7.87(3)	0.0787(3)

Positron Emission Probabilities

	Energy (keV)	**Probability × 100**	**Nature**	**log *ft***
$\beta^+_{0,7}$	98.7 (20)	0.0080 (7)	allowed	6.984
$\beta^+_{0,6}$	174.3 (20)	6.0 E-5 (20)	2nd forbidden	10.20
$\beta^+_{0,5}$	421.1 (20)	1.040 (20)	allowed	7.581
$\beta^+_{0,4}$	584.1 (20)	0.0086 (22)	2nd forbidden	10.26
$\beta^+_{0,2}$	1458.9 (20)	18.29 (16)	allowed	8.621
$\beta^+_{0,1}$	2697.2 (20)	0.25 (17)	2nd forbidden	11.6

Electron Capture Probabilities

	Energy (keV)	Probability × 100	Nature	log *ft*
$\varepsilon_{0,8}$	709.5(20)	16.86(5)	allowed	6.687(3)
$\varepsilon_{0,7}$	1120.7(20)	21.40(5)	allowed	6.984(2)
$\varepsilon_{0,6}$	1195.9(20)	0.015(5)	2nd forbidden	10.20(15)
$\varepsilon_{0,5}$	1443.1(20)	8.99(6)	allowed	7.581(4)
$\varepsilon_{0,4}$	1606.1(20)	0.023(6)	2nd forbidden	10.26(11)
$\varepsilon_{0,2}$	2480.9(20)	2.43(3)	allowed	8.621(5)
$\varepsilon_{0,1}$	3719.2(20)	0.005(3)	2nd forbidden	11.6(3)

Electron Capture Probabilities

	Energy (keV)	Probability × 100	Nature	log *ft*
$\varepsilon_{0,15}$	107.7(20)	0.209(7)	allowed	6.911(23)
$\varepsilon_{0,14}$	118.4(20)	0.0167(5)	unknown	8.096(21)
$\varepsilon_{0,13}$	171.2(20)	0.2159(18)	allowed	7.320(12)
$\varepsilon_{0,12}$	268.0(20)	3.688(13)	allowed	6.489(7)
$\varepsilon_{0,11}$	446.1(20)	9.940(18)	allowed	6.509(4)
$\varepsilon_{0,10}$	465.7(20)	12.66(4)	allowed	6.442(4)
$\varepsilon_{0,9}$	517.2(20)	3.965(15)	allowed	7.038(4)

X Ray Emissions

	Energy (keV)	Photons per 100 disintegrations
XL	0.615-0.792	0.581 (17)
$XK\alpha_2$	6.39091(5)	7.53 (10)
$XK\alpha_1$	6.40391(3)	14.75 (17)
$XK\beta_3$	7.05804(7)	3.05 (5)
$XK\beta_1$		
$XK\beta''_5$	7.1083(4)	

Auger Electron Emissions

	Energy (keV)	Electrons per 100 disintegrations
e_{AL}	0.510 – 0.594	111.8 (8)
e_{AK}		46.04 (30)
KLL	5.370-5.645	35.61 (25)
KLX	6.158-6.400	9.76 (13)
KXY	6.926-7.105	0.666 (15)

7. **DRAFT**

18 March 2008

Evaluation of Decay Data: Relevant IAEA Coordinated Research Projects

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Presented to IAEA-ICTP Workshop on Nuclear Structure and Decay Data: Theory and Evaluation, 28 April 2008

Summary

Specific IAEA Coordinated Research Projects (CRPs) have been directed towards the generation of recommended high-quality decay data for a number of important applications. Decay-scheme data for specific radionuclides have required study and evaluation through an agreed set of procedures. The role of the IAEA Nuclear Data Section in creating these dedicated data files is described, and both the objectives and resulting decay data from these most relevant CRPs are also reviewed.

1. Introduction

Two primary aims of the IAEA Nuclear Data Section (NDS) are to develop and disseminate atomic and nuclear data in forms appropriate for a wide range of applications, as requested by IAEA Member States [1]. Hence, NDS staff prepare and maintain a significant number of databases, including atomic and molecular data for fusion energy and plasma research that are accessible through a separate server [2]. NDS staff are also involved in various forms of technology transfer activity to assist scientists of developing countries in their use of these atomic and nuclear databases.

Data development within the NDS is conducted mainly through Coordinated Research Projects (CRPs). Usually these projects result in the production of a new (or significant upgrades of an existing) database; typically 5-12 scientific groups from different countries work together under IAEA contracts or agreements over a period of normally 3 to 5 years, maintaining contact throughout the course of the CRP. Examples of recent CRPs sponsored and organised by the NDS are listed in Table 1 (duration and participant numbers are subject to change).

Following a brief description of the IAEA-NDS and how to gain access to their facilities and databases, the contents of this paper focus on those CRPs devoted over recent years to improving the recommended decay data used in both energy- and non-energy-based applications. Specific decay-data requirements were identified by users and consultants, and a suitable evaluation procedure was adopted to achieve the desired objectives.

Table 1: Recent IAEA-NDS Coordinated Research Projects (CRPs).

Short Title	Duration	No. of Participants
RIPL-II: Input Parameters for Modelling Nuclear Reactions	1998-2001	13
Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications	**1998-2003**	13
Prompt Gamma Activation Analysis	1999-2003	10
Atomic and Molecular Data for Fusion Plasma Diagnostics	2001-05	12
Molecular Processes in Edge Plasmas	2001-05	11
Neutron Cross-Section Standards	2002-06	14
Tritium Inventory in Fusion Machines	2002-07	12
Nuclear Data for Th-U Fuel Cycle	2002-07	11
RIPL-III: Parameters for Nuclear Reaction Applications – Non-energy Applications	2003-07	12
Cross Sections for Production of Therapeutic Radionuclides	2003-07	8
Atomic and Molecular Data for Plasma Modelling	2004-08	14
Atomic Data for Heavy Element Impurities in Fusion Reactors	2005-10	12
Updated Decay Data Library for Actinides	**2005-09**	9
Reference Database for Ion Beam Analysis	2005-09	9
Reference Database for Neutron Activation Analysis	2005-09	8
Charged-Particle Interactions in Medical Therapy Applications	2007-10	13
Data for Surface Composition Dynamics Relevant to Erosion Processes	2007-12	10
Minor Actinide Neutron Reaction Data	2007-11	12
Nuclear Data for Fusion Materials Testing Facilities	2008-12 (?)	10 (?)

1.1 Nuclear data

Nuclear data are commonly categorized in terms of two main groups:

- **Nuclear reaction data:** Encompasses cross sections, angular and energy distributions of secondary particles, resonance parameters and related quantities. These libraries are complete for neutron-induced reactions up to 20 MeV. While coverage of higher neutron energies and photonuclear and charged-particle induced reactions is less comprehensive, these gaps are being filled as a consequence of the increased compilation efforts of the various data centres.
- **Nuclear structure and decay data:** Atomic masses, half-lives, decay schemes, nuclear level properties, and energies and intensities of emitted particles and γ rays are included in these data. The major database is ENSDF, while related bibliographic information is contained in NSR. There are many other nuclear structure and decay data libraries, mostly derived from or related to ENSDF and including the *Table of Isotopes* [3], *Isotope Explorer* [4] and NUBASE [5].

This information can also be classified on the basis of bibliographic detail, experimental data and evaluated data. All data are available on the internet (*http://www-nds.iaea.org*).

- **Bibliographic data:** References with some description of the contents, but no numerical data. Examples are CINDA (Computer Index of Neutron Data) and NSR (Nuclear Science References).
- **Experimental data:** Results of individual measurements as reported by the authors. The most important example of a compiled library of experimental nuclear reaction data is EXFOR/CSISRS.
- **Evaluated data:** Recommended values are based on all available data from experiments and/or theory, derived from a critical analysis of the experimental data and their uncertainties, inter- and extrapolation, and/or nuclear model calculations. The resulting libraries are assembled in strictly defined formats such as ENDF-6 (internationally-accepted format of nuclear data for applications) or ENSDF (format of the Evaluated Nuclear Structure Data File).

1.2 International nuclear data networks

Two international networks are coordinated by the IAEA to collect, compile, evaluate and distribute nuclear data (Table 2):

- Network of Nuclear Reaction Data Centres (NRDC) [6],
- Network of Nuclear Structure and Decay Data Evaluators (NSDD) [7].

The centres participating in these nuclear data networks are involved in the various stages of data preparation between measurement and application (i.e., compilation, review, evaluation, processing and distribution).

Table 2: Nuclear data networks.

Network of Nuclear Reaction Data Centres	Network of Nuclear Structure and Decay Data Evaluators
IAEA Nuclear Data Section, Vienna, Austria	**IAEA Nuclear Data Section,** Vienna, Austria
OECD, NEA Data Bank, Paris, France	**US National Nuclear Data Center,** Brookhaven, USA (maintains Master database)
US National Nuclear Data Center, Brookhaven National Laboratory, USA	**18 data evaluation centres (mid-2008):** Australia, Bulgaria, Canada, France, PRChina (2), IAEA, India (2), Japan, Kuwait, Russian Federation and USA (6)
Russian Nuclear Data Centre, IPPE, Obninsk, Russian Federation	**Data dissemination centres:** USA and IAEA
9 co-operating specialised centres: PRChina, Hungary, Japan (2), Republic of Korea, Russian Federation (3) and Ukraine	

1.2.1 Network of Nuclear Reaction Data Centres (NRDC)

Specialized data centres cooperate with the major centres in the various functions of the NRDC (particularly data compilation and evaluation). This sharing of the compilation of nuclear reaction cross-section data on a worldwide basis is normally defined on the basis of their geographical location and data expertise, and is coordinated by the IAEA Nuclear Data Section.

1.2.2 Network of Nuclear Structure and Decay Data Evaluators

Nuclear structure and decay data are compiled and evaluated by means of a collaborative programme organised through the International Network of Nuclear Structure and Decay Data Evaluators (NSDD) and established in 1974 under the auspices of the International Atomic Energy Agency (IAEA). This network began at a time when the workload was heavily reliant on USA input. A more equitable involvement of other national laboratories and universities was envisaged, and partially achieved. Network contacts, affiliations and their mass chain responsibilities are listed in Table 3. The total NSDD evaluation effort is equivalent to about 9 full-time equivalent scientists per annum (FTE), albeit approximately 12 FTE are required to maintain the desired currency and quality of ENSDF.

Table 3: International Network of Nuclear Structure and Decay Data Evaluators (2008).

Country/affiliation	Contact and co-workers	Assigned mass chains
Argentina		
CNEA, Buenos Aires	G.V. Marti	(178, 191, 193)
Australia		
ANU, Canberra	T. Kibédi	172-175
Bulgaria		
University of Sofia	D.L. Balabanski S.P. Lalkovski	(112, 200)
Canada		
McMaster University, Hamilton	B. Singh J.A. Cameron	1, 31-44, 64, 89, 98, 100, 149, 151, 164, 188, 190, 194
China		
CNDC, CIAE, Beijing	Ge Zhigang Huang Xiaolong	51-56, 62, 63, 195-198
Jilin University, Changchun	Huo Junde	
France		
CEA Bruyères-le-Châtel	J. Blachot	101, 104, 107-109, 111, 113-117
India		
IIT, Roorkee	A.K. Jain	218-229
Manipal University	M. Gupta	(260-294)
Japan		
JAEA, Ibaraki-ken	J. Katakura T. Tamura	120-129
Kuwait		
University of Kuwait	A.R. Farhan	74-80
Russian Federation		
PNPI, St. Petersburg	I.A. Mitropolsky A. Rodionov Yu. Khazov	130-135
United Kingdom		
University of Oxford	N.J. Stone	-
United States of America		
NNDC, BNL	J.K. Tuli E. Browne-Moreno T.W. Burrows D.J.A. De Frenne P. Obložinský C.W. Reich A.A. Sonzogni	45-50, 57, 58, 60, 61, 65-73, 82, 84-88, 94-97, 99, 102, 103, 105, 106, 110, 112, 118, 119, 136-148, 150, 152-163, 165, 230-240, >249
LBNL, Berkeley	C.M. Baglin M.S. Basunia R.B. Firestone S.-C. Wu	21-30, 59, 81, 83, 90-93, 166-171, 180-187, 189, 191-193, 210-217
ORNL, Oak Ridge	M.S. Smith M.J. Martin	241-249
TUNL, Duke University, Durham	J.H. Kelley D.R. Tilley H.R. Weller	2-20
ANL	F.G. Kondev	176-179, 199-209
Texas A&M	N. Nica	(140, 147, 252)
IAEA		
Vienna, Austria	D.H Abriola A.L. Nichols	(94, 96)

( ) denotes partially shared responsibility.

The organisers of the International Network of Nuclear Structure and Decay Data Evaluators have become aware of an increasing problem in maintaining and updating ENSDF evaluations with the necessary regularity. Evidence of a shortfall in effort has been detected over the previous ten years as evaluators in Europe have retired without any obvious replacements. While some progress has been made in recruitment through the commitment of nuclear physics institutes in India and elsewhere for this essential work, these welcome additions are not fully commensurate with the losses experienced in Europe, a region of the world that might have been expected to ensure some re-generation of expertise in this vital area of research and development.

1.3 Access to IAEA-NDS data libraries

The IAEA Nuclear Data Section holds a total of about 100 nuclear data libraries, constituting enormous scientific and economic value. All libraries and the related documentation are available free of charge to scientists in IAEA Member States. An overview is given in the document *Index of Nuclear Data Libraries Available from the* IAEA *Nuclear Data Section* [8], and brief descriptions of the contents and format of most libraries are published in the IAEA-NDS-report series [9].

The main method of distributing numerical nuclear data in the early 21st century is via the internet, and therefore the IAEA Nuclear Data Section offers a variety of such electronic services. At the same time, conventional mail services have been maintained for the convenience of users with their varying needs and technical infrastructures (i.e., sending customized retrievals or complete libraries as hardcopy and CD-ROM, as well as by e-mail). Users are also kept up to date with information on new data libraries and other developments through the *IAEA Nuclear Data Newsletter* [10].

- **Worldwide Web (WWW)**: The web page of IAEA Nuclear Data Services can be found at the web addresses *http://www-nds.iaea.org* (IAEA Vienna, Austria), *hhtp://www-nds.indcentre.org.in* (BARC, India), and *http://www-nds.ipen.br* (IPEN, Brazil). This page contains interactive access to the major databases as well as an overview of all nuclear data libraries and databases available from the IAEA *(IAEA Nuclear Data Guide)*, access to various reports, documents and manuals, nuclear data utility programs, and the *IAEA Nuclear Data Newsletter*.

- Hardcopy documents published by NDS include handbooks, research and meeting reports (INDC report series), data library documents (IAEA-NDS report series), and the *IAEA Nuclear Data Newsletter*. Most new reports are available electronically on the WWW in PDF format. NDS staff can be contacted by e-mail to request hardcopy documents, and other mail services and nuclear data related information [11].

1.4 Technology transfer

Technology transfer to developing countries is carried out in several ways by the NDS:

- Technical co-operation projects to provide online nuclear data services to countries with insufficient internet connections to the NDS through the installation of mirror servers in Brazil and India.

- Nuclear data workshops are organized on a regular basis, and are usually held at the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. Regular topics have included “Nuclear Reaction Data and Nuclear Reactors: Physics, Design

and Safety" and "Nuclear Data for Science and Technology" (varying from medical physics to materials analysis). More appropriately, over the previous 6 years a combination of IAEA and IAEA-ICTP workshops have been dedicated to "Nuclear Structure and Decay Data: Theory and Evaluation".

2. Coordinated Research Project: Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications (STI/PUB/1287, May 2007; *http://www-pub.iaea.org/MTCD/publications/PDF/P1287_Volume_1+2.pdf*)

The question of γ-ray detector efficiency calibration arose during the CRP on Transactinium Decay Data (Section 3.1) when the importance of reputable reference standards became apparent. A strong recommendation was made to prepare an internationally-accepted file of X- and γ-ray decay data of nuclides used to calibrate detector efficiencies. Furthermore, the International Nuclear Data Committee (INDC) proposed a preparative meeting with experts associated with the International Committee for Radionuclide Metrology (ICRM) to pursue this aim. An IAEA Consultants' Meeting was held at the Centre d' Etudes Nucléaires de Grenoble in May 1985 to discuss the quality of all relevant data and define a suitable programme to resolve the various issues [12]. As a consequence of these discussions, a CRP on "X-ray and Gamma-ray Standards for Detector Calibration" was established in 1986 by the IAEA Nuclear Data Section. Participants in the programme were specialists in γ-ray spectroscopy, and the related areas of standards and data evaluation. Their objective was to produce a recommended set of decay parameters for selected radionuclides judged as the most important for the efficiency calibration of equipment used to detect and quantify X- and γ-ray emissions. Various factors, such as source preparation and source-detector geometry, may affect the quality of measurements made with intrinsic germanium and other γ-ray spectrometers. However, the accuracy of such measurements depends invariably upon the accuracy of the efficiency versus energy calibration curve, and hence upon the accuracy of the decay data for the radionuclides from which calibration standard sources are prepared. Both half-lives and X- and γ-ray emission probabilities need to be known to good accuracy. Participants were given the task of establishing a data file that would be internationally accepted. Valuable contributions were also provided by multinational intercomparison projects organised by the International Committee for Radionuclide Metrology (ICRM) and the Bureau International des Poids et Mesures (BIPM).

A set of recommended half-life and emission probability data was prepared by participants of the IAEA Coordinated Research Project on "X-ray and Gamma-ray Standards for Detector Calibration". The results from this work represented a significant improvement in the quality of specific decay parameters required for the efficiency calibration of X- and γ-ray detectors. Data inadequacies were highlighted, several of the identified inconsistencies remain unresolved, and further efforts are required to address these uncertainties. Accomplishments of this CRP included:

- assessment of the existing relevant data during 1986/87,
- coordination of measurements within the existing project and extensive cooperation among the participating research groups,
- performance of a large number of measurements stimulated by the CRP, and
- preparation of an IAEA-TECDOC report which consolidated most of the data needed for γ-ray detector efficiency calibration [13].

The resulting data were internationally accepted as a significant contribution to the improved quality of X- and γ-ray spectrometry. However, the recommended database that

evolved from this CRP has now been superseded by the results of a new IAEA initiative that began in 1998 to update calibrant decay data.

2.1. X-ray and gamma-ray decay data revisited (1998-2003)

A strong recommendation was formulated at the 1997 biennial meeting of the International Nuclear Data Committee for the IAEA-NDS to re-visit and place further emphasis on the development of improved decay data for standards applications. This recommendation arose as a consequence of the publication of relevant measured data beyond 1990 that were not included in the original CRP. Many such studies had been catalysed by the demands of this earlier CRP, and new efforts were required to incorporate the new data and extend the existing database to encompass the related needs of a number of important applications such as environmental monitoring and nuclear medicine. High-quality decay data are essential in the efficiency calibration of X- and γ-ray detectors that are used to quantify radionuclidic content by determining the intensities of any resulting X- and γ rays. A Consultants' Meeting was held at IAEA Headquarters in 1997 to assess the current needs, and identify the most suitable radionuclides [14]. The expert participants at this meeting advised the establishment of a new Coordinated Research Project entitled "Update of X-ray and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications".

Members of the new CRP reviewed and modified the list of radionuclides most suited for detector calibration, and were able to include some of the specific needs of such nuclear applications as safeguards, material analysis, environmental monitoring, nuclear medicine, waste management, dosimetry and basic spectroscopy. All evaluations were based on the available experimental data, supplemented with the judicious use of well-established theory. As with the previous CRP, three types of data (half-lives, energies, and emission probabilities) were compiled and evaluated. Consideration was also given to the use of the γ-γ coincidence technique for efficiency calibrations, as well as adopting a number of prompt high-energy γ rays from specific nuclear reactions. Well-defined evaluation procedures were applied to determine the recommended half-lives and emission probabilities for all prominent X- and γ rays emitted by each selected radionuclide.

2.2 Main issues

2.2.1 Update of 1991 database

IAEA-TECDOC-619 contains recommended decay data for 36 radionuclides, extending up to γ-ray energy of 3.6 MeV [13]. These data were revisited and revised where appropriate, as a consequence of the availability of new experimental data measured and published after 1990. New measurements of half-lives had also been published for at least 29 of the original 36 radionuclides. Most of the γ-ray energies were taken from Ref. [15], while original references were cited when such data were not available from this source. Only average X-ray energies and their emission probabilities were given in IAEA-TECDOC-619 - the new work eliminates this shortcoming through a systematic analysis of the emissions of the individual $K_{\alpha 1}$, $K_{\alpha 2}$, $K_{\beta 1}$ and $K_{\beta 2}$ components. However, X-ray energies were not evaluated, but taken from Schönfeld and Rodloff [16] and Browne and Firestone [17].

2.2.2 Additional radionuclides

A comprehensive list of 62 radionuclides and two heavy element decay chains was originally prepared at the Consultants' Meeting, and adopted as a suitable starting point by the participants of the CRP. Decay data were compiled,

evaluated and recommended for the half-lives, and X-ray and γ-ray emission probabilities. These radionuclides were re-evaluated in an international exercise led by laboratories involved in the Decay Data Evaluation Project (DDEP) [18] and affiliated to the International Committee for Radionuclide Metrology (ICRM), with the IAEA-CRP providing impetus and the necessary coordination to achieve the desired objectives.

2.2.3 Extension of the energy range

New nuclear techniques suffer from a lack of high-energy calibration standards (for example, radiotherapy). Hence, there is an urgent need to provide such data for the calibration of γ-ray detectors up to 25 MeV. Appropriate radionuclides and nuclear reactions have been identified, and γ-ray emission probabilities were compiled and evaluated. Various options were explored in order to provide energy and intensity calibration γ-lines above 10 MeV.

2.2.4 Other features

Angular correlation coefficients were evaluated for a few appropriate radionuclides of relevance to the γ-γ coincidence method of calibration. Attention was also focused on the analysis of uncertainties, including an investigation of the feasibility and usefulness of including uncertainty correlations in the evaluation procedures. A limited number of nuclides were evaluated in this manner. One conclusion arising from this exercise was the need to establish rules for the documentation of experiments that would enable the evaluators to estimate input covariances from the published decay data.

2.3 Specific radionuclides as standards

A recommended list of 62 nuclides evolved from the meetings of the IAEA CRP (Table 4), including specific parent-daughter combinations and two heavy-element decay chains. A primary standard is a nuclide for which γ-ray emission probabilities are calculated from various data that do not include significant γ-ray measurements (emission probabilities are usually close to 1.0, expressed per decay); these data may include internal conversion coefficients and the intensities of weak beta branches. Secondary standards are nuclides for which the recommended γ-ray intensities depend on prior measurements of the γ-ray intensities. When relative intensities had been measured, these parameters were evaluated as well as the normalisation factor; this combination of data was then used to generate absolute emission probabilities. Thus, both relative intensities and absolute emission probabilities were included in the evaluation exercise, and both can be extracted or derived from the database.

2.4 High-energy gamma rays

The radioactive sources discussed above permit the precise determination of the efficiency of a germanium detector up to about 2.7 MeV with either a ^{24}Na or ^{228}Th source, or to 3.45 MeV with a ^{56}Co source. Some sources of radiation can be used to extend the efficiency calibration to above 10 MeV, and were also considered. Except for one radioactive nuclide (^{66}Ga), these sources of radiation are based on nuclear reactions. While other reactions could be used, only thermal neutron capture and (p, γ) reactions were considered. Gamma rays emitted from the following nuclear reactions were considered for adoption as calibration standards:

^{14}N(n, γ)^{15}N*

Table 4: Selected radionuclides and applications.

Nuclide	X/γ-Ray Standard	Dosimetry Standard	Medical Applications	Environmental Monitoring	Waste Management	Safeguards
^{22}Na	P	-	x	-	-	-
^{24}Na	P	-	-	-	-	-
^{40}K	S	-	-	x	-	-
^{46}Sc	P	-	-	-	-	-
^{51}Cr	S	-	x	-	-	-
^{54}Mn	P	-	-	x	x	-
^{56}Mn	P	-	x	-	-	-
^{55}Fe	S	-	x	-	x	-
^{59}Fe	S	-	x	-	-	-
^{56}Co	S	-	-	-	-	-
^{57}Co	P (122 keV)	-	x	-	-	x
^{58}Co	P	-	-	x	-	-
^{60}Co	P	-	x	x	x	x
^{64}Cu	-	-	x	-	-	-
^{65}Zn	S	-	-	x	x	-
^{66}Ga	S	-	x	-	-	-
^{67}Ga	S	-	x	-	-	-
^{68}Ga	-	-	x	-	-	-
^{75}Se	S	-	x	-	-	-
^{85}Kr	-	-	-	x	-	-
^{85}Sr	P	-	x	x	-	-
^{88}Y	P (1836 keV) S (898 keV)	-	-	-	-	-
^{93m}Nb	-	x	-	-	-	-
^{94}Nb	P	-	-	-	-	-
^{95}Nb	P	-	-	x	-	x
^{99}Mo–^{99m}Tc	P (140.5 keV)	-	x	-	-	-
^{99m}Tc	P (140.5 keV)	-	x	-	-	-
^{103}Ru	-	-	x	x	-	x
^{106}Ru–^{106}Rh	S	-	x	x	-	x
^{110m}Ag (^{110}Ag)	S	-	-	x	x	-
^{109}Cd	S	-	-	x	-	-
^{111}In	P	-	x	-	-	-
^{113}Sn	P	-	-	-	-	-
^{125}Sb	-	-	-	x	-	x
^{123m}Te	-	-	x	-	x	-
^{123}I	P	-	x	-	-	-
^{125}I	S	x	x	-	-	-
^{129}I	S	-	-	x	x	-
^{131}I	S	x	x	x	-	x
^{134}Cs	S	-	-	x	-	x

Table 4: Selected radionuclides and applications (cont.).

Nuclide	X/γ-Ray Standard	Dosimetry Standard	Medical Application	Environmental Monitoring	Waste Management	Safeguards
^{137}Cs	P	x	-	x	x	x
^{133}Ba	S	-	x	-	-	-
^{139}Ce	P	-	-	x	-	-
^{141}Ce	S	-	-	x	-	x
^{144}Ce–^{144}Pr	S	-	x	x	-	x
^{153}Sm	-	-	x	-	-	x
^{152}Eu	S	-	-	x	x	x
^{154}Eu	S	-	-	x	x	x
^{155}Eu	S	-	-	x	x	x
^{166m}Ho–^{166}Ho	S	-	x	-	-	x
^{170}Tm	S	-	-	-	-	-
^{169}Yb	S	-	x	-	-	-
^{192}Ir	S	x	x	-	-	-
^{198}Au	P	-	-	-	-	-
^{203}Hg	P	-	-	-	-	-
^{201}Tl	-	-	x	-	-	-
^{207}Bi	P (569.7 keV)	-	x	-	-	-
^{226}Ra decay chain	S	x	-	x	x	x
^{228}Th decay chain	P	-	-	x	-	x
^{234m}Pa	-	-	-	x	x	-
^{241}Am	P	-	-	x	x	x
^{243}Am	-	-	-	-	x	x

P primary efficiency calibration standard.
S secondary efficiency calibration standard.

^{35}Cl(n, γ)^{36}Cl*

^{48}Ti(n, γ)^{49}Ti*

$^{50, 52, 53}$Cr(n, γ)$^{51, 53, 54}$Cr*

^{11}B(p, γ)^{12}C*

^{14}N(p, γ)^{15}O*

^{23}Na(p, γ)^{24}Mg*

^{27}Al(p, γ)^{28}Si*

The cross sections, and the energies and transition probabilities of their most prominent high-energy γ rays have been evaluated.

The high-energy γ-ray data were sometimes taken from a single reference, and were not subjected to the detailed evaluation of the other data. Furthermore, the data were of somewhat uneven quality. While some of the measurements had been undertaken with metrological goals in mind, other measurements were less well defined.

2.4.1 ^{66}Ga

^{66}Ga is the only radionuclide that has been used in the energy region above 3600 keV. This nuclide has a half-life of 9.3 hours, and can be produced by ^{63}Cu(α, n), ^{66}Zn(p, n) and ^{64}Zn(α, 2n) reactions. New relative intensities have been determined to good accuracy for twenty-one gamma rays emitted by ^{66}Ga [19], and in good agreement with the equivalent measurements of Raman *et al.* [20]. Both the evaluated relative intensities and absolute emission probabilities of the main gamma rays are listed in Table 5. However, two limitations are immediately apparent: a half-life of 9.3 hours means that this radionuclide can only be used by gamma-ray spectroscopists with access to an appropriate production facility, and the uncertainties in the recommended emission probabilities above 3 MeV are of the order of 8% and rather large.

2.4.2 Thermal neutron capture reactions

Efficiency calibrations can be derived using γ rays from the thermal neutron capture reaction on selected target materials. Of the many thermal neutron capture reactions that could have been assessed, only a few were considered by the CRP. ^{14}N(n, γ)^{15}N reaction was judged to be of particular interest: as shown in Table 6, there are twelve suitable gamma rays ranging from 3 to 11 MeV that have uncertainties of ~ 1%, although the uncertainties in the emission probabilities of higher-energy gamma rays at 9149 and 10829 keV are 4.1% and 1.5%, respectively. The ^{35}Cl(n, γ)^{36}Cl reaction was also assessed, with twenty-four strong gamma rays ranging from 0.517 to 8.58 MeV of which ten are above 5 MeV.

Some ratios of γ-ray emission probabilities are given in Table 7. The adoption of these reactions depends on the availability of a neutron source, and the usefulness of any particular reaction depends on the reaction cross section, a suitable sample, and the lack of any interference from background radiation (including the production of the same reaction outside the target).

2.4.3 Proton capture reactions

Proton capture reactions can be used to provide γ rays to calibrate germanium detectors. Although there are some experimental difficulties, these reactions have the advantage that simple γ-ray spectra are often produced when the proton energy is chosen to coincide with a resonance. Some useful proton resonances and the related γ-ray emission probability ratios are listed in Table 8.

2.5 Recommended X-ray and gamma-ray decay data standards, 2007

A new set of recommended half-life and emission probability data has been prepared by participants in the IAEA-CRP to Update X- and Gamma-ray Decay Data Standards for Detector Calibration and Other Applications. The results from this work represent a further significant improvement in the quality of specific decay parameters required for the efficiency calibration of X- and γ-ray detectors. Examples of the data as presented to the reader of the technical report are given in Appendix A.

Table 5: Absolute emission probabilities per decay and relative probabilities of twenty-one gamma rays from the decay of ^{66}Ga.

E_γ (keV)	$P_{\gamma i}$ [a]	$P_{\gamma i}/P_{\gamma 1039keV}$
686.080(6)	0.00252(22)	0.00681(20)
833.5324(21)	0.059(5)	0.1593(6)
1039.220(3)	0.37(3)	1.000(3)
1333.112(5)	0.0117(9)	0.03175(13)
1418.754(5)	0.0061(5)	0.01657(8)
1508.158(7)	0.0055(4)	0.01497(7)
1898.823(8)	0.0039(3)	0.01051(8)
1918.329(5)	0.0199(16)	0.05368(23)
2189.616(6)	0.053(4)	0.1442(6)
2422.525(7)	0.0188(15)	0.05085(24)
2751.835(5)	0.227(18)	0.6135(26)
3228.800(6)	0.0151(12)	0.04082(22)
3380.850(6)	0.0146(12)	0.03960(23)
3422.040(8)	0.0086(7)	0.02314(16)
3432.309(7)	0.00288(24)	0.00777(10)
3766.850(9)	0.00149(13)	0.00403(15)
3791.004(8)	0.0109(9)	0.02941(24)
4085.853(9)	0.0127(10)	0.03445(20)
4295.187(10)	0.038(3)	0.1030(8)
4461.202(9)	0.0084(7)	0.0226(3)
4806.007(9)	0.0186(15)	0.0503(3)

[a] uncertainties of $P_{\gamma i}$ are relative to the uncertainty of $P_{\gamma 1039keV}$.

Table 6: Evaluated thermal neutron capture cross sections ($\sigma_{\gamma i}$) for selected γ_i rays from the $^{14}N(n, \gamma)^{15}N$ reaction, and corresponding γ_i-ray emission probabilities $P_{\gamma i}$(abs) per neutron capture as evaluated on the basis of data from Refs. [21, 22].

$E_{\gamma i}$ (keV)	$P_{\gamma i}$(abs)				$\sigma_{\gamma i}$ (mb)
	Kennett *et al.* [21] (1986)	Jurney *et al*. [22] (1997)	UWM[a]	LWM[b] recommended	
1678.293(25)	0.0723(18)	0.0796(9)[c]	0.076(4)	0.076(4)	6.1(3)
1681.228(50)	0.0154(15)	0.0164(4)	0.0159(5)	0.0163(4)	1.31(3)
1884.780(18)	0.1866(25)	0.1877(20)	0.1872(20)	0.1873(20)	15.04(20)
1999.679(27)	0.0399(9)	0.0411(5)	0.0405(6)	0.0408(5)	3.28(5)
2520.443(22)	0.0579(7)	0.0558(9)	0.0569(11)	0.0571(10)	4.59(8)
2830.805(36)	0.0173(3)	0.0171(4)	0.0172(3)	0.0172(3)	1.38(3)
3531.982(20)	0.0924(9)	0.0894(11)	0.0909(15)	0.0912(15)	7.32(13)
3677.737(17)	0.1489(15)	0.1452(16)	0.1471(19)	0.1472(19)	11.82(18)
4508.783(14)	0.1654(17)	0.1671(17)	0.1663(17)	0.1663(17)	13.35(17)
5269.162(17)	0.3003(20)	0.2986(30)	0.2995(20)	0.2998(20)	24.07(24)
5297.826(20)	0.2131(18)	0.2123(22)	0.2127(18)	0.2128(18)	17.08(19)
5533.391(18)	0.1975(21)	0.1958(21)	0.1967(21)	0.1967(21)	15.80(21)
5562.059(21)	0.1065(12)	0.1068(12)	0.1067(12)	0.1067(12)	8.57(12)
6322.433(16)	0.1867(14)	0.1823(22)	0.1845(22)	0.1854(20)	14.89(20)
7298.980(32)	0.0973(9)	0.0939(12)	0.0956(17)	0.0961(16)	7.72(14)
8310.156(39)	0.0422(5)	0.0412(9)	0.0417(5)	0.0420(5)	3.37(5)
9148.95(9)	0.0148(6)	0.0148(6)	0.0148(6)	0.0148(6)	1.19(5)
10829.110(59)	0.1365(21)	0.143(6)	0.1398(33)	0.1372(21)	11.02(19)

[a] unweighted mean values.
[b] least squares weighted mean values.
[c] uncertainty adjusted to (18) based on chi-squared test.

Table 7: Emission probability ratios of γ_1 rays (populating) and γ_2 rays (depopulating a common level) after thermal neutron capture.

Reaction	$E_{\gamma 1}$ (keV)	$E_{\gamma 2}$ (keV)	P1/P2	Ref.
$^{35}Cl(n, \gamma)^{36}Cl$	5715.20	2863.82	0.96(4)	[20, 23-25]
	5902.69	2676.31	0.698(12)	[20, 23-25]
	6110.80	1951.1278[a]	1.037(11)	[20, 23-25]
	6110.80	517.07006	0.866(10)	[20, 23-25]
	6619.57	1959.343	0.612(9)	[20, 23-25]
	6977.79	1601.068	0.603(10)	[20, 23-25]
	7790.28	788.4230	0.493(6)	[20, 23-25]
$^{48}Ti(n, \gamma)^{49}Ti$	4881.32	1498.63	0.981(10)	[26]
	6418.38	341.69	0.906(9)	[26]
	6555.83	1585.95	0.487(6)	[26]
	6760.06	1381.72	0.518(5)	[26]
$^{52}Cr(n, \gamma)^{53}Cr$	5618.13	2321.09	0.980(8)	[27]
$^{53}Cr(n, \gamma)^{54}Cr$	6644.47	2239.16	0.907(8)	[27]
	7098.84	1784.69	0.750(8)	[27]
	8882.88	835.03	0.562(7)	[27]

[a] subsequent emission of three γ rays in cascade.

Table 8: Proton capture reactions with subsequent emission of γ_1 and γ_2 rays in cascade; emission probabilities are P_1 and P_2, and E_p is the proton resonance energy, while energies are taken from Ref. [3].

Reaction	E_p (keV)	$E_{\gamma 1}$ (keV)	$E_{\gamma 2}$ (keV)	P1/P2	Ref.
$^{11}B(p, \gamma)^{12}C$	675	12140	4438.03	1.000(<1)[a]	[28]
	1388	12790	4438.03	1.000(<1)[a]	[28]
	2626	13920	4438.03	1.000(<1)[a]	[28]
$^{14}N(p, \gamma)^{15}O$	278	5182(1)	2373(1)	1.000(38)	[29]
		6174.9(1)	1380.1(17)	1.000(7)	[29]
		6791.4(17)	763.4(17)	1.000(37)	[29]
	1058	5239.9(3)	3042.8(6)	1.028(12)	[29]
$^{23}Na(p, \gamma)^{24}Mg$	1318	11588	1368.633	0.960(2)	[28]
	1417	8925.55	2754.028	0.9850(11)	[28]
$^{27}Al(p, \gamma)^{28}Si$	767	7706	2838.67(5)	0.981(2)	[28]
	992	10762.9	1778.969(12)	0.806(10)	[28]
	1317	6580	4500	1.017(6)	[28]

[a] another 1-2% uncertainty arises from the angular distribution, even when applied at $\theta = 55°$.

Emphasis has been placed on the X- and γ rays most suited as detector efficiency calibrants, and only these emissions have been included in the final CRP dataset (i.e., only a limited number of strong lines are recommended). Complete decay-data listings are not necessarily included in the final technical document; however, the user is referred to relevant parallel publications by laboratories involved in the DDEP [30-33], and web pages located through:

http://www.nucleide.org/DDEP_WG/DDEPdata.htm

The accomplishments of the CRP include:

- re-evaluations of all existing relevant data from the 1986-90 programme;
- extension of the recommended database to satisfy the needs of a number of important applications;
- specific measurements were undertaken, particularly with respect to high-energy γ-ray emissions;
- preparation of an IAEA technical report which summarizes the recommended decay data for X- and γ-ray detector efficiency calibration and other applications [34].

As before, one important expectation is that the resulting set of data will be internationally accepted as a significant contribution to improving the quality of both X- and γ-ray spectroscopy.

3. Coordinated Research Project: Updated Decay Data Library for Actinides

Transactinium nuclides are important in the nuclear fuel cycles of both thermal and fast reactors, and have found increasing application in other fields. The IAEA convened an Advisory Group Meeting on Transactinium Isotope Nuclear Data (TND) at the Kernforschungszentrum Karlsruhe in 1975 [35]. Users and measurers were brought together to review the status and requirements of the nuclear data for transactinium nuclides relevant to fission reactor research and technology. One of the areas specifically addressed at this meeting was the status of the decay data for these nuclides; participants recommended that the IAEA implement a Coordinated Research Project to review, measure and evaluate the required transactinium decay data.

The accuracies requested for many of the data were quite high, especially the γ-ray emission probabilities that presented challenging experimental problems. Nevertheless, during the seven years of the CRP, some of these problems were solved, and a considerable amount of data was produced with the required accuracy (at least for the prominent transitions of most interest to the user). The work of the CRP not only helped improve the existing capabilities of the participating laboratories, but also encouraged the development of such capabilities at other laboratories. Together with the systematic production of highly accurately measured decay data, this interaction between laboratories represented one of the more significant long-term effects of the work.

3.1 Recommended transactinium decay data (1985-86)

The CRP highlighted a significant number of data requirements and succeeded in satisfying many of them. Improvements were subsequently been made in the quality of specific decay data for the transactinium nuclides, although several of the identified decay data needs remained unsatisfied. Specific goals were accomplished:

(a) Evaluated the accuracy requirements for decay data requested by users at the Advisory Group Meetings, and grouped them into three general categories:

(i) those satisfied by available data;

(ii) those which lie beyond the capabilities of measurement techniques (of 1985/6);

(iii) those not satisfied, but are achievable with existing experimental capabilities.

(b) Assessed the status of the existing data in the light of these requirements, and maintained an awareness of new measurements.

(c) Identified and coordinated the measurement expertise in order to acquire the required data.

(d) Prepared a report that presented a critical evaluation of the data and summarized their status [36].

The CRP participants concluded that, despite the large body of accurate decay data produced by the laboratories up to 1985/86, much remained to be done. A number of the accuracy requirements were not met. The outstanding transactinium decay data requirements have indeed encouraged others to become involved in producing highly accurate data, and plans were initiated in 2005 by IAEA-NDS staff to establish a new CRP to re-evaluate these data and update the recommended database.

3.2 Updated Decay Data Library for Actinides (2005-2009)

The previous CRP on actinide decay data addressed the preparation of a database directly, and provided the catalyst for a series of new measurements that continued well into the 1990s. All of this new work and earlier data needed to be re-compiled and evaluated to produce an updated set of recommended decay data to replace the existing IAEA database (of 1985/86). Furthermore, the International Nuclear Data Committee (INDC) in their advice to the Nuclear Data Section on nuclear data issues for 2002 and 2004 had noted the need for further improvements to the actinide decay data files for a wide range of applications. Thus, an appropriate CRP began in late 2005, with the following aims:

- promotion of actinide decay data research and development;
- evaluation of actinide decay data - proposed actinides and associated decay chains include: ^{226}Ra and daughters, ^{232}Th and daughters, ^{231}Th, ^{231}Pa, ^{233}Pa, $^{232\text{-}237}$U, ^{239}U, ^{237}Np, ^{239}Np, $^{238\text{-}242}$Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{242}Cm, ^{244}Cm and ^{252}Cf;
- assembly of recommended decay data files for the agreed set of actinides, and all recommended data to be added to the NDS home page.

Scientists from several research laboratories in eight countries are involved in the agreed work programme to quantify with greater accuracy the complete decay scheme data for approximately 40 actinides and 45 of their daughters (Table 9). Specific measurements have also been carried out using sources prepared and stored at Argonne National Laboratory, USA. Individual participants have completed and are undertaking comprehensive evaluations by means of the well-defined methodology adopted for the Decay Data Evaluation Project [18]. Two Research Coordination Meetings have taken place at IAEA Headquarter in Vienna [37, 38]. Participants discussed and selected specific nuclides for evaluation, and agreed the procedures to be adopted. Progress was reviewed at the second Research Coordinated Meeting, and recommendations for new measurements and evaluations to address existing deficiencies in the data were also discussed. Examples of the recommended decay data and their origins from within the technical literature are

given in Appendix B. Further details of some of these decay data evaluations can be found in the studies of Chechev [39], Chechev and Kuzmenko [40], and Chisté *et al*. [41].

Although the decay scheme evaluations will continue for a further one or two years, a number of anomalies have already been observed during the course of the initial studies (Table 10). Most of the inadequacies could be addressed through well-defined measurement programmes as outlined below, although source availability will prove problematic for some of the proposed studies. The most significant issues are identified with the conflicting α and γ decay data for ^{224,226}Ra, the comprehensive lack of uncertainties in the ^{233}Th decay data, and the inadequate nature of the decay schemes derived for ^{236,236m}Np and ^{242,244,244m}Am.

The actinide decay data of importance in the proposed database include half-lives, branching fractions, and α-particle and γ-ray energies and emission probabilities – their definition to good accuracy provides the means of monitoring the presence and transport of these actinides in nuclear facilities, as well as assisting in the detection of any clandestine activities. Most of the remaining CRP activities will focus on the comprehensive evaluation of the decay scheme data for the agreed set of actinides and their natural decay products. Recommended data files are available on the DDEP-LNHB Web site located at *http://www.nucleide.org/DDEP_WG/DDEPdata.htm*, and in ENSDF (Evaluated Nuclear Structure Data File) and ENDF-6 formats for their inclusion within specialized nuclear applications libraries.

4. Concluding Remarks

The survival and maintenance of the quality of ENSDF depends on the recruitment of new data evaluators to replace the ageing nuclear physicists undertaking this important work. Unless new blood can be introduced soon, there is a serious danger that the current loose confederation of dedicated participants will fade away and as a consequence the core nuclear physics databases will become hopelessly outdated. An urgent need has arisen for younger scientists to join the NSDD evaluation network and to contribute to the nuclear data activities. There can be no doubt that the assistance of the worldwide nuclear physics research community is urgently required to ensure the survival of ENSDF at the necessary level of credibility, reliability and quality. Anyone with the necessary expertise, supportive infrastructure and personal interest in undertaking mass chain evaluations for ENSDF should contact Jagdish Tuli at NNDC, Brookhaven National Laboratory, USA.

Decay-data studies undertaken under the auspices of the International Atomic Energy Agency are strongly linked to the needs of Member States, and are therefore applications oriented. All resulting nuclear data are brought together on the IAEA-NDS web site located at http://www-nds.iaea.org/.

Specific inadequacies in our knowledge of important decay-data parameters have been identified through IAEA-sponsored Advisory Group Meetings and Consultants' Meetings. Therefore, at various periods of time over the previous 30 years, staff within the IAEA Nuclear Data Section have been encouraged by Member States to organise Coordinated Research Projects (CRPs) to resolve difficulties and uncertainties identified with:

- decay data of the transactinium nuclides (1977-85);
- X-ray and γ-ray standards for detector calibration (1986-90);
- update of X-ray and γ-ray decay data standards for detector calibration and other applications (1998-2003);
- updated decay data library of actinides (2005-09).

Table 9: Actinide and decay chain data - radionuclides selected for extensive re-evaluation.

Responsible evaluator	Actinides	Natural decay products
M.-M. Bé	^{234,238}U, ^{243}Am, ^{252}Cf	^{210}Tl, ^{210,214}Pb, ^{210,214}Bi, ^{210,214,218}Po, ^{218}At, ^{218,222}Rn, ^{226}Ra
V.P. Chechev	^{233}Th, ^{233}Pa, ^{237,239}U, ^{236,236m,237,238,239}Np, ^{238,239,240,241,242}Pu, ^{241}Am, ^{242,244}Cm	^{227}Ac
Huang Xiaolong	^{231}Th, ^{235}U	^{213}Bi, ^{213}Po, ^{217}At, ^{217}Rn, ^{221,223}Fr, ^{225}Ra, ^{225}Ac
F.G. Kondev	^{243,245,246}Cm	^{206}Hg, ^{206,207,209}Tl, ^{209,211}Pb
A. Luca	^{234}Th, ^{236}U	^{228}Ra
G. Mukherjee	^{229}Th, ^{233}U	-
A.L. Nichols	^{228}Th, ^{242,242m,244,244m}Am	^{208}Tl, ^{212}Pb, ^{212,215}Bi, ^{212,216}Po, ^{211,219}At, ^{219,220}Rn, ^{224}Ra
A.K. Pearce	^{232}Th, ^{231}Pa, ^{232}U	^{223}Ra, ^{228}Ac
Unallocated, April 2007	-	^{211}Bi, ^{211,215}Po, ^{215}At

Table 10: Some anomalies and inadequacies in the evaluated actinide decay data.

Radionuclide	Comments
^{224}Ra	Discrepancy between related measurements of absolute emission probability of 240.99-keV γ ray and the α-particle emission probabilities to the ground and first excited states of ^{220}Rn.
^{226}Ra	Modest discrepancy between related measurements of absolute emission probability of 186.21-keV γ ray and the α-particle emission probabilities to the ground and first excited states of ^{222}Rn.
^{233}Th	Measured γ-ray emission probabilities are reported without uncertainties.
^{233}Pa	Precise measurements of low-energy γ rays and LX-rays would assist greatly in resolving difficulties in decay scheme evaluation.
^{237}U	Half-life measurements merited to fortify earlier experimental studies.
^{239}U	Large numbers of observed γ rays are unplaced in decay scheme.
^{236}Np, ^{236}Np^{m}	Inadequate experimental data.
^{242}Am	Half-life studies merited to fortify the three existing measurements; γ-ray studies would also be beneficial.
^{244}Am	Half-life studies required to fortify only one known measurement; γ-ray studies would also be beneficial.
^{244}Am^{m}	Half-life measurements are required to quantify the value and uncertainty with much greater confidence; γ-ray studies would also be extremely beneficial (only one known decay data measurement).
^{242}Cm	Accurate measurements of 44-, 102-, 157- and 210-keV γ-ray emission probabilities merited.

New measurements have been performed and in-depth evaluations undertaken in order to formulate recommended decay data for the relevant radionuclides, as specified at the various Consultants' Meetings.

A comprehensive form of in-depth evaluation methodology has been developed in conjunction with the Decay Data Evaluation Programme (DDEP). The various agreed evaluation procedures have been applied to all relevant decay data for each individual radionuclide, representing a high degree of analysis. Such detail is extremely labour intensive, and the limited amount of expertise worldwide prevents general application to the full range of mass chain evaluations.

Much has been achieved to resolve a wide range of specific difficulties and discrepancies, and a number of extremely useful applications-based decay-data files have been assembled by the IAEA Nuclear Data Section to ensure that the most up-to-date values are adopted by users in Member States. Further work is merited, including the need to measure specific actinide decay data in order to address observed problems and discrepancies. One further intention will be to maintain strong technical links between the relatively modest number of experts to be found working within the DDEP and involved in IAEA-CRPs dedicated to the evaluation and recommendation of decay data.

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M.A. Kellett (CRP on "Updated Decay Data Library for Actinides").

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APPENDIX A

X-RAY AND γ-RAY DECAY DATA STANDARDS FOR DETECTOR CALIBRATION AND OTHER APPLICATIONS

RECOMMENDED EXAMPLE DATA

Recommended radionuclide half-lives

Nuclide	Half-life (days) 1 year = 365.2422 days	
	value	uncertainty
11-Na-22	950.57	± 0.23
11-Na-24	0.62329	± 0.00006
19-K-40	(4.563	± 0.013) 10^{+11}
21-Sc-46	83.79	± 0.04
24-Cr-51	27.7009	± 0.0020
25-Mn-54	312.29	± 0.26
25-Mn-56	0.107449	± 0.000019
26-Fe-55	1002.7	± 2.3
26-Fe-59	44.494	± 0.013
27-Co-56	77.236	± 0.026
27-Co-57	271.80	± 0.05
27-Co-58	70.86	± 0.06
27-Co-60	1925.23	± 0.27
29-Cu-64	0.52929	± 0.00018
30-Zn-65	243.86	± 0.20
31-Ga-66	0.3889	± 0.0034
31-Ga-67	3.2616	± 0.0004
31-Ga-68	0.04703	± 0.00007
34-Se-75	119.778	± 0.029
36-Kr-85	3927	± 8
38-Sr-85	64.851	± 0.005
39-Y-88	106.625	± 0.024
41-Nb-93m	(5.73	± 0.22) 10^{+3}
41-Nb-94	(7.3	± 0.9) 10^{+6}
41-Nb-95	34.985	± 0.012
42-Mo-99	2.7478	± 0.0007
43-Tc-99m	0.250281	± 0.000022
44-Ru-103	39.247	± 0.013
44-Ru-106	371.8	± 1.8
45-Rh-106	0.000348	± 0.000004
47-Ag-110m	249.85	± 0.10
48-Cd-109	461.4	± 1.2
49-In-111	2.8049	± 0.0006
50-Sn-113	115.09	± 0.04
51-Sb-125	1007.48	± 0.21
52-Te-123m	119.45	± 0.25

Recommended radionuclide half-lives

Nuclide	Half-life (days) 1 year = 365.2422 days	
	value	uncertainty
53-I-123	0.55098	± 0.00009
53-I-125	59.402	± 0.014
53-I-129	(5.89	± 0.23) 10^{+9}
53-I-131	8.0228	± 0.0024
55-Cs-134	753.5	± 1.0
55-Cs-137	(1.099	± 0.004) 10^{+4}
56-Ba-133	3848.7	± 1.2
58-Ce-139	137.642	± 0.020
58-Ce-141	32.503	± 0.014
58-Ce-144	285.1	± 0.6
62-Sm-153	1.938	± 0.010
63-Eu-152	4941	± 7
63-Eu-154	3138.1	± 1.4
63-Eu-155	1736	± 6
67-Ho-166	1.1165	± 0.0013
67-Ho-166m	(4.4	± 0.7) 10^{+5}
69-Tm-170	127.8	± 0.8
70-Yb-169	32.016	± 0.006
77-Ir-192	73.822	± 0.009
79-Au-198	2.6950	± 0.0007
80-Hg-203	46.594	± 0.012
81-Tl-201	3.0422	± 0.0017
83-Bi-207	(1.18	± 0.03) 10^{+4}
88-Ra-226	(5.862	± 0.022) 10^{+5}
90-Th-228	698.60	± 0.23
91-Pa-234m	0.000805	± 0.000011
95-Am-241	(1.5785	± 0.0023) 10^{+5}
95-Am-243	(2.692	± 0.008) 10^{+6}

Data uncertainties are defined as standard deviations corresponding to the 1σ confidence level.

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
11-Na-22	511	-	1.798	± 0.002	annihilation radiation
11-Na-22	1274.537	± 0.003	0.99940	± 0.00014	
11-Na-24	1368.626	± 0.005	0.999935	± 0.000005	
11-Na-24	2754.007	± 0.011	0.99872	± 0.00008	
19-K-40	1460.822	± 0.006	0.1066	± 0.0013	
21-Sc-46	889.271	± 0.002	0.999833	± 0.000005	
21-Sc-46	1120.537	± 0.003	0.99986	+0.00004 -0.00036	
24-Cr-51	320.0835	± 0.0004	0.0987	± 0.0005	
25-Mn-54	834.838	± 0.005	0.999746	± 0.000011	
25-Mn-56	846.7638	± 0.0019	0.9885	± 0.0003	
25-Mn-56	1810.726	± 0.004	0.269	± 0.004	
25-Mn-56	2113.092	± 0.006	0.142	± 0.003	
25-Mn-56	2523.06	± 0.05	0.0102	± 0.0002	
26-Fe-59	142.651	± 0.002	0.00972	± 0.00015	
26-Fe-59	192.349	± 0.005	0.0292	± 0.0003	
26-Fe-59	1099.245	± 0.003	0.5659	± 0.0021	
26-Fe-59	1291.590	± 0.006	0.4321	± 0.0025	
27-Co-56	846.7638	± 0.0019	0.999399	± 0.000023	
27-Co-56	977.363	± 0.004	0.01422	± 0.00007	
27-Co-56	1037.833	± 0.0024	0.1403	± 0.0005	
27-Co-56	1175.088	± 0.0022	0.02249	± 0.00009	
27-Co-56	1238.2736	± 0.0022	0.6641	± 0.0016	
27-Co-56	1360.196	± 0.004	0.04280	± 0.00013	
27-Co-56	1771.327	± 0.003	0.1545	± 0.0004	
27-Co-56	2015.176	± 0.005	0.03017	± 0.00014	
27-Co-56	2034.752	± 0.005	0.07741	± 0.00013	
27-Co-56	2598.438	± 0.004	0.1696	± 0.0004	
27-Co-56	3009.559	± 0.004	0.01038	± 0.00019	
27-Co-56	3201.93	± 0.011	0.03203	± 0.00013	
27-Co-56	3253.402	± 0.005	0.0787	± 0.0003	
27-Co-56	3272.978	± 0.006	0.01855	± 0.00009	
27-Co-56	3451.119	± 0.004	0.00942	± 0.00006	
27-Co-57	14.41295	± 0.00031	0.0915	± 0.0017	
27-Co-57	122.06065	± 0.00012	0.8551	± 0.0006	
27-Co-57	136.4736	± 0.00029	0.1071	± 0.0015	
27-Co-58	511		0.300	± 0.004	annihilation radiation
27-Co-58	810.759	± 0.002	0.9945	± 0.0001	
27-Co-60	1173.228	± 0.003	0.9985	± 0.0003	
27-Co-60	1332.492	± 0.004	0.999826	± 0.000006	
29-Cu-64	511		0.3572	± 0.0028	annihilation radiation
29-Cu-64	1345.77	± 0.16	0.00475	± 0.00010	
30-Zn-65	511		0.0284	± 0.0004	annihilation radiation

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
30-Zn-65	1115.539	± 0.002	0.5060	± 0.0022	
31-Ga-66	833.5324	± 0.0021	0.059	± 0.005	
31-Ga-66	1039.220	± 0.003	0.37	± 0.03	
31-Ga-66	1333.112	± 0.005	0.0117	± 0.0009	
31-Ga-66	1418.754	± 0.005	0.0061	± 0.0005	
31-Ga-66	1508.158	± 0.007	0.0055	± 0.0004	
31-Ga-66	1898.823	± 0.008	0.0039	± 0.0003	
31-Ga-66	1918.329	± 0.005	0.0199	± 0.0016	
31-Ga-66	2189.616	± 0.006	0.053	± 0.004	
31-Ga-66	2422.525	± 0.007	0.0188	± 0.0015	
31-Ga-66	2751.835	± 0.005	0.227	± 0.018	
31-Ga-66	3228.800	± 0.006	0.0151	± 0.0012	
31-Ga-66	3380.850	± 0.006	0.0146	± 0.0012	
31-Ga-66	3422.040	± 0.008	0.0086	± 0.0007	
31-Ga-66	3791.004	± 0.008	0.0109	± 0.0009	
31-Ga-66	4085.853	± 0.009	0.0127	± 0.0010	
31-Ga-66	4295.187	± 0.010	0.038	± 0.003	
31-Ga-66	4461.202	± 0.009	0.0084	± 0.0007	
31-Ga-66	4806.007	± 0.009	0.0186	± 0.0015	
31-Ga-67	91.265	± 0.005	0.0307	± 0.0011	
31-Ga-67	93.310	± 0.005	0.378	± 0.009	
31-Ga-67	184.576	± 0.010	0.209	± 0.007	
31-Ga-67	208.950	± 0.010	0.0237	± 0.0008	
31-Ga-67	300.217	± 0.010	0.168	± 0.006	
31-Ga-67	393.527	± 0.010	0.0466	± 0.0016	
31-Ga-68	511		1.7828	± 0.0022	annihilation radiation
31-Ga-68	1077.34	± 0.05	0.0322	± 0.0003	
34-Se-75	66.0518	± 0.0008	0.01112	± 0.00012	
34-Se-75	96.7340	± 0.0009	0.0342	± 0.0003	
34-Se-75	121.1155	± 0.0011	0.172	± 0.003	
34-Se-75	136.0001	± 0.0006	0.582	± 0.007	
34-Se-75	198.6060	± 0.0012	0.0148	± 0.0004	
34-Se-75	264.6576	± 0.0009	0.589	± 0.003	
34-Se-75	279.5422	± 0.0010	0.2499	± 0.0013	
34-Se-75	303.9236	± 0.0010	0.01316	± 0.00008	
34-Se-75	400.6572	± 0.0008	0.1147	± 0.0009	
36-Kr-85	513.997	± 0.005	0.00435	± 0.00010	
38-Sr-85	514.0048	± 0.0022	0.985	± 0.004	
39-Y-88	898.036	± 0.004	0.9390	± 0.0023	
39-Y-88	1836.052	± 0.013	0.9938	± 0.0003	
41-Nb-93m	30.77	± 0.02	(5.59	± 0.16) 10^{-6}	
41-Nb-94	702.639	± 0.004	0.99815	± 0.00006	
41-Nb-94	871.114	± 0.003	0.99892	± 0.00003	
41-Nb-95	765.803	± 0.006	0.99808	± 0.00007	

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
42-Mo-99/43-Tc-99m	40.58323	± 0.00017	0.01022	± 0.00027	
42-Mo-99/43-Tc-99m	140.511	± 0.001	0.896	± 0.017	
42-Mo-99/43-Tc-99m	181.094	± 0.002	0.0601	± 0.0011	
42-Mo-99/43-Tc-99m	366.421	± 0.015	0.01194	± 0.00023	
42-Mo-99/43-Tc-99m	739.500	± 0.017	0.1212	± 0.0015	
42-Mo-99/43-Tc-99m	777.921	± 0.020	0.0428	± 0.0008	
43-Tc-99m	140.511	± 0.001	0.885	± 0.002	
43-Tc-99m	142.683	± 0.001	0.00023	± 0.00002	
44-Ru-103	39.760	± 0.010	0.00071	± 0.00003	
44-Ru-103	53.275	± 0.010	0.00384	± 0.00006	
44-Ru-103	294.98	± 0.02	0.00289	± 0.00006	
44-Ru-103	443.80	± 0.02	0.00344	± 0.00003	
44-Ru-103	497.08	± 0.02	0.9131	± 0.0007	
44-Ru-103	557.04	± 0.02	0.00855	± 0.00005	
44-Ru-103	610.33	± 0.02	0.0578	± 0.0003	
44-Ru-106/45-Rh 106	511.8534	± 0.0023	0.2050	± 0.0021	
44-Ru-106/45-Rh-106	616.22	± 0.09	0.00724	± 0.00013	
44-Ru-106/45-Rh-106	621.93	± 0.06	0.0986	± 0.0011	
44-Ru-106/45-Rh-106	873.49	± 0.05	0.00435	± 0.00008	
44-Ru-106/45-Rh-106	1050.41	± 0.06	0.01488	± 0.00022	
44-Ru-106/45-Rh-106	1128.07	± 0.05	0.00399	± 0.00006	
47-Ag-110m	446.812	± 0.003	0.0365	± 0.0005	with ^{110}Ag
47-Ag-110m	620.3553	± 0.0017	0.0272	± 0.0008	with ^{110}Ag
47-Ag-110m	657.7600	± 0.0011	0.9438	± 0.0008	with ^{110}Ag
47-Ag-110m	677.6217	± 0.0012	0.1056	± 0.0006	with ^{110}Ag
47-Ag-110m	687.0091	± 0.0018	0.0645	± 0.0003	with ^{110}Ag
47-Ag-110m	706.6760	± 0.0015	0.1648	± 0.0008	with ^{110}Ag
47-Ag-110m	744.2755	± 0.0018	0.0471	± 0.0003	with ^{110}Ag
47-Ag-110m	763.9424	± 0.0017	0.2231	± 0.0009	with ^{110}Ag
47-Ag-110m	818.0244	± 0.0018	0.0733	± 0.0004	with ^{110}Ag
47-Ag-110m	884.6781	± 0.0013	0.740	± 0.012	with ^{110}Ag
47-Ag-110m	937.483	± 0.003	0.3451	± 0.0027	with ^{110}Ag
47-Ag-110m	1384.2931	± 0.0020	0.247	± 0.005	with ^{110}Ag
47-Ag-110m	1475.7792	± 0.0023	0.0403	± 0.0005	with ^{110}Ag
47-Ag-110m	1505.0280	± 0.0020	0.1316	± 0.0016	with ^{110}Ag
47-Ag-110m	1562.294	± 0.018	0.0121	± 0.0003	with ^{110}Ag
48-Cd-109	88.0336	± 0.0011	0.03626	± 0.00020	
49-In-111	171.28	± 0.03	0.9066	± 0.0025	
49-In-111	245.35	± 0.04	0.9409	± 0.0006	
50-Sn-113	255.134	± 0.010	0.0211	± 0.0008	
50-Sn-113	391.698	± 0.003	0.6494	± 0.0017	
51-Sb-125	176.314	± 0.002	0.0682	± 0.0007	
51-Sb-125	380.452	± 0.008	0.01520	± 0.00015	
51-Sb-125	427.874	± 0.004	0.2955	± 0.0024	

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
51-Sb-125	463.365	± 0.004	0.1048	± 0.0009	
51-Sb-125	600.597	± 0.002	0.1776	± 0.0018	
51-Sb-125	606.713	± 0.003	0.0502	± 0.0005	
51-Sb-125	635.950	± 0.003	0.1132	± 0.0010	
51-Sb-125	671.441	± 0.006	0.01783	± 0.00016	
52-Te-123m	158.97	± 0.05	0.8399	± 0.0008	
53-I-123	158.97	± 0.05	0.8325	± 0.0021	
53-I-123	528.96	± 0.05	0.0132	± 0.0008	
53-I-125	35.4919	± 0.0005	0.0667	± 0.0017	
53-I-129	39.578	± 0.004	0.0742	± 0.0008	
53-I-131	80.1850	± 0.0019	0.02607	± 0.00027	
53-I-131	284.305	± 0.005	0.0606	± 0.0006	
53-I-131	364.489	± 0.005	0.812	± 0.008	
53-I-131	636.989	± 0.004	0.0726	± 0.0008	
53-I-131	722.911	± 0.005	0.01796	± 0.00020	
55-Cs-134	563.243	± 0.003	0.0837	± 0.0003	
55-Cs-134	569.327	± 0.003	0.1538	± 0.0004	
55-Cs-134	604.720	± 0.003	0.97650	± 0.00018	
55-Cs-134	795.83	± 0.03	0.855	± 0.003	
55-Cs-134	801.945	± 0.004	0.0870	± 0.0003	
55-Cs-134	1365.186	± 0.004	0.03017	± 0.00012	
55-Cs-137	661.657	± 0.003	0.8499	± 0.0020	
56-Ba-133	53.1622	± 0.0006	0.0214	± 0.0003	
56-Ba-133	79.6142	± 0.0012	0.0265	± 0.0005	
56-Ba-133	80.9979	± 0.0011	0.329	± 0.003	
56-Ba-133	276.3989	± 0.0012	0.0716	± 0.0005	
56-Ba-133	302.8508	± 0.0005	0.1834	± 0.0013	
56-Ba-133	356.0129	± 0.0007	0.6205	± 0.0019	
56-Ba-133	383.8485	± 0.0012	0.0894	± 0.0006	
58-Ce-139	165.8575	± 0.0011	0.799	± 0.0004	
58-Ce-141	145.4433	± 0.0014	0.4829	± 0.0020	
58-Ce-144/59-Pr-144	33.568	± 0.010	0.00235	± 0.00012	^{144}Ce
58-Ce-144/59-Pr-144	40.98	± 0.10	0.0041	± 0.0025	^{144}Ce
58-Ce-144/59-Pr-144	80.12	± 0.05	0.0152	± 0.0010	^{144}Ce
58-Ce-144/59-Pr-144	133.515	± 0.004	0.1109	± 0.0016	^{144}Ce
58-Ce-144/59-Pr-144	696.505	± 0.004	0.01342	± 0.00014	^{144}Pr - per ^{144}Ce decay
58-Ce-144/59-Pr-144	1489.148	± 0.003	0.00296	± 0.00005	^{145}Pr - per ^{144}Ce decay
58-Ce-144/59-Pr-144	2185.645	± 0.005	0.00680	± 0.00018	^{146}Pr - per ^{144}Ce decay
62-Sm-153	69.67301	± 0.00018	0.0473	± 0.0003	
62-Sm-153	83.36716	± 0.00017	0.00192	± 0.00007	
62-Sm-153	89.48593	± 0.00021	0.00158	± 0.00015	
62-Sm-153	97.43095	± 0.00017	0.00772	± 0.00018	
62-Sm-153	103.1801	± 0.00013	0.293	± 0.003	
62-Sm-153	172.85295	± 0.00021	0.000737	± 0.000020	

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
63-Eu-152	121.7817	± 0.0003	0.2841	± 0.0013	ε
63-Eu-152	244.6974	± 0.0008	0.0755	± 0.0004	ε
63-Eu-152	344.2785	± 0.0012	0.2658	± 0.0012	β^-
63-Eu-152	411.1165	± 0.0012	0.02237	± 0.00010	β^-
63-Eu-152	443.965	± 0.003	0.03125	± 0.00014	ε
63-Eu-152	778.9045	± 0.0024	0.1296	± 0.0006	β^-
63-Eu-152	867.380	± 0.003	0.04241	± 0.00023	ε
63-Eu-152	964.072	± 0.018	0.1462	± 0.0006	ε
63-Eu-152	1085.837	± 0.010	0.1013	± 0.0006	ε
63-Eu-152	1089.737	± 0.005	0.01731	± 0.00010	β^-
63-Eu-152	1112.076	± 0.003	0.1340	± 0.0006	ε
63-Eu-152	1212.948	± 0.011	0.01415	± 0.00009	ε
63-Eu-152	1299.142	± 0.008	0.01632	± 0.00009	β^-
63-Eu-152	1408.013	± 0.003	0.2085	± 0.0009	ε
63-Eu-154	123.0706	± 0.0009	0.404	± 0.005	
63-Eu-154	247.9288	± 0.0007	0.0689	± 0.0007	
63-Eu-154	591.755	± 0.003	0.0495	± 0.0005	
63-Eu-154	692.4205	± 0.0018	0.0179	± 0.0003	
63-Eu-154	723.3014	± 0.0022	0.2005	± 0.0021	
63-Eu-154	756.8020	± 0.0023	0.0453	± 0.0005	
63-Eu-154	873.1834	± 0.0023	0.1217	± 0.0012	
63-Eu-154	996.262	± 0.006	0.1050	± 0.0010	
63-Eu-154	1004.725	± 0.007	0.1785	± 0.0017	
63-Eu-154	1246.121	± 0.004	0.00862	± 0.00008	
63-Eu-154	1274.429	± 0.004	0.349	± 0.003	
63-Eu-154	1596.4804	± 0.0028	0.01783	± 0.00017	
63-Eu-155	26.531	± 0.021	0.00316	± 0.00022	
63-Eu-155	45.2990	± 0.0010	0.0131	± 0.0005	
63-Eu-155	60.0086	± 0.0010	0.0122	± 0.0005	
63-Eu-155	86.0591	± 0.0010	0.00154	± 0.00017	
63-Eu-155	86.5479	± 0.0010	0.307	± 0.003	
63-Eu-155	105.3083	± 0.0010	0.211	± 0.006	
67-Ho-166	80.576	± 0.002	0.0655	± 0.0008	
67-Ho-166	1379.437	± 0.006	0.00933	± 0.00016	
67-Ho-166	1581.833	± 0.007	0.00186	± 0.00004	
67-Ho-166	1662.439	± 0.006	0.00118	± 0.00005	
67-Ho-166m	80.5725	± 0.0013	0.1266	± 0.0023	
67-Ho-166m	184.4107	± 0.0011	0.725	± 0.005	
67-Ho-166m	215.871	± 0.007	0.0266	± 0.0017	
67-Ho-166m	259.736	± 0.010	0.01078	± 0.00010	
67-Ho-166m	280.4630	± 0.0023	0.2954	± 0.0025	
67-Ho-166m	300.741	± 0.003	0.0373	± 0.0004	
67-Ho-166m	365.768	± 0.006	0.0246	± 0.0004	
67-Ho-166m	410.956	± 0.003	0.1135	± 0.0018	

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
67-Ho-166m	451.540	± 0.004	0.02915	± 0.00014	
67-Ho-166m	464.798	± 0.006	0.0125	± 0.0004	
67-Ho-166m	529.825	± 0.004	0.094	± 0.004	
67-Ho-166m	570.995	± 0.005	0.0543	± 0.0020	
67-Ho-166m	611.579	± 0.006	0.0131	± 0.0021	
67-Ho-166m	670.526	± 0.004	0.0534	± 0.0021	
67-Ho-166m	691.253	± 0.007	0.0132	± 0.0007	
67-Ho-166m	711.697	± 0.003	0.549	± 0.012	
67-Ho-166m	752.280	± 0.004	0.122	± 0.003	
67-Ho-166m	810.286	± 0.004	0.573	± 0.011	
67-Ho-166m	830.565	± 0.004	0.0972	± 0.0018	
67-Ho-166m	950.988	± 0.004	0.02744	± 0.00019	
69-Tm-170	78.59	± 0.02	3.4E-05	± 0.000003	
69-Tm-170	84.25474	± 0.00008	0.0248	± 0.0009	
70-Yb-169	63.12044	± 0.00004	0.4405	± 0.0024	
70-Yb-169	93.61447	± 0.00008	0.02571	± 0.00017	
70-Yb-169	109.77924	± 0.00004	0.1736	± 0.0009	
70-Yb-169	118.18940	± 0.00014	0.01870	± 0.00010	
70-Yb-169	130.52293	± 0.00006	0.1138	± 0.0005	
70-Yb-169	177.21307	± 0.00006	0.2232	± 0.0010	
70-Yb-169	197.95675	± 0.00007	0.3593	± 0.0012	
70-Yb-169	261.07712	± 0.00009	0.01687	± 0.00008	
70-Yb-169	307.73586	± 0.00010	0.10046	± 0.00045	
77-Ir-192	205.79430	± 0.00009	0.0334	± 0.0004	
77-Ir-192	295.95650	± 0.00015	0.2872	± 0.0014	
77-Ir-192	308.45507	± 0.00017	0.2968	± 0.0015	
77-Ir-192	316.50618	± 0.00017	0.8275	± 0.0021	
77-Ir-192	468.06885	± 0.00026	0.4781	± 0.0024	
77-Ir-192	484.5751	± 0.0004	0.03189	± 0.00024	
77-Ir-192	588.5810	± 0.0007	0.04517	± 0.00022	
77-Ir-192	604.41105	± 0.00025	0.0820	± 0.0004	
77-Ir-192	612.46215	± 0.00026	0.0534	± 0.0008	
79-Au-198	411.80205	± 0.00017	0.9554	± 0.0007	
79-Au-198	675.8836	± 0.0007	0.00806	± 0.00007	
79-Au-198	1087.6842	± 0.0007	0.00159	± 0.00003	
80-Hg-203	279.1952	± 0.0010	0.8148	± 0.0008	
81-Tl-201	135.312	± 0.034	0.02604	± 0.00022	
81-Tl-201	167.450	± 0.030	0.100	± 0.0010	
81-Tl-208	277.37	± 0.03	0.0237	± 0.0011	per ^{228}Th decay - ^{228}Th decay chain
81-Tl-208	583.187	± 0.002	0.3055	± 0.0017	per ^{228}Th decay - ^{228}Th decay chain
81-Tl-208	860.56	± 0.03	0.0448	± 0.0004	per ^{228}Th decay - ^{228}Th decay chain
81-Tl-208	2614.511	± 0.010	0.3585	± 0.0007	per ^{228}Th decay - ^{228}Th decay chain
82-Pb-212	115.183	± 0.005	0.00623	± 0.00022	^{228}Th decay chain
82-Pb-212	238.632	± 0.002	0.436	± 0.003	^{228}Th decay chain

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
82-Pb-212	300.09	± 0.01	0.0318	± 0.0013	^{228}Th decay chain
82-Pb-214	53.2275	± 0.0021	0.01066	± 0.00014	^{226}Ra decay chain
82-Pb-214	241.997	± 0.003	0.0719	± 0.0006	^{226}Ra decay chain
82-Pb-214	295.224	± 0.002	0.1828	± 0.0014	^{226}Ra decay chain
82-Pb-214	351.932	± 0.002	0.3534	± 0.0027	^{226}Ra decay chain
83-Bi-207	569.698	± 0.002	0.9776	± 0.0003	
83-Bi-207	1063.656	± 0.003	0.7458	± 0.0049	
83-Bi-207	1770.228	± 0.009	0.0687	± 0.0003	
83-Bi-212	727.33	± 0.01	0.0674	± 0.0012	^{228}Th decay chain
83-Bi-212	785.37	± 0.09	0.0111	± 0.0001	^{228}Th decay chain
83-Bi-212	1620.74	± 0.01	0.0151	± 0.0003	^{228}Th decay chain
83-Bi-214	609.316	± 0.003	0.4516	± 0.0033	^{226}Ra decay chain
83-Bi-214	665.453	± 0.022	0.01521	± 0.00011	^{226}Ra decay chain
83-Bi-214	768.367	± 0.011	0.04850	± 0.00038	^{226}Ra decay chain
83-Bi-214	806.185	± 0.011	0.01255	± 0.00011	^{226}Ra decay chain
83-Bi-214	934.061	± 0.012	0.03074	± 0.00025	^{226}Ra decay chain
83-Bi-214	1120.287	± 0.010	0.1478	± 0.0011	^{226}Ra decay chain
83-Bi-214	1155.19	± 0.02	0.01624	± 0.00014	^{226}Ra decay chain
83-Bi-214	1238.110	± 0.012	0.05785	± 0.00045	^{226}Ra decay chain
83-Bi-214	1280.96	± 0.02	0.01425	± 0.00012	^{226}Ra decay chain
83-Bi-214	1377.669	± 0.012	0.03954	± 0.00033	^{226}Ra decay chain
83-Bi-214	1401.516	± 0.014	0.01324	± 0.00011	^{226}Ra decay chain
83-Bi-214	1407.993	± 0.007	0.02369	± 0.00019	^{226}Ra decay chain
83-Bi-214	1509.217	± 0.008	0.02108	± 0.00021	^{226}Ra decay chain
83-Bi-214	1661.316	± 0.013	0.01037	± 0.00010	^{226}Ra decay chain
83-Bi-214	1729.640	± 0.012	0.02817	± 0.00023	^{226}Ra decay chain
83-Bi-214	1764.539	± 0.015	0.1517	± 0.0012	^{226}Ra decay chain
83-Bi-214	1847.420	± 0.025	0.02000	± 0.00018	^{226}Ra decay chain
83-Bi-214	2118.536	± 0.008	0.01148	± 0.00011	^{226}Ra decay chain
83-Bi-214	2204.071	± 0.021	0.0489	± 0.0010	^{226}Ra decay chain
83-Bi-214	2447.673	± 0.010	0.01536	± 0.00015	^{226}Ra decay chain
86-Rn-220	549.76	± 0.04	0.00115	± 0.00015	^{228}Th decay chain
88-Ra-224	240.986	± 0.006	0.0412	± 0.0004	^{228}Th decay chain
88-Ra-226	186.211	± 0.013	0.03533	± 0.00028	^{226}Ra decay chain
90-Th-228	84.373	± 0.003	0.0117	± 0.0005	^{228}Th decay chain
90-Th-228	131.612	± 0.004	0.00124	± 0.00006	^{228}Th decay chain
90-Th-228	215.985	± 0.004	0.00226	± 0.00020	^{228}Th decay chain
91-Pa-234m	258.24	± 0.07	0.00073	± 0.000009	daughter of ^{234}Th (^{238}U)
91-Pa-234m	742.814	± 0.022	0.00096	± 0.00003	daughter of ^{234}Th (^{238}U)
91-Pa-234m	766.358	± 0.020	0.00318	± 0.00005	daughter of ^{234}Th (^{238}U)
91-Pa-234m	786.272	± 0.022	0.00054	± 0.00001	daughter of ^{234}Th (^{238}U)
91-Pa-234m	1001.025	± 0.022	0.00832	± 0.00010	daughter of ^{234}Th (^{238}U)
95-Am-241	26.3446	± 0.0002	0.024	± 0.0003	
95-Am-241	33.1963	± 0.0003	0.00121	± 0.00003	

Recommended gamma-ray energies and emission probabilities ordered by radionuclide

Nuclide	Energy (keV)		Emission Probability per decay		Comments
	Eγ	uncertainty	Pγ	uncertainty	
95-Am-241	59.5409	± 0.0001	0.3578	± 0.0009	
95-Am-243	43.53	± 0.02	0.0589	± 0.0010	
95-Am-243	74.66	± 0.02	0.672	± 0.012	

Data uncertainties are defined as standard deviations corresponding to the 1σ confidence level.

^{51}Cr

Half-life evaluated by M. J. Woods (NPL, UK), September 2003.
Decay scheme evaluated by E. Schönfeld (PTB, Germany) and R. G. Helmer (INEEL. USA), February 2000.

Recommended data:

Half-life

$T_{1/2}$ = 27.7009 (20) d

Selected gamma ray

E_γ (keV)	P_γ per decay
320.0835 (4) [a]	0.0987 (5) [b]

[a] from Ref. [1].
[b] from direct emission probability measurements.

Selected X-rays

Origin		E_X (keV)	P_X per decay
V	Kα	4.94 - 4.95	0.202 (3)
V	Kβ	5.43 - 5.46	0.0269 (7)

Input data:

Half-life

Half-life (d)	Reference
27.7010 (12) [a]	Unterweger *et al* [H1]
27.71 (3)	Walz *et al* [H2]
27.704 (3)	Rutledge *et al* [H3]
27.690 (5)	Houtermans *et al* [H4]
27.72 (3)	Lagoutine *et al* [H5]
27.703 (8)	Tse *et al* [H6]
27.75 (1) [b]	Visser *et al* [H7]
28.1 (17) [b]	Araminowicz and Dresler [H8]
27.76 (15) [b]	Emery *et al* [H9]
27.80 (51) [b]	Bormann *et al* [H10]
27.7009 (20)	

[a] uncertainty increased to (25) to ensure weighting factor not greater than 0.50.
[b] rejected as an outlier.

References - half-life

[H1] M. P. Unterweger, D. D. Hoppes, F. J. Schima, Nucl. Instrum. Meth. Phys. Res. **A312** (1992) 349
[H2] K. F. Walz, K. Debertin, H. Schrader, Int. J. Appl. Radiat. Isot. **34** (1983) 1191.
[H3] A. R. Rutledge, L. V. Smith, J. S. Merritt, AECL-6692 (1980).
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[H5] F. Lagoutine, J. Legrand, C. Bac, Int. J. Appl. Radiat. Isot. **26** (1975) 131.
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[H9] J. F. Emery, S. A. Reynolds, E. I. Wyatt, G. I. Gleason, Nucl. Sci. Eng. **48** (1972) 319.
[H10] M. Bormann, A. Behrend, I. Riehle, O. Vogel, Nucl. Phys. **A115** (1968) 309.

Gamma ray: measured and evaluated emission probability

Eγ (keV) [1]	[2]	[3]	[4]	[5]	[6]	[7]
320.0835	0.098 (6)	0.09 (1)	0.0972 (15)	0.102 (6)	0.0975 (20)	0.102 (10)

Eγ (keV) [1]	[8]	[9]	[10]	**Evaluated**
320.0835	0.0985 (9)	0.1030 (19)	0.0986 (8)	0.0987 (5)

Evaluated emission probabilities are the weighted averages calculated according to the Limitation of Relative Statistical Weights Method; no value has a relative weighting factor greater than 0.50.

References - radiations

[1] R. G. Helmer, C. van der Leun, Nucl. Instrum. Meth. Phys. Res. **A450** (2000) 35.
[2] M. E. Bunker, J. W. Starner, Phys. Rev. **97** (1955) 1272, and **99** (1955) 1906.
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[10] T. Barta, L. Szücs, A. Zsinka, Appl. Radiat. Isot. **42** (1991) 490.

Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{203}Hg

Half-life evaluated by M. J. Woods (NPL, UK), September 2003.
Decay scheme evaluated by A. L. Nichols (IAEA and AEA Technology, UK), January 2002.

Recommended data:

Half-life

$T_{1/2}$ = 46.594 (12) d

Selected gamma rays

E_γ (keV)	P_γ per decay
279.1952 (10) [a]	0.8148 (8)

[a] from Ref. [1].

Selected X-rays

Origin		E_X (keV)	P_X per decay
Tl	L	8.953 - 14.738	0.0543 (9)
Tl	Kα_2	70.8325 (8)	0.0375 (4)
Tl	Kα_1	72.8725 (8)	0.0633 (6)
Tl	Kβ_1'	82.118 - 83.115	0.0215 (4)
Tl	Kβ_2'	84.838 - 85.530	0.0064 (2)

Input data:

Half-life

Half-life (d)	Reference
46.619 (27)	Unterweger *et al* [H1]
46.612 (19)	Walz *et al* [H2]
46.60 (1)	Rutledge *et al* [H3]
46.582 (2) [a]	Houtermans *et al* [H4]
46.76 (8) [b]	Emery *et al* [H5]
47.00 (3) [b]	Lagoutine *et al* [H6]
46.594 (12)	

[a] uncertainty increased to (9) to ensure weighting factor not greater than 0.50.
[b] rejected as an outlier.

References - half-life

[H1] M. P. Unterweger, D. D. Hoppes, F. J. Schima, Nucl. Instrum. Meth. Phys. Res. **A312** (1992) 349.
[H2] K. F. Walz, K. Debertin, H. Schrader, Int. J. Appl. Radiat. Isot. **34** (1983) 1191.
[H3] A. R. Rutledge, L. V. Smith, J. S. Merritt, AECL-6692 (1980).
[H4] H. Houtermans, O. Milosevic, F. Reichel, Int. J. Appl. Radiat. Isot. **31** (1980) 153.
[H5] J. F. Emery, S. A. Reynolds, E. I. Wyatt, G. I. Gleason, Nucl. Sci. Eng. **48** (1972) 319.
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Gamma ray: energy and emission probability

Comments:

γ-ray energy of 279.1952 keV have been adopted from Ref. [1].
279.1952-keV γ-ray is of mixed (25%M1 + 75%E2) multipolarity, and α_{tot} = 0.2271 (12) and α_K = 0.1640 (10) have been adopted from Ref. [2], in good agreement with specific measurements [3-6].
beta-particle emission probabilities were calculated from the limit of 0.0001 (1) set on the beta transition to the ½$^+$ ground state of ^{203}Tl [7, 8], to give 0.9999 (1) for the transition to the first excited state of ^{203}Tl ($5/2^- \rightarrow 3/2^+$).
as defined above, transition probability of 0.9999 (1) for the 279.1952-keV γ ray was used in conjunction with α_{tot} to calculate an absolute emission probability of 0.8148 (8).

X-rays: energies and emissions

Calculated using the evaluated γ-ray data, and atomic data from Refs. [9-11].

References - radiations

[1] R. G. Helmer, C. van der Leun, Nucl. Instrum. Meth. Phys. Res. **A450** (2000) 35.
[2] H. H. Hansen, European Appl. Res. Rept., Nucl. Sci. Technol. **6**, No. 4 (1985) 777.
[3] J. G. V. Taylor, Can. J. Phys. **40** (1962) 383.
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Detailed tables and comments can be found on:
http://www.nucleide.org/DDEP_WG/DDEPdata.htm

^{226}Ra with Daughters

Half-life evaluated by M. J. Woods (NPL, UK), September 2003.
Decay scheme evaluated by R. G. Helmer (INEEL, USA), August 2002.

Recommended data:

Half-life (^{226}Ra)
$T_{1/2} = 5.862\ (22) \times 10^5$ d

Selected gamma rays

Only γ rays with emission probabilities greater than 0.010 are included.

Parent	E_γ (keV)	P_γ per decay
^{214}Pb	53.2275 (21) [a]	0.01066 (14)
^{226}Ra	186.211 (13) [a]	0.03533 (28)
^{214}Pb	241.997 (3) [a]	0.0719 (6)
^{214}Pb	295.224 (2) [a]	0.1828 (14)
^{214}Pb	351.932 (2) [a]	0.3534 (27)
^{214}Bi	609.316 (3) [b]	0.4516 (33)
^{214}Bi	665.453 (22) [a]	0.01521 (11)
^{214}Bi	768.367 (11) [b]	0.04850 (38)
^{214}Bi	806.185 (11) [b]	0.01255 (11)
^{214}Bi	934.061 (12) [a]	0.03074 (25)
^{214}Bi	1120.287 (10) [a]	0.1478 (11)
^{214}Bi	1155.19 (2) [a]	0.01624 (14)
^{214}Bi	1238.110 (12) [a]	0.05785 (45)
^{214}Bi	1280.96 (2) [a]	0.01425 (12)
^{214}Bi	1377.669 (12) [a]	0.03954 (33)
^{214}Bi	1401.516 (14) [c]	0.01324 (11)
^{214}Bi	1407.993 (7) [b]	0.02369 (19)
^{214}Bi	1509.217 (8) [b]	0.02108 (21)
^{214}Bi	1661.316 (13) [b]	0.01037 (10)
^{214}Bi	1729.640 (12) [b]	0.02817 (23)
^{214}Bi	1764.539 (15) [b]	0.1517 (12)
^{214}Bi	1847.420 (25) [a]	0.02000 (18)
^{214}Bi	2118.536 (8) [b]	0.01148 (11)
^{214}Bi	2204.071 (21) [b]	0.0489 (10)
^{214}Bi	2447.673 (10) [b]	0.01536 (15)

[a] from Ref. [1].
[b] from Ref. [2].
[c] from Ref. [3].

Input data:

Half-life

Half-life (d)	Reference
584035 (853) [a]	Ramthun [H1]
585131 (3204)	Martin and Tuck [H2]
590609 (4135)	Sebaoun [H3]
592436 (4749)	Kohman *et al* [H4]
$5.862\ (22) \times 10^5$	

[a] uncertainty increased to (2250) to ensure weighting factor not greater than 0.50.

References - half-life

[H1] H. Ramthun, Nukleonik **8** (1966) 244.
[H2] G. R. Martin, D. G. Tuck, Int. J. Appl. Radiat. Isot. **5** (1959) 141.
[H3] W. Sebaoun, Ann. Phys., Paris **1** (1956) 680.
[H4] T. P. Kohman, D. P. Ames, J. Sedlet, Nat. Nucl. Energy Series **14** (1949) 1675.

Gamma rays: measured and evaluated relative emission probabilities

Eγ (keV)	[4]	[5]	[6] [a]	[7]	[8]	[3]	Evaluated
53.2	-	-	-	-	2.329 (23)	2.384 (20)	2.360 (27)
186.21	8.7 (11)	9.2 (10)	8.58 (5)	7.6 (8)	7.812 (31)	7.85 (5)	7.824 (26)
241.99	17.5 (17)	16.1 (24)	16.23 (10)	16.1 (10)	15.90 (5)	15.98 (6)	15.93 (4)
295.22	40 (4)	42 (5)	41.85 (26)	40.8 (12)	40.36 (12)	40.61 (13)	40.48 (9)
351.93	86 (9)	82 (11)	81.5 (5)	78.5 (24)	78.16 (23)	78.34 (23)	78.25 (16)
609.32	≡100	100	100	100	100	100	100
665.45	3.6 (4)	3.36 (37)	3.51 (20)	3.33 (10)	3.359 (17)	3.386 (21)	3.369 (13)
768.37	11.4 (12)	11.9 (17)	10.91 (8)	10.39 (31)	10.66 (5)	10.768 (29)	10.740 (29)
806.18	3.0 (4)	2.92 (43)	2.90 (22)	2.76 (11)	2.788 (22)	2.777 (14)	2.780 (12)
934.06	7.3 (7)	7.0 (9)	6.88 (5)	6.70 (20)	6.783 (34)	6.834 (36)	6.806 (25)
1120.29	34 (3)	-	33.13 (22)	32.3 (10)	32.71 (10)	32.77 (12)	32.73 (8)
1155.19	4.0 (5)	-	3.5 (4)	4.3 (7)	3.594 (36)	3.595 (17)	3.595 (15)
1238.11	14.9 (15)	-	12.87 (9)	12.7 (4)	12.83 (6)	12.80 (4)	12.810 (33)
1280.96	3.6 (5)	-	3.17 (17)	3.15 (11)	3.147 (28)	3.159 (16)	3.156 (14)
1377.67	9.9 (11)	-	8.82 (25)	8.52 (25)	8.69 (4)	8.794 (30)	8.755 (35)
1401.52	3.5 (4)	-	2.91 (16)	3.0 (4)	2.924 (20)	2.934 (13)	2.932 (11)
1407.99	6.2 (7)	-	5.37 (6)	5.5 (5)	5.233 (26)	5.250 (19)	5.245 (15)
1509.22	5.5 (5)	-	4.76 (5)	4.63 (15)	4.61 (6)	4.682 (31)	4.668 (31)
1661.32	2.72 (25)	-	2.33 (12)	2.37 (22)	2.271 (34)	2.299 (14)	2.296 (14)
1729.64	7.5 (7)	-	6.60 (4)	6.33 (15)	6.226 (31)	6.245 (32)	6.238 (25)
1764.54	40 (4)	-	34.48 (25)	33.3 (10)	33.54 (10)	33.63 (9)	33.59 (7)
1847.42	5.3 (5)	-	4.57 (6)	4.35 (13)	4.448 (36)	4.419 (28)	4.429 (25)
2118.54	3.03 (29)	-	2.56 (3)	2.65 (25)	2.536 (20)	2.548 (21)	2.543 (15)
2204.07	12.38 (27)	-	11.02 (9)	11.1 (3)	10.74 (5)	10.75 (9)	10.83 (20)
2447.67	4.0 (4)	-	3.42 (3)	3.30 (10)	3.402 (24)	3.409 (36)	3.402 (21)

[a] data rejected as outliers.

Evaluated emission probabilities are the weighted averages calculated according to the Limitation of Relative Statistical Weights Method, and using the data from Refs. [3-5, 7, 8]; no value has a relative weighting factor greater than 0.50.

Absolute emission probabilities for specific γ rays have been measured by several authors [9-13]. Generally, the uncertainties in the relative emission probabilities from these authors have larger uncertainties than those for the relative values in the above table. Therefore, the above relative emission probabilities have been normalized simply by use of P_γ(609 keV) = 0.4516 (33) from the average of the values from Refs. [9-13].

References - radiations

[1] Y. A. Akovali, Nucl. Data Sheets **75** (1995) 127; *ibid*, **77** (1996) 271.
[2] R. G. Helmer, R. J. Gehrke, R. C. Greenwood, Nucl. Instrum. Meth. **166** (1970) 547.
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Detailed tables and comments can be found on http://www.nucleide.org/DDEP_WG/DDEPdata.htm

APPENDIX B

UPDATED ACTINIDE DECAY DATA

EXAMPLE DATA

Health Warning: all decay data are subject to change (see Section 3.2)

$^{242}_{95}Am_{147}$

1 Decay Scheme

Am-242 decays by β^- emission to the first excited level and the ground state of Cm-242 (83.1%), and by electron capture decay to the first excited level and ground state of Pu-242 (16.9%).

2 Nuclear Data

$T_{½}(^{242}Am)$	:	16.01	(2)	h
$Q^-(^{242}Am)$	:	664.5	(4)	keV
$Q_{EC}(^{242}Am)$	:	751.3	(7)	keV

2.1 β^- Transitions

	Energy keV	Probability x 100	Nature	lg *ft*
$\beta^-_{0,1}$	622.4 (5)	45.8 (2)	1st forbidden non-unique	6.84
$\beta^-_{0,0}$	664.5 (4)	37.3 (1)	1st forbidden non-unique	7.03

2.2 Electron Capture Transitions

	Energy keV	Probability x 100	Nature	lg *ft*	P_K	P_L	P_M
$EC_{0,1}$	706.8 (7)	10.6 (1)	1st forbidden non-unique	7.26	0.7261 (23)	0.2016 (15)	0.0532 (10)
$EC_{0,0}$	751.3 (7)	6.3 (1)	1st forbidden non-unique	7.55	0.7303 (22)	0.1987 (15)	0.0522 (10)

2.3 Gamma Transitions and Internal Conversion Coefficients

	Energy keV	$P_{\gamma+ce}$ x 100	Multipolarity	α_K	α_L	α_{M+}	α_{total}
$\gamma_{1,0}$(Cm)	42.13 (5)	45.8 (2)	E2	-	836 (12)	319 (5)	1155 (17)
$\gamma_{1,0}$(Pu)	44.54 (2)	10.6 (1)	E2	-	544 (8)	204 (3)	748 (11)

3 Atomic Data

3.1 Pu

ω_K	:	0.971	(4)
ω_L	:	0.521	(20)
n_{KL}	:	0.790	(5)

3.1.1 X Radiations

		Energy keV	Relative probability
X_L			
	$L\ell$	12.124 }	
	$L\alpha$	14.087 - 14.282 }	
	$L\eta$	16.333 }	192.17
	$L\beta$	16.498 – 18.541 }	
	$L\gamma$	21.420 – 22.153 }	
X_K			
	$K\alpha_2$	99.525	63.17
	$K\alpha_1$	103.734	100
	$K\beta_3$	116.244 }	
	$K\beta_1$	117.228 }	36.65
	$K\beta_5$	117.918 }	
	$K\beta_2$	120.540 }	
	$K\beta_4$	120.969 }	12.81
	$KO_{2,3}$	121.543 }	

3.1.2 Auger Electrons

	Energy keV	Relative probability
Auger L	6.09 – 13.83	$4.7 \times 10^{+3}$
Auger K		
KLL	75.263 – 85.357	100
KLX	92.607 – 103.729	61.90
KXY	109.93 – 121.78	9.05

3.2 Cm

ω_K : 0.972 (4)
ω_L : 0.538 (23)
n_{KL} : 0.785 (5)

3.2.1 X Radiations

		Energy keV	Relative probability
X_L			
	$L\ell$	12.633	
	$L\alpha$	14.746 - 14.961	
	$L\eta$	17.314	
	$L\beta$	17.286 – 19.688	
	$L\gamma$	22.735 – 23.527	

3.2.2 Auger Electrons

	Energy keV	Relative probability
Auger L	6.19 – 14.46	

4 Electron Emissions

		Energy keV	Electrons per 100 disint.
e_{AL}	(Pu)	6.09 – 13.83	9.9 (5)
e_{AK}	(Pu)		
	KLL	75.263 – 85.357	0.21 (3)
	KLX	92.607 – 103.729	0.13 (2)
	KXY	109.93 – 121.78	0.019 (3)
e_{AL}	(Cm)	6.19 – 14.46	15.4 (9)
$ec_{1,0\,T}$	(Pu)	21.44 – 44.53	10.58 (10)
$ec_{1,0\,L}$	(Pu)	21.44 – 26.48	7.70 (7)
$ec_{1,0\,M+}$	(Pu)	38.61 – 44.53	2.88 (3)
$ec_{1,0\,T}$	(Cm)	17.60 – 42.11	45.76 (20)
$ec_{1,0\,L}$	(Cm)	17.60 – 23.16	33.12 (15)
$ec_{1,0\,M+}$	(Cm)	35.79 – 42.11	12.64 (5)
$\beta^-_{0,1}$			
	max:	622.4 (5)	45.8 (2)
	avg:	185.92 (14)	
$\beta^-_{0,0}$			
	max:	664.5 (4)	37.3 (1)
	avg:	200.17 (14)	

5 Photon Emissions

5.1 X-Ray Emissions

		Energy keV	Photons per 100 disint.
XL	(Pu)	12.124 – 22.153	10.8 (5)
$XK\alpha_2$	(Pu)	99.525	3.55 (4)
$XK\alpha_1$	(Pu)	103.734	5.62 (6)
$XK\beta_3$	(Pu)	116.244 }	
$XK\beta_1$	(Pu)	117.228 }	2.06 (4)
$XK\beta_5$	(Pu)	117.918 }	
$XK\beta_2$	(Pu)	120.540 }	
$XK\beta_4$	(Pu)	120.969 }	0.72 (2)
$XKO_{2,3}$	(Pu)	121.543 }	
XL	(Cm)	12.633 – 23.527	18.0 (9)

5.2 Gamma Emissions

	Energy keV	Photons per 100 disint.
$\gamma_{1,0}$(Cm)	42.13 (5)	0.040 (1)
$\gamma_{1,0}$(Pu)	44.54 (2)	0.014 (1)

6 Main Production Modes

Multiple neutron capture and β^- decay on U-238 in reactor fuel:
U-238(n,γ)U-239(β^-)Np-239(β^-)Pu-239(n,γ)Pu-240, etc.

Am-241(n,γ)Am-242

^{242}Am

Comments on evaluation of decay data

by A. L. Nichols

Evaluated: March 2007

Evaluation Procedure

Limitation of Relative Statistical Weight Method (LWM) was applied to average the decay data when appropriate.

Decay Scheme

A relatively simple decay scheme was constructed from the β^-/EC ratio and branching fraction measurements of Hoff *et al.* (1955Ho67, 1959Ho02), Baranov and Shlyagin (1955Ba31), Asaro *et al.* (1960As05), Gasteiger *et al.* (1969Ga17), Aleksandrov *et al.* (1969Al20) and Gabeskiriya (1972Ga35). There are no known well-defined gamma-ray spectroscopic studies.

Some confusion arose during the course of the 1950s as to the correct identity of the ground and metastable states of ^{242}Am. This problem was resolved in 1960 by Asaro *et al.* (1960As05) when the 16-hour half-life activity was shown to be the ground state. The possibile existence of an alpha branch has been extensively considered by Barnes *et al.* (1959Ba22) and Aleksandrov *et al.* (1969Al20). While Barnes *et al.* found such a branch (BF_α = 0.00476(14)), subsequent studies have shown no evidence for this particular decay mode, and Aleksandrov *et al.* were only able to set a limit of less than 10^{-7} of the total ^{242}Am decay.

Nuclear Data

^{242}Am needs to be better characterised for improved quantification of the production and decay heat contribution of ^{242}Cm.

Half-life

The recommended half-life of 16.01(2) hours has been adopted from three known sets of measurements (1953Ke38, 1969Al20, 1982Wi05). Five independent half-life measurements were individually reported by Aleksandrov *et al.* (1969Al20) from which a value of 16.07(14) hours was calculated (LWM). A limited data set of effectively three studies is rather unsatisfactory, and further measurements are required to determine the half-life with much greater confidence.

Half-life measurements.

Reference	Half-life (hours)
1953Ke38	16.01 ± 0.02
1969Al20	16.07 ± 0.14
1982Wi05	16.1 ± 0.1
Recommended value	16.01 ± 0.02

Gamma Rays

Energies

All gamma-ray transition energies were calculated from the structural details of the proposed decay scheme. The nuclear level energies of Akovali were adopted (2002Ak06), and used to determine the energies and associated uncertainties of the gamma-ray transitions that depopulate the first excited states of ^{242}Pu and ^{242}Cm.

Emission Probabilities

There are no known dedicated measurements of the gamma-ray emission probabilities. Under these unsatisfactory circumstances, the proposed gamma-ray decay data were derived from the tabulated P_{ce}/P_{β} data of Baranov and Shlyagin (1955Ba31) and the BF_{β} measurements (1959Ba22, 1959Ho02, 1969Al20, 1969Ga17, 1972Ga35). A BF_{β} of 0.831(3) was derived in terms of LWM, with the uncertainty extended to the minimum value measured (± 0.003); this parameter was adopted in preference to the equivalent LWM calculation for the β^-/EC ratio (i.e. 4.88(8) compared with a value of 4.92(9) calculated from the weighted mean BF_{β}).

β^-/EC ratio and BF_{β}.

Reference	BF_{β}	β^-/EC
1955Ba31	0.82	4.6
1955Ho67	0.81	4.2
1959Ba22	0.836 ± 0.008*	5.1 ± 0.2
1959Ho02	0.836 ± 0.003	5.1 ± 0.1*
1960As05	0.836*	5.1
1969Al20	0.82 ± 0.01*	4.6 ± 0.3
1969Ga17	0.828 ± 0.004	4.8 ± 0.1*
1972Ga35	0.827 ± 0.003*	4.78 ± 0.08
Recommended value	0.831 ± 0.003	[4.88 ± 0.08]

* Emphasis of the publication, and assumed to be the primary measurement.

Baranov and Shlyagin determined the conversion-electron emission intensities separately for both the electron-capture and beta decay processes, along with the β^- decay in equivalent units (1955Ba31) to furnish the following ratios:

P_{ce}(EC component)/$P_{\beta-}$ = 153.5/1200, and

P_{ce}(β^- component)/$P_{\beta-}$ = 661/1200.

Using these data and BF_{β} of 0.831(3):

$P_{ce}(\beta^-) = (661/1200) \times P_{\beta-}$ = 0.458(2) for the 42.13-keV gamma ray,

and $P_{ce}(EC) = (153.5/1200) \times P_{\beta-}$ = 0.106(1) for the 44.54-keV gamma ray.

These values were then used in conjunction with the theoretical internal conversion coefficients to calculate the absolute gamma-ray emission probabilities. One problem involves the assignment of uncertainties to the $P_{ce}/P_{\beta-}$ values as determined by Baranov and Shlyagin. Both parameters are the ratios of two equivalent measurements, and therefore the resulting uncertainties were assumed to be minimal.

Quite remarkably, the resulting gamma-ray emission probabilities are in good agreement with the tabulated spetroscopic data of Vylov *et al.* (1980VyZZ) which are listed as 42.129(7) keV and 0.039(5)%, and 44.542(25) keV and 0.015(3)%. Accurate, high-resolution gamma-ray measurements are required to confirm the validity of the proposed decay scheme.

Gamma-ray emission: recommended energies, emission probabilities, multipolarities and theoretical internal conversion coefficients (frozen orbital approximation).

	E_γ (keV)	P_γ^{abs}	Multi	α_K	α_L	α_{M+}	α_{tot}	
$\gamma_{1,0}$ (Cm)	42.13(5)	0.040 ± 0.001	E2	-	836(12)	319(5)	1155(17)	β^-
$\gamma_{1,0}$ (Pu)	44.54(2)	0.014 ± 0.001	E2	-	544(8)	204(3)	748(11)	EC

Multipolarities and Internal Conversion Coefficients

The nuclear level scheme specified by Akovali has been used to define the multipolarities of the gamma transitions on the basis of known spins and parities (2002Ak06). Recommended internal conversion coefficients have been determined from the theoretical tabulations of Band *et al.* (2002Ba25, 2002Ra45) by means of the methodology of Kibedi *et al.* (2005KiZW).

Beta-particle Emissions

Energies and emission probabilities

Beta-particle energies were calculated from the nuclear level energies of Akovali (2002Ak06) and a Q_{β^-} value of 664.5 ± 0.4 keV taken from Audi *et al.* (2003Au03).

Assuming virtually full internal conversion of the 42.13-keV gamma transition, the beta-particle emission probabilities were calculated from BF_β of 0.831(3) and $P_{ce}(\beta^-)$ of 0.458(2):

Beta-particle Emission Probabilities per 100 Disintegrations of ^{242}Am.

	E_β (keV)	av. E_β (keV)	P_β	Transition type	log *ft*
$\beta^-_{0,1}$	622.4 ± 0.5	185.92 ± 0.14	45.8 ± 0.2	1st forbidden non-unique	6.84
$\beta^-_{0,0}$	664.5 ± 0.4	200.17 ± 0.14	37.3 ± 0.1	1st forbidden non-unique	7.03

EC Transitions

Energies and transition probabilities

EC transition energies were calculated from the nuclear level energies of Akovali (2002Ak06) and a Q_{EC} value of 751.3 ± 0.7 keV from Audi *et al.* (2003Au03).

Assuming virtually full internal conversion of the 44.54-keV gamma transition, the EC transition probabilities were calculated from BF_{EC} of 0.169(3) and P_{ce}(EC) of 0.106(1):

EC Transition Probabilities per 100 Disintegrations of ^{242}Am.

	E_{EC} (keV)	P_{EC}	Transition type	log *ft*	P_K	P_L	P_M
$EC_{0,1}$	706.8 ± 0.7	10.6 ± 0.1	1st forbidden non-unique	7.26	0.7261(23)	0.2016(15)	0.0532(10)
$EC_{0,0}$	751.3 ± 0.7	6.3 ± 0.1	1st forbidden non-unique	7.55	0.7303(22)	0.1987(15)	0.0522(10)

Atomic Data

The x-ray and Auger electron data have been calculated using the evaluated gamma-ray data, and the atomic data from 1996Sc06, 1998ScZM and 1999ScZX.

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$^{244}_{95}Am_{149}$

1 Decay Scheme

Am-244 decays by β^- emission to a single excited level of Cm-244 (9^{th} excited state).

2 Nuclear Data

$T_{½}(^{244}Am)$: 10.1 (1) h

$Q^-(^{244}Am)$: 1427.3 (10) keV

2.1 β^- Transitions

	Energy keV	Probability x 100	Nature	lg *ft*
$\beta^-_{0,9}$	387.1 (10)	100	(1^{st} forbidden non-unique)	5.63

2.3 Gamma Transitions and Internal Conversion Coefficients

	Energy keV	$P_{\gamma+ce}$ x 100	Multipolarity	α_K	α_L	α_{M+}	α_{total}
$\gamma_{1,0}$(Cm)	42.965 (10)	100 (8)	E2	-	760 (11)	290 (4)	1050 (15)
$\gamma_{2,1}$(Cm)	99.383 (4)	100 (8)	E2	-	13.9 (2)	5.4 (1)	19.3 (3)
$\gamma_{3,2}$(Cm)	153.863 (2)	72 (2)	E2	0.174 (3)	1.90 (3)	0.74 (1)	2.81 (4)
$\gamma_{4,3}$(Cm)	205.575 (4)	0.66 (15)	E2	0.141 (2)	0.541 (8)	0.205 (3)	0.887 (13)
$\gamma_{9,4}$(Cm)	538.402 (16)	0.69 (14)	E2	0.0292 (4)	0.0149 (2)	0.0054 (1)	0.0495 (7)
$\gamma_{9,3}$(Cm)	743.977 (5)	71 (2)	54%M1 + 46%E2	0.059 (4)	0.0130 (7)	0.0050 (3)	0.077 (5)
$\gamma_{9,2}$(Cm)	897.840 (7)	28 (8)	E2	0.0122 (2)	0.00358 (5)	0.00124 (2)	0.0170 (3)

3 Atomic Data

3.1 Cm

ω_K	:	0.972	(4)
ω_L	:	0.538	(23)
n_{KL}	:	0.785	(5)

3.1.1 X Radiations

		Energy keV	Relative probability
X_L			
	Lℓ	12.633	}
	Lα	14.746 - 14.961	}
	Lη	17.314	} 2.9 x 10^{+3}
	Lβ	17.286 – 19.688	}
	Lγ	22.735 – 23.527	}
X_K			
	$K\alpha_2$	104.590	63.8
	$K\alpha_1$	109.271	100
	$K\beta_3$	122.304	}
	$K\beta_1$	123.403	} 37.4
	$K\beta_5$	124.124	}
	$K\beta_2$	126.889	}
	$K\beta_4$	127.352	} 13.0
	$KO_{2,3}$	127.970	}

3.1.2 Auger Electrons

	Energy keV	Relative probability
Auger L	6.19 – 14.46	7.0 x 10^{+4}
Auger K		
KLL	78.858 – 89.973	100
KLX	97.226 – 109.267	62
KXY	115.57 – 128.23	9.5

4 Electron Emissions

		Energy keV	Electrons per 100 disint.
e_{AL}	(Cm)	6.19 – 14.46	86 (6)
e_{AK}	(Cm)		
	KLL	78.858 – 89.973	0.124 (20)
	KLX	97.226 – 109.267	0.077 (13)
	KXY	115.57 – 128.23	0.0118 (20)
$ec_{1,0\ T}$	(Cm)	18.439 – 42.948	100 (8)
$ec_{1,0\ L}$	(Cm)	18.439 – 23.995	72 (6)
$ec_{1,0\ M+}$	(Cm)	36.628 – 42.948	28 (2)
$ec_{2,1\ T}$	(Cm)	74.857 – 99.366	95 (8)
$ec_{2,1\ L}$	(Cm)	74.857 – 80.413	68 (6)
$ec_{2,1\ M+}$	(Cm)	93.046 – 99.366	27 (2)
$ec_{3,2\ T}$	(Cm)	25.613 – 153.846	53.1 (15)
$ec_{3,2\ K}$	(Cm)	25.613 (2)	3.2 (1)
$ec_{3,2\ L}$	(Cm)	129.337 – 134.893	35.9 (10)
$ec_{3,2\ M+}$	(Cm)	147.526 – 153.846	14.0 (4)
$ec_{9,3\ T}$	(Cm)	615.721 – 743.954	5.08 (16)
$ec_{9,3\ K}$	(Cm)	615.721 (5)	3.89 (12)
$ec_{9,3\ L}$	(Cm)	719.445 – 725.001	0.86 (3)
$ec_{9,3\ M+}$	(Cm)	737.634 – 743.954	0.33 (1)
$\beta^-_{0,9}$			
	max:	387.1 (10)	100
	avg:	109.6 (3)	

5 Photon Emissions

5.1 X-Ray Emissions

		Energy keV	Photons per 100 disint.
XL	(Cm)	12.633 – 23.527	100 (6)
$XK\alpha_2$	(Cm)	104.590	2.20 (15)
$XK\alpha_1$	(Cm)	109.271	3.45 (23)
$XK\beta_3$	(Cm)	122.304 }	
$XK\beta_1$	(Cm)	123.403 }	1.29 (9)
$XK\beta_5$	(Cm)	124.124 }	
$XK\beta_2$	(Cm)	126.889 }	
$XK\beta_4$	(Cm)	127.352 }	0.45 (4)
$XKO_{2,3}$	(Cm)	127.970 }	

5.2 Gamma Emissions

	Energy keV	Photons per 100 disint.
$\gamma_{1,0}$(Cm)	42.965 (10)	0.096 (8)
$\gamma_{2,1}$(Cm)	99.383 (4)	5.0 (5)
$\gamma_{3,2}$(Cm)	153.863 (2)	19 (1)
$\gamma_{4,3}$(Cm)	205.575 (4)	0.35 (8)
$\gamma_{9,4}$(Cm)	538.402 (16)	0.66 (13)
$\gamma_{9,3}$(Cm)	743.977 (5)	66 (6)
$\gamma_{9,2}$(Cm)	897.840 (7)	28 (8)

6 Main Production Modes

Multiple neutron capture and β^- decay on U-238 in reactor fuel:
U-238(n,γ)U-239(β^-)Np-239(β^-)Pu-239(n,γ)Pu-240, etc.

Am-243(n,γ)Am-244

^{244}Am

Comments on evaluation of decay data

by A. L. Nichols

Evaluated: January 2007

Evaluation Procedure

Limitation of Relative Statistical Weight Method (LWM) was applied to average the decay data when appropriate (but see below).

Decay Scheme

A relatively simple decay scheme was constructed from the gamma-ray studies of 1962Va08, 1963Ha29, 1967Sc34 and 1984Ho02. Only the gamma-ray measurements of Hoff *et al*. provide any estimates of the uncertainties in the gamma-ray probabilities expressed in terms of their relative intensity per 100 neutron captures in a high-flux reactor (1984Ho02). All other studies contained no information with respect to their overall uncertainties. Thus, no weighted mean data could be derived, and the data of 1984Ho02 were adopted wholesale and re-adjusted when deemed necessary (expressed in terms of the 743.977-keV gamma-ray emission probability (100%)). Further measurements are merited to quantify the gamma-ray emission probabilities and decay scheme with greater certainty.

Nuclear Data

^{244}Am is an important actinide for high burn-up fuel within the reactor core, and needs to be better characterised for improved assessments of accelerator-driven systems (ADS) and ^{244}Cm decay heat contribution.

Half-life

The recommended half-life has been adopted from the single known measurement of Vandenbosch and Day (1962Va08). Further measurements are required to determine this half-life with much greater confidence.

Half-life measurement.

Reference	Half-life (hours)
1962Va08	10.1 ± 0.1

Gamma Rays

Energies

All gamma-ray transition energies were calculated from the structural details of the proposed decay scheme. The nuclear level energies of Akovali were adopted (2003Ak04), and used to determine the energies and associated uncertainties of the gamma-ray transitions between the various populated-depopulated levels. However, Akovali recommended the gamma-ray energies determined by Hoff *et al.* (1984Ho02) by means of two curved-crystal spectrometers – minor differences do occur between the calculated energies of the higher energy transitions (538.402(16), 743.977(5) and 897.840(7) keV) and those observed by Hoff *et al*.

Emission Probabilities

Relative emission probabilities and their uncertainties were determined from measurements of Hoff *et al*. (1984Ho02). These data were estimated to be in reasonably good agreement with the earlier measurements of Vandenbosch and Day, and Schuman (1962Va08, 1967Sc34), although these latter two sets of data possessed no uncertainties. Under these unsatisfactory circumstances, the data of Hoff *et al.* had to be adopted wholesale as the only suitable starting point in the attempted construction of a consistent decay scheme. Adjusted were made to the relative emission probabilities of the 99.383-, 153.863- and 205.575-keV gamma rays (adjusted from 7.0(12) to 7.5(13), 25(5) to 28.6(60), and 0.52(12) to 0.53(12), respectively) to conform with the expected population-depopulation balance for the 501.79-, 296.21- and 142.35-keV nuclear levels of ^{244}Cm. Furthermore, a relative emission probability had to be calculated for the 42.96-keV gamma ray for which there were no data at all (from a population-depopulation balance of the 42.96-keV nuclear level of ^{244}Cm (populated by the 99.38-keV gamma ray and depopulated by the 42.96-keV gamma ray)). Downward adjustments were made to the uncertainties of specific gamma-ray transitions and emissions through consideration of these and other data that are judged to be heavily correlated (99.383- and 153.863-keV gamma rays compared with 743.977-keV gamma ray and each other).

Measured relative gamma-ray emission probabilities.

	E_γ (keV)	P_γ^{rel}		
		1962Va08	**1967Sc34**	**1984Ho02**
$\gamma_{1,0}$ (Cm)	42.965(10)	-	-	-
$\gamma_{2,1}$ (Cm)	99.383(4)	-	-	0.23(4) → 7.0(12)
$\gamma_{3,2}$ (Cm)	153.863(2)	72 → 100	-	0.82(16) → 25(5)
$\gamma_{4,3}$ (Cm)	205.575(4)	0.4 → 0.6	-	0.017(4) → 0.52(12)
$\gamma_{9,4}$ (Cm)	538.402(16)	0.4 → 0.6	-	0.033(7) → 1.0(2)
$\gamma_{9,3}$ (Cm)	743.977(5)	72 → 100	66.2 → 100	3.3(9) → 100
$\gamma_{9,2}$ (Cm)	897.840(7)	28 → 39	27.6 → 42	1.4(4) → 42(12)

Gamma-ray emissions: recommended energies, relative emission probabilities, multipolarities and theoretical internal conversion coefficients (frozen orbital approximation).

E_γ (keV)	P_γ^{rel}	Multipolarity	α_K	α_L	α_{M+}	α_{tot}	
42.965(10)	0.145(12)*	E2	-	760(11)	290(4)	1050(15)	β^-
99.383(4)	7.5(13)§	E2	-	13.9(2)	5.4(1)	19.3(3)	β^-
153.863(2)	28.6(60)§	E2	0.174(3)	1.90(3)	0.74(1)	2.81(4)	β^-
205.575(4)	0.53(12)§	E2	0.141(2)	0.541(8)	0.205(3)	0.887(13)	β^-
538.402(16)	1.0(2)	E2	0.0292(4)	0.0149(2)	0.0054(1)	0.0495(7)	β^-
743.977(5)	100	M1 + E2 δ = – 0.92(8)	0.059(4)	0.0130(7)	0.0050(3)	0.077(5)	β^-
897.840(7)	42(12)	E2	0.0122(2)	0.00358(5)	0.00124(2)	0.0170(3)	β^-

* Determined from the calculated theoretical internal conversion coefficients and the transition probability of the 99.383-keV gamma ray feeding the 42.965-keV nuclear level of ^{244}Cm.

§ Adjusted to conform with respect to the expected population-depopulation balances for the 501.79-, 296.21- and 142.35-keV nuclear levels of ^{244}Cm.

A normalisation factor of 0.66(6) was calculated from the relative emission probabilities of the three gamma rays that depopulate the 1040.188-keV nuclear level:

$$\sum^{3} P_{\gamma}(1+\alpha_{tot}) \times F = 100\%$$

$$[P^{rel}(897.84\,keV)(1+\alpha_{tot}) + P^{rel}(743.97keV)(1+\alpha_{tot}) + P^{rel}(538.40keV)(1+\alpha_{tot})] \times F = 100$$

$$F = 100 / 151.4635 = 0.66 \pm 0.06$$

Multipolarities and Internal Conversion Coefficients

The nuclear level scheme specified by Akovali has been used to define the multipolarities of the gamma transitions on the basis of known spins and parities (2003Ak04). Hansen *et al.* undertook angular correlation measurements to confirm the assignment of the 1040.2-keV nuclear level as the only ^{244}Cm nuclear level populated directly by β^- decay (1963Ha29), in which the depopulating 743.977-keV gamma ray was defined as (46 ± 4)% quadrupole [E2] and (54 ± 4)% dipole [M1] to give a mixing ratio (δ) of – 0.92(8) for this transition. Recommended internal conversion coefficients have been determined from the theoretical tabulations of Band *et al.* (2002Ba25, 2002Ra45) by means of the methodology of Kibedi *et al.* (2005KiZW).

Beta-particle Emission

Energy and emission probability

The single beta-particle energy was calculated from the structural detail of the proposed decay scheme. A nuclear level energy of 1040.188(12) keV from Akovali (2003Ak04) and a Q_{β^-} value of 1427.3 ± 1.0 keV from Audi *et al.* (2003Au03) were used to determine the energy and uncertainty of the beta-particle transition. By definition, this single beta transition was assigned an emission probability of 100%.

Beta-particle Emission Probability per 100 Disintegrations of ^{244}Am.

	E_β (keV)	P_β	Transition type	log *ft*
$\beta^-_{0,9}$	387.1 ± 1.0	100	(1st forbidden non-unique)	5.63

Atomic Data

The x-ray and Auger electron data have been calculated using the evaluated gamma-ray data, and the atomic data from 1996Sc06, 1998ScZM and 1999ScZX.

References

1962Va08 S.E. VANDENBOSCH, P. DAY, The decay scheme of 10.1-h Am^{244}, Nucl. Phys. 30 (1962) 177-190. [half-life, P_β, P_{ce}, relative P_γ]

1963Ha29 P.G. HANSEN, K. WILSKY, C.V.K. BABA, S.E. VANDENBOSCH, Decay of an isomeric state in Cm^{244}, Nucl. Phys. 45 (1963) 410-416. [nuclear levels, δ]

1967Sc34 R.P. SCHUMAN, Nuclear chemistry: resonance activation integral measurements, IN-1126 (1967) 19. [relative P_γ]

1984Ho02 R.W. HOFF, T. VON EGIDY, R.W. LOUGHEED, D.H. WHITE, H.G. BÖRNER, K. SCHRECKENBACH, G. BARREAU, D.D. WARNER, Levels of ^{244}Cm populated by the beta decay of 10-h ^{244}Am^{g} and 26-min ^{244}Am^{m}, Phys. Rev. C29 (1984) 618-622. [relative P_γ, multipolarity]

1996Sc06 E. SCHÖNFELD, H. JANβEN, Evaluation of atomic shell data, Nucl. Instrum. Meth. Phys. Res. A369 (1996) 527-533. [X_K, X_L, Auger electrons]

1998ScZM E. SCHÖNFELD, G. RODLOFF, Tables of the energies of K-Auger electrons for elements with atomic numbers in the range from Z = 11 to Z = 100, PTB Report PTB-6.11-98-1, October 1998. [Auger electrons]

1999ScZX E. SCHÖNFELD, G. RODLOFF, Energies and relative emission probabilities of K X-rays for elements with atomic numbers in the range from Z = 5 to Z = 100, PTB Report PTB-6.11-1999-1, February 1999. [X_K]

2002Ba25 I.M. BAND, M.B. TRZHASKOVSKAYA, C.W. NESTOR, Jr., P.O. TIKKANEN, S. RAMAN, Dirac–Fock internal conversion coefficients, At. Data Nucl. Data Tables 81 (2002) 1-334. [ICC]

2002Ra45 S. RAMAN, C.W. NESTOR, Jr., A. ICHIHARA, M.B. TRZHASKOVSKAYA, How good are the internal conversion coefficients now? Phys. Rev. C66 (2002) 044312, 1-23. [ICC]

2003Ak04 Y.A. AKOVALI, Nuclear data sheets for A = 244, Nucl. Data Sheets 99 (2003) 197-273. [nuclear levels]

2003Au03 G. AUDI, A.H. WAPSTRA, C. THIBAULT, The AME2003 atomic mass evaluation (II). Tables, graphs and references, Nucl. Phys. A729 (2003) 337-676. [Q-value]

2005KiZW T. KIBÉDI, T.W. BURROWS, M.B. TRZHASKOVSKAYA, C.W. NESTOR, Jr., A new tool to interpolate conversion coefficients and E0 electronic factors, pp. 268-271 in Proc. Int. Conf. on Nuclear Data for Science and Technology, Eds: R.C. HAIGHT, M.B. CHADWICK, T. KAWANO, P. TALOU, AIP Conference Series 769 (2005). [ICC]

8.

Evaluated Nuclear Structure Data File

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Evaluated Nuclear Structure Data File

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BROOKHAVEN NATIONAL LABORATORY

ENSDF

- Source For
  - Table of Isotopes
  - Nuclear Data Sheets
  - Nuclear Wallet Cards
  - NUDAT
- Update – continuous
- Distributed – six monthly

BROOKHAVEN NATIONAL LABORATORY

General

- Evaluated results of a single experiment or combined results of a number of experiments yielding basically the same kind of information, e.g., (HI,xng), or Coulomb excitations. The collection is called a Data Set.
- The adopted properties of the nucleus.

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GS Properties

- Q(beta-)
- N-Separation Energy
- P-Separation Energy
- Alpha-Decay Q value
- Half-life
- Spin-parity
- Decay Modes
- Static Moments

BROOKHAVEN NATIONAL LABORATORY

Level Properties

- Spin-parity
- Half-life
- Angular momentum transfer
- Spectroscopic factor
- Decay branching
- Static moments
- Configuration
- Experiments in which level is seen

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Level Properties –Special Cases

- Configuration assignments
- Band assignments, parameters
- Isomer shifts, isotope shifts
- Charge distribution of gs, often only a reference
- Deformation parameters of gs (model dependent)
- Excitation probabilities (BEL, BML) when the T1/2 and gs branching are not known

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Radiation Properties

- Placement in level scheme
- Energy
- Intensity – Relative and Absolute through normalization. Per 100 decay modes for alphas.
  Transition Intensity. EC, B+ decay (theory).
  Partial EC probabilities.
- Multipolarity and Mixing Ratios
- Total Internal Conversion Coefficients
- Logft values/ Hindrance Factors
- Reduced Transition Probability-down – W.u.

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ENSDF Content

- Collection of Data Sets by A and Z

  Abstract (Comments)
  Reference
  Adopted Levels, Gammas

  Experimental Data Sets
  - Radioactive Decay
  - Nuclear Reactions

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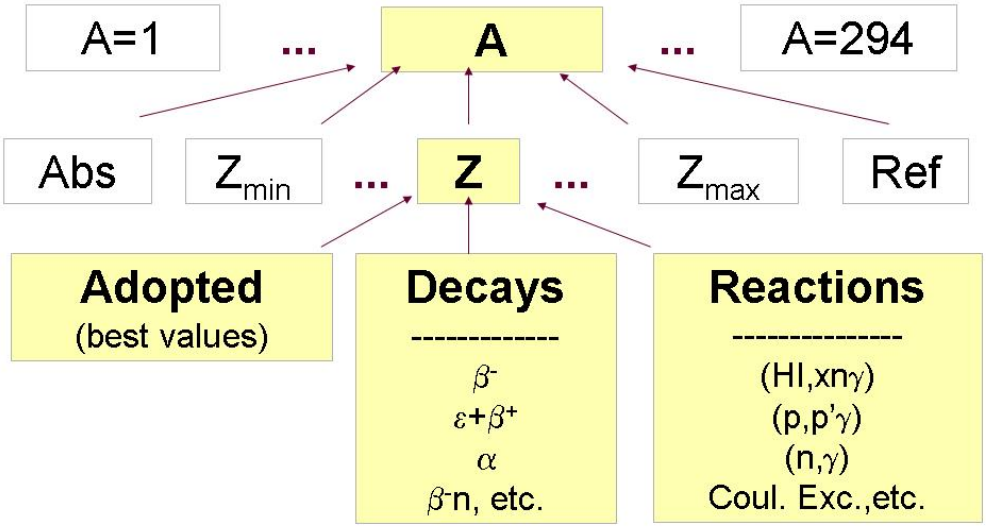
ENSDF Schematic



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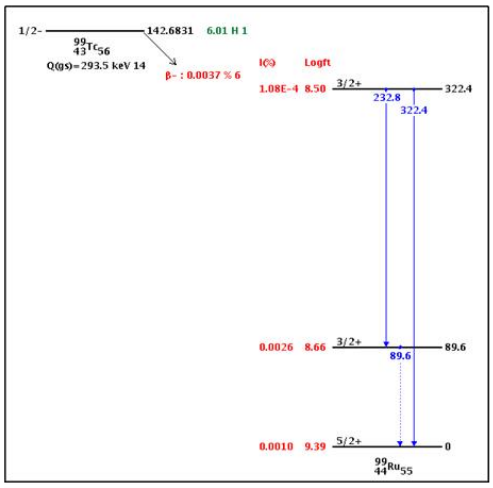
Record Types

ID	LEVEL
History	BETA
XREF	EC
Comments	ALPHA
Q-value	PARTICLE
Parent	GAMMA
Normalization	END

BROOKHAVEN NATIONAL LABORATORY

^{99}Tc Decay Scheme



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^{99}Tc decay-ENSDF data set

```
99RU     99TC B- DECAY (6.01 H)
99RU   N 1.0          1.0
99TC   P 142.6831   111/2-
99RU   L         0    5/2+
99RU   L     89.60   213/2+
99RU   B 346.7       20   0.0026
99RU   G 89.6        3
99RU   L    322.40   183/2+
99RU   B              0.000108 5
```

BROOKHAVEN NATIONAL LABORATORY

Identification Record

Required for all data sets.Must precede all other records.

```
99RU     99TC B- DECAY (6.01 H)
```

Field (Col.)	Name
1-5	NUCID
10-39	DSID
40-65	DSREF
66-74	PUB
75-80	DATE (year/month)

BROOKHAVEN NATIONAL LABORATORY

History Record

```
99RU   H TYP=FUL$AUT=L. K. PEKER$
```

Field (Col.)	Name
1-5	NUCID
6	Blank
7	Blank
8	H
9	Blank
10-80	History

BROOKHAVEN NATIONAL LABORATORY

Q-value Record

```
99RU  Q -2103      107464     7 8478
```

Field (Col.)	Name		
1-5	NUCID		
8	Q	Letter ‘Q’ is required	
10-19	Q^-	20-21	DQ^-
22-29	SN	30-31	DSN
32-39	SP	40-41	DSP
42-49	QA	50-55	DQA
56-80	QREF		

BROOKHAVEN NATIONAL LABORATORY

Cross-Reference Record

```
99RU  XA99TC B- DECAY (2.111E+5 Y)
```

Field (Col.)	Name	
1-5	NUCID	
8	X	Letter ‘X’ is required
9	DSSYM	Any ASCII character
10-39	DSID	*Must* exactly match one of IDs

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Comment Record

```
99RU C   Isomeric shift : 1971Po02
99RU CG E,RI$       Weighted average
99RU CL E(A),J(A) Band J=5/2+
```

Field (Col.)	Name	
1-5	NUCID	
7	Letter ‘C’, ‘D’, or ‘T’ is required	
8	RTYPE	Blank or record type
9	PSYM	Blank, or symbol
10-80	CTEXT	Text of the comment.

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Parent Record

```
99TC   P 142.6831   111/2-
```

Field	Name	
1-5	NUCID	
8	P (required)	
9	Blank or integer	
10-19	E Energy	20-21 DE
22-39	JPI	
40-49	T	50-55 DT
65-74	QP	75-76 DQP
77-80	Ionization State	

BROOKHAVEN NATIONAL LABORATORY

Normalization Record

```
99RU  N 1.0          1.0
```

Field	Name	
8	N (required)	
10-19	NR	20-21 DNR
22-29	NT	30-31 DNT
32-39	BR	40-41 DBR
42-49	NB	50-55 DNB
56-62	NP	63-64 DNP

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Prod Normalization Record

Field	Name	
8	N (required)	
10-19	NR*BR	20-21 DNR
22-29	NT*BR	30-31 DNT
42-49	NB*BR	50-55 DNB
56-62	NP	63-64 DNP
77	Blank or C	78 Opt (1-7)

BROOKHAVEN NATIONAL LABORATORY

Level Record

```
99RU   L          0      5/2+
```

Field	Name		
1-5	NUCID		
8	L (required)		
10-19	E Energy	20-21 DE	
22-39	JPI		
40-49	T	50-55 DT	
56-64	L (angular momentum transfer)		
65-74	S (spect at)	75-76 DS	
77	Flag	78-79 MS	80 Q

BROOKHAVEN NATIONAL LABORATORY

Beta Record

```
99RU   B 346.7       20   0.0026
```

Field	Name		
1-5	NUCID		
8	B (required)		
10-19	E Energy	20-21 DE	
22-29	IB Intensity	30-31 DIB	
42-49	Logft	50-55 DFT	
77	Flag		
78-79	Forbiddenness	80 Q	

BROOKHAVEN NATIONAL LABORATORY

EC Record

Field	Name		
1-5	NUCID		
8	E (required)		
10-19	E Energy	20-21 DE	
22-29	IB Intensity	30-31 DIB	
32-39	IE Intensity	40-41 DIE	
42-49	Logft	50-55 DFT	
65-74	TI	75-76 DTI	77 Flag
78-79	Forbiddenness	80 Q	

BROOKHAVEN NATIONAL LABORATORY

Alpha Record

Field	Name	
1-5	NUCID	
8	A (required)	
10-19	E Energy	20-21 DE
22-29	IA Intensity	30-31 DIA
32-39	HF	40-41 DHF
77	Flag	
80	Q	

BROOKHAVEN NATIONAL LABORATORY

Gamma Record

```
99RU   G 89.6        3
```

Field	Name		
8	G (required)		
10-19	E Energy	20-21 DE	
22-29	RI rel Intensity	30-31 DRI	
32-41	M multipolarity		
42-49	MR mix ratio	50-55 DMR	
56-62	CC total CC	63-64 DCC	
65-74	TI	75-76 DTI	
77	Flag	78 COIN	80 Q

BROOKHAVEN NATIONAL LABORATORY

(Delayed-) Particle Record

Field	Name		
8	D (for delayed)	9	particle (N,P,..)
10-19	E Energy	20-21 DE	
22-29	IP % Intensity	30-31 DIP	
32-39	EI lev en int nuc		
40-49	T Width	50-55 DT	
56-64	L angular momentum transfer		
77	Flag	78 COIN	80 Q

BROOKHAVEN NATIONAL LABORATORY

Evaluated Nuclear Structure Data File

Purpose/Philosophy/Guidelines

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Purpose/Philosophy/Guidelines

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BROOKHAVEN NATIONAL LABORATORY

Purpose/Philosophy

- Present set of critically evaluated properties of nuclides based on best known experimental information to date
- Present best data available for each type of experiment
- Present best infomation for each nuclide
- Concise, consistent, and well-documented

BROOKHAVEN NATIONAL LABORATORY

Minimum Standards

- A-Chain completeness – all nuclides
- Nuclide completeness – all data sets
- Data set completeness – ID to END record

  Decay data sets: Parent record

  Adopted sets: Q record

  etc.

  Uncertainty, units, documentation

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Physical Properties

- Adopted Properties

  General – Q, history, XREF, comments

  Levels - E, J^{π}, $T_{1/2}$, branching, static mom

  Gammas - E, branching, multipolarity, cc, BLW

- Decay Properties
- Nuclear Reaction Properties

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Guidelines - extraction of data

- Quote authors' measured quantities
- Document any deviations
- Note authors' assumptions
- Check for missed references
- Check authors' quoted older values

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Guidelines - presentation of data -1

- Order of comments
- E = not needed for reaction
- Target J^{π} should be given
- Key no: measured, etc.
- Do not combine different kinds of data sets
- Specify source of data

BROOKHAVEN NATIONAL LABORATORY

Guidelines – presentation -2

- Gammas order by increasing Eg
- Significant digits
- Uncertainty limited to 25
- Multiplets
- Xsection, Analyzing-power, A2, A4 not given
- BEL up for levels, down for gammas
- Delayed gammas-give as IT decay

BROOKHAVEN NATIONAL LABORATORY

Guidelines – presentation -3

- Normalization condition should be given
- Parent record, all fields should be given
- Replace `/' by `:' for multiple ratios
- Unresolved discrepancies should be pointed out
- Uncertainty not error
- E(ec), E(b-) only when accurate, measured

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Guidelines - Systematics

- Log T1/2(alpha) vs Log E(alpha) is linear
- Takahashi gross beta decay theory reliable to better than a factor of 3
- Alpha decay HF
- Certain pairs of configuration lead to isomeric transitions
- GS feeding from local systematics
- Mass systematics from Audi

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Guideline - Style

- APS style adopted
- Accepted abbreviations
- Key no. is plural. Space after `,'

BROOKHAVEN NATIONAL LABORATORY

9.

Bibliographic Databases

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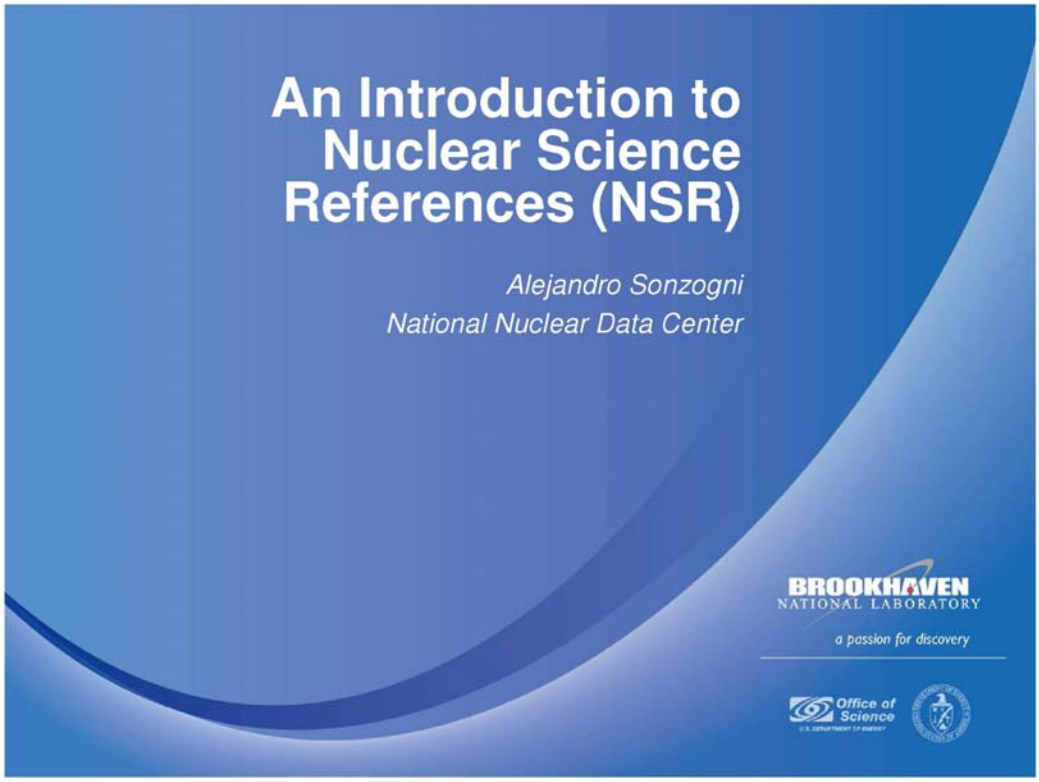
Disclaimer



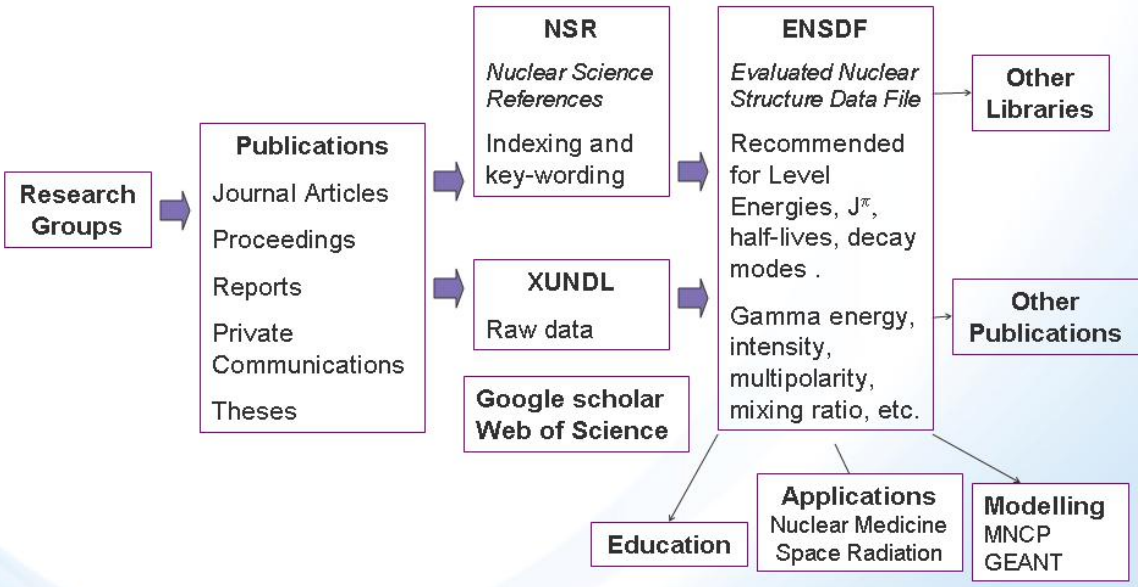
NSR Nuclear Science References
www.nndc.bnl.gov/nsr

NSR (Nuclear Science References) is a bibliographic database containing nearly 200,000 nuclear science articles, indexed according to content. About 4,000 are added each year covering 80 journals as well as conference proceedings, laboratory reports, theses and private communications. Each article included in NSR is read and assigned a number of variables that succinctly described the content. These variables, also known as keywords, are then incorporated in a database.

One unique feature of NSR is the ability to selectively retrieve articles out of a vast number, satisfying a particular set of conditions. Articles can be retrieved according to: first author, author, nuclide, reaction, target, measured quantity, publication year, type of publication (primary or secondary), journal, topics, etc.

NSR manager at the NNDC: Manojeet Bhattacharya, nsr@bnl.gov. Contributions mainly from the NNDC and IAEA-NDS. All programming by Dave Winchell, formerly at the NNDC.

Nuclear Structure Evaluation



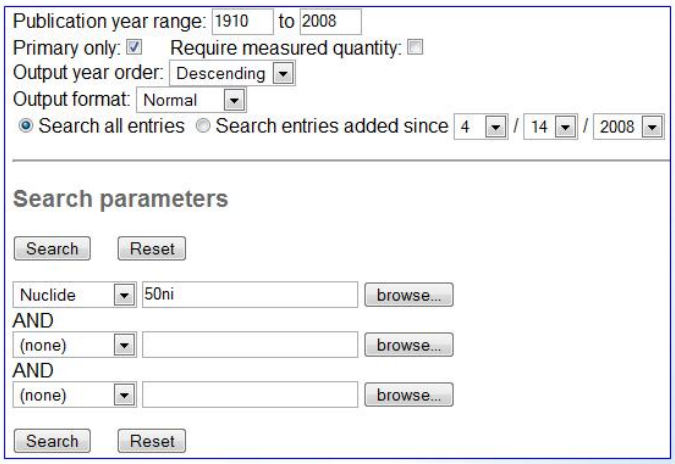
NSR Example #1

Retrieve all articles associated with a given nucleus, for instance, ^{50}Ni

Go to www.nndc.bnl.gov/nsr and click on the Indexed search hyperlink

Select Nuclide in the first Drop down menu and type "^{50}ni"

Click on Search



As of 14 April 2008, 17 articles should appear from 1972 to 2007

NSR Example #1

Some of the initialization parameters are fairly easy to understand, such as Publication year range, Output year order, Output format and Search all entries / Search entries added since. A couple of them require some explanation:

Primary only
Articles that are appear in NSR that were published in journals are considered "Primary entries", while articles published in books, conference proceedings, laboratory reports, or private communications, are considered "Secondary entries". Conference articles that appear in journals are primary; the rest are considered secondary.

Require measured quantity
Checking this check box will result in retrieving articles reporting the results of experimental studies.

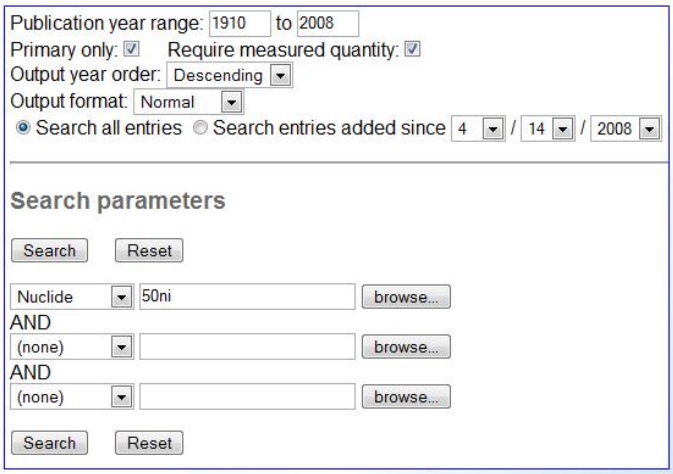
NSR Example #2

Retrieve all articles associated with a given nucleus, for instance, ^{50}Ni that were published in journals and that report experimental results

Go to www.nndc.bnl.gov/nsr and click on the indexed search hyperlink

Select Nuclide in the first Drop down menu and type "50ni". Also, check on Primary only and on Require measured quantity

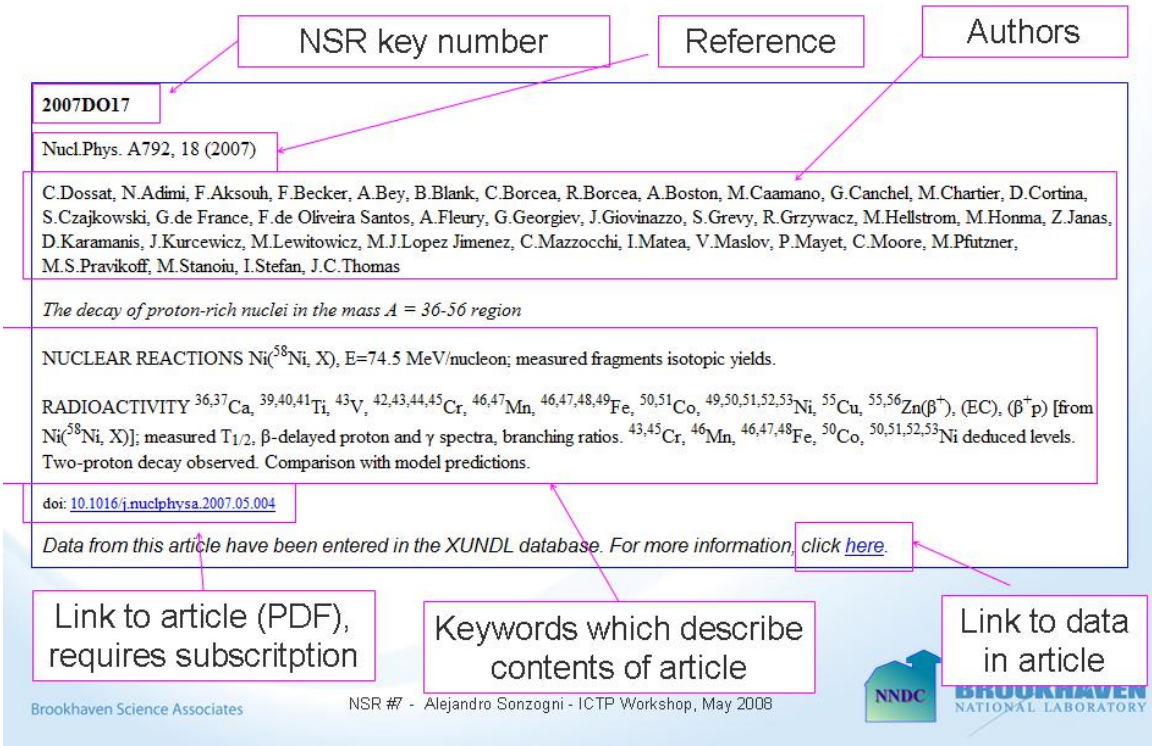
Click on Search



As of 14 April 2008, two articles should appear

Let us examine one element of the search results

NSR Example #2



NSR Key Numbers
These are 9-character long strings: The first four identify the publication year, the following two are usually the first two letters of the first author's last name, for instance, SM for Smith. If the last two characters are numeric, the article corresponds to a primary entry; if they are not, the article is a secondary entry. NSR key numbers are assigned by the NSR database manager and are unique to each article.

NSR Keywords
Describe briefly the article's content. They follow a firm set of guidelines and they sinificantly increase NSR search abilities.

DOI (Data Object Identifier), contains the link to the article. Typically, the abstract and references can be viewed for free. The whole article in PDF format can be accessed if you have a paid subscription to the journal.

Some articles contain experimental information, which can be stored in the **XUNDL** database (eXperimental Unevaluated Nuclear Data List) - data are stored in the ENSDF format.

NSR Example #3

Find articles that report experimental values of ^{44}Ti half-life

1) Go to www.nndc.bnl.gov/nsr and select indexed search
2) Check on Required measured quantity
3) Select "Nuclide" from menu and type "44ti"
4) Click on search

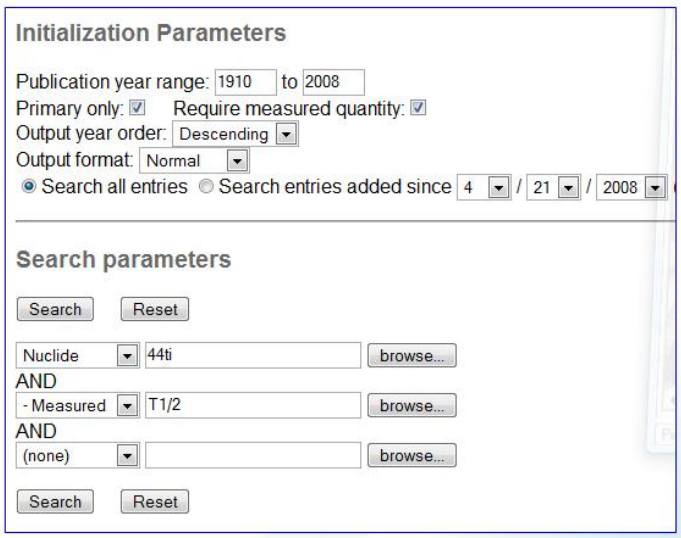
We find more than 140 articles - however, only some of them report half-life values.

Constraining the search further:

5) Select "Measured" on the second menu and then click the corresponding "browse" button - a list with possible measured quantities will be shown.
   Scroll down until we find and click on the "T1/2" hyperlink - we should now be directed back to the "index search" page.
   Click on Search - some eleven articles should now be listed.

NSR Example #3

Finding articles that report experimental values of ^{44}Ti half-life. The form should look like:



The "Measured" fields are of enormous help to perform ENSDF evaluations. For instance:

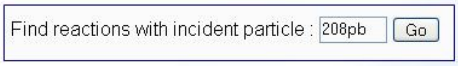
- Selecting G-SPECTRA will allow a search for articles reporting measured gamma-ray spectra, a field that has been dominant in nuclear structure research over the previous 30 years.
- The most common decay modes are Electron Capture (EC), Positron Emission (β+), Beta minus (β-), Isomeric Transition (IT), Alpha (α), Spontaneous Fission (SF) and Proton emission (P). By selecting A-DECAY, we will retrieve articles dealing with alpha-decay, etc.
- Studies of nuclear levels at high values of angular momentum are covered by selecting HIGH-SPN.
- Articles dealing with shape parameters can be retrieved by selecting DEFORMATION.
- Selecting DIPOLE/QUADRUPOLE will retrieve articles reporting magnetic dipole moments/electric quadrupole moments.

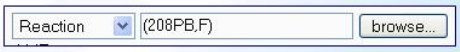
Warning: Do not trust NSR blindly! Some of the "Measured" fields may be more restrictive than you think.

NSR Example #4

Problem: you vaguely remembered an article of interest that used ^{208}Pb as a beam. How to find this article:

1) In the "Indexed search" page - select "Reaction" from the menu and then click on corresponding "browse" button.
2) Type "208pb" in the first text box and click on go button
   Now click on the reaction of interest, i.e. (208PB,F)
3) You should be directed back to the indexed search page - click the "search" button to complete the query





NSR Example #5

Similar problem as before: you vaguely remember the name of one of the authors of the article you are looking for.

1) Go to "Indexed search".

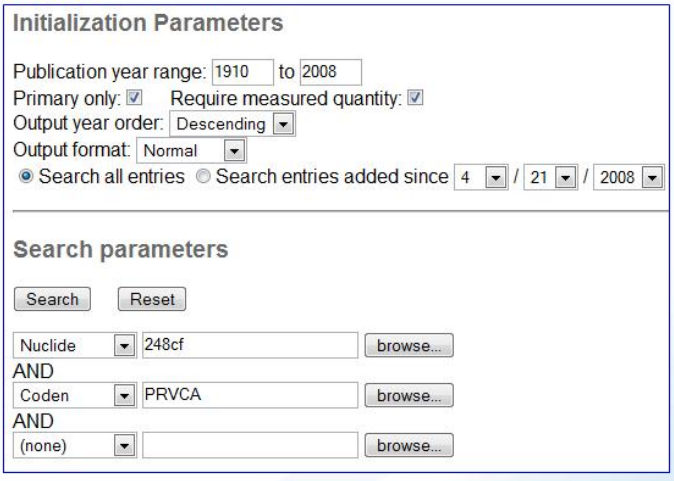
2) Select "Author" and click on corresponding "browse" button.

3) Type at least the first two letters of the author's last name, i.e. "da", and click "go".

4) A list of all the last names in NSR starting with "da" will be produced, select one, i.e. davids, c.n. You should be directed back to the indexed search page. Click the "search" button to complete the query.

NSR Example #6

Finding articles that deal with ^{248}Cf and were published in Physical Review C. The journal selection is carried out by selecting Coden and clicking on browse:



Browsing is a very powerful tool to check NSR contents and help define searches

More on NSR Key Numbers

Key numbers are used through ENSDF to make reference to a particular article. The following is a comment from ^{208}Pb adopted levels:

> $T_{1/2}$: from B(E3)=0.611 9, a weighted average of 0.611 12 (1983Sp02) in Coulomb excitation, and 0.612 13 (1980Go12) in (e,e'). The value of 32 ps 11 reported by 1962We14 in β^- decay appears to be in error. Other: 15.4 ps 12 from B(E2) in (α,α').
> Isomer shift=6.25 28 from muonic atom (1977Sh07).

A given article can be accessed by means of the NSR link manager: for instance, we can look at the contents of 1983Sp02 with the following link: www.nndc.bnl.gov/nsr/nsrlink.jsp?1983sp02,b

Two parameters are passed to the JSP page, the key number and the output format, in this case b.

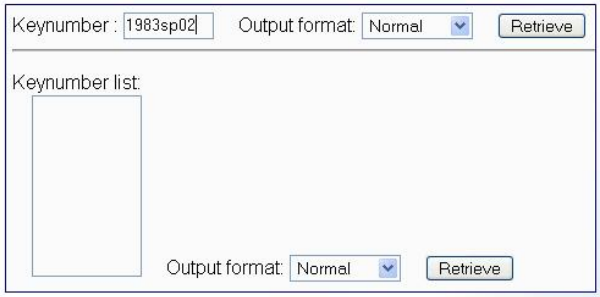
If the output parameter is h, the output is an html page generated by the NNDC. If b, you will be redirected to the publishers' page. If x, you will obtain an output in the exchange format, the raw format of the NSR database.

NSR Example #7

One can also search on key numbers; go to www.nndc.bnl.gov/nsr and click on the Keynumber retrieval hyperlink.

One can retrieve information for a single key number, or for a number of them.

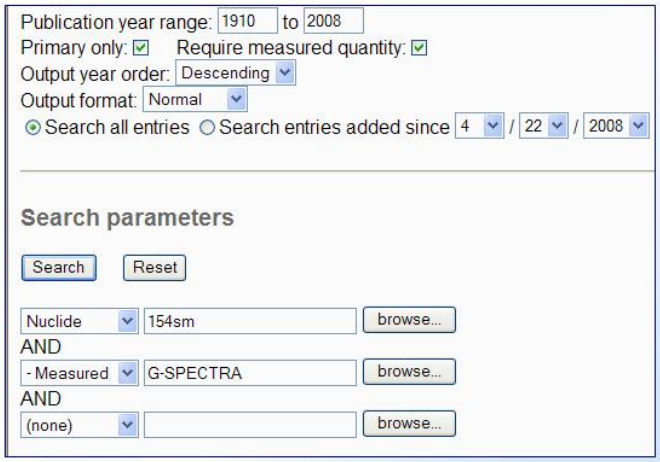
There are several options for the output. A very interesting one is the bibTex option, that generates a bibTex file to be used in LaTex word processing



NSR Example #8

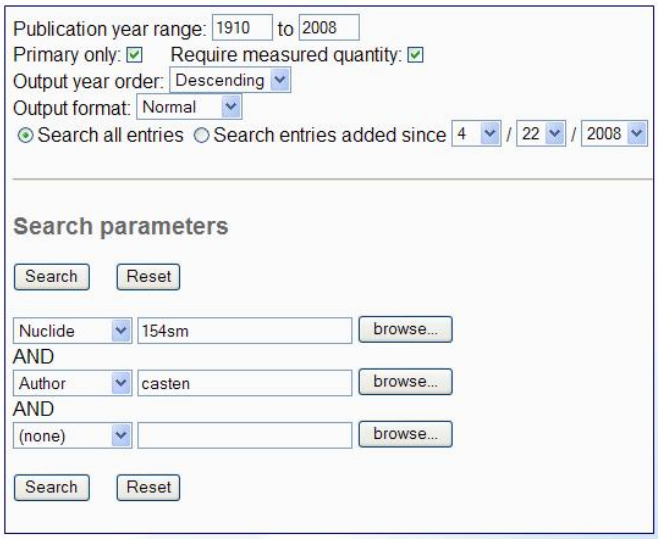
NSR Index search page permits the selection of up to 3 parameters and search the AND condition between them. More complex searches can be achieved by further filtering with the Combine/View lists feature.

For instance, we want to find experimental articles on gamma spectra measurements for ^{154}Sm. The search form will look like:



NSR Example #8

We could also search for experimental articles on ^{154}Sm by one particular author, for instance 'casten'. The search form will look like:



NSR Example #8

The last two results can be combined by clicking on the Combine/view lists Hyperlink. If we want the "and" of the two, the form will look like:

Combine lists:

1 AND 2 Combine

Output format: Normal Output year order: Descending

Current lists:

List #	Search/Initialization strings	Number found
1	Indexed quantity search: Nuclide=154sm AND Measured=G-SPECTRA YLO:1910; YHI:2008; PRIM:yes; EXPR:yes; Cutoff:None	29
2	Indexed quantity search: Nuclide=154sm AND Author=casten YLO:1910; YHI:2008; PRIM:yes; EXPR:yes; Cutoff:None	1

Clear Lists

And this will retrieve the single article in which Casten is an author.

NSR Example #8

Similarly, "1 and not 2" will return the 28 articles in list 1 where Casten is not an author.

Combine lists:

1 AND NOT 2 Combine

Output format: Normal Output year order: Descending

Current lists:

List #	Search/Initialization strings	Number found
1	Indexed quantity search: Nuclide=154sm AND Measured=g-spectra YLO:1910; YHI:2008; PRIM:yes; EXPR:yes; Cutoff:None	29
2	Indexed quantity search: Nuclide=154sm AND Author=casten YLO:1910; YHI:2008; PRIM:yes; EXPR:yes; Cutoff:None	1

This simple example illustrates the power of combining lists. However, care should be exercised when dealing with some of the subjects.

10.

ENSDF – Evaluations: Methodology and Worked Examples

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Workshop on
NUCLEAR STRUCTURE AND DECAY DATA EVALUATION

Edgardo Browne

Decay Data

1. Statistical treatment of data
2. Properties of the parent nucleus
3. Gamma rays
4. Decay scheme normalization
5. Beta particles
6. Electron capture
7. Alpha particles
8. Level structure and decay scheme

1. Statistical Treatment of Data

- Weighted and unweighted averages
- Limits
- Discrepant data
- Limitation of relative statistical weight method

2. Properties of the Parent Nucleus

- Energy, spin/parity, half-life, Q-value

3. Gamma Rays

- Energy (E_γ)
- Relative intensity (I_γ)
- Multipolarity and mixing ratio (δ)
- Internal conversion coefficient (α_i)
- Total transition intensity [I_γ (1 + α)]
- Absolute intensity (%I_γ)

4. Beta Particles

- Relative intensity (I_β), absolute intensity (%I_β)
- Average energy (I_{avg})
- Log *ft*
- Energy (E_β)

5. Electron Capture

- Relative probability (I_ε), absolute probability ($\%I_\varepsilon$)
- Relative sub-shell probabilities (P_K, P_L, P_M, P_N)
- Log *ft*

6. Alpha Particles

- Energy (E_α)
- Relative intensity (I_α), absolute intensity ($\%I_\alpha$)
- Hindrance factor (HF)

7. Level Structure and Decay Scheme

- Level energy (E)
- Level spin/parity (Jπ), particle configuration (CONF)
- Level half-life ($T_{1/2}$)
- Decay scheme normalization

1. Statistical Treatment of Data

- Average, Weighted Average (weight = $1/\sigma_i^2$)
- Limits (given by authors: <10; changed by evaluator: 5 ***5***)
- Confidence level for limits deduced by evaluators from transition intensity balances
- Discrepant data – *Limitation of Relative Statistical Weight (LWEIGHT)*

Averages

Unweighted

$x(avg) = 1 / n \sum x_i$

$\sigma_{x(avg)} = [\, 1 / n\,(n-1) \sum (x(avg) - x_i)^2]^{1/2}$ Std. dev.

Weighted

$x(avg) = W \sum x_i / \sigma_{xi}^2$; $W = 1 / \sum \sigma_{xi}^{-2}$

$\chi^2 = \sum (x(avg) - x_i)^2 / \sigma_{xi}^2$ Chi sqr.

$\chi_\nu^2 = 1 / (n-1) \sum (x(avg) - x_i)^2 / \sigma_{xi}^2$ Red. Chi sqr

$\sigma_{x(avg)}$ = larger of $W^{1/2}$ and $W^{1/2} \chi_\nu$. Std. dev.

Limits

B_m = measured value

σ = standard deviation

B_0 = true value

Example: -2 ± 3

For a Gaussian distribution the formulae to convert measured values to limits are:

$B_0 < B_m + 1.28\,\sigma$ (90% confidence limit); example: < 1.84

$B_0 < B_m + 1.64\,\sigma$ (95% confidence limit); example: < 2.92

$B_0 < B_m + 2.33\,\sigma$ (99% confidence limit); example; < 4.99

Discrepant Data

Simple definition: A set of data for which $\chi_\nu^2 > 1$.

But, χ_ν^2 has a Gaussian distribution, i.e. varies with the degrees of freedom ($n - 1$).

Better definition: A set of data is discrepant if χ_ν^2 is greater than χ_ν^2 (critical), where χ_ν^2 (critical) is such that there is a 99% probability that the set of data is discrepant.

Limitation of Relative Statistical Weight Method

For discrepant data ($\chi^2_\nu > \chi^2_\nu$(critical)) with at least three sets of input values, we apply the method of *Limitation of Relative Statistical Weight*. The program identifies any measurement that has a relative weight >50% and increases the uncertainty to reduce the weight to 50%. χ^2_ν is recalculated and produces a new average and a best value as follows:

If $\chi^2_\nu \leq \chi^2_\nu$(critical), the program chooses the weighted average and uncertainty (the larger of the internal and external values).

If $\chi^2_\nu > \chi^2_\nu$(critical), the program chooses either the weighted or the unweighted average, depending on whether the uncertainties in the average values make them overlap with each other. If that is so, the program chooses the weighted average and (internal or external) uncertainty. Otherwise, the program chooses the unweighted average. In either case, the uncertainty may expand to cover the most precise input value

2. Properties of the Parent Nucleus

- Level energy (keV): 0.0, 328.0 *25*, 942 *4*, 0.0 + X
- Spin/parity: 1/2+, (3/2+), 5-, 6(+), (5/2-,7/2-)
- Half-life: 3.8 d *2*, 432.2 y *7*, 2 m, 35 ms *10*, ~3 s, 1.2×10^{15} y
- Units: sidereal y (= 365.25636 d), d, h, m, s, ms, ms, ns, ps, fs, …
- Q-value (keV): 2003Au03 (G. Audi et al., Nucl. Phys. **A729**, 337 (2003))
- Theoretical values: 1997Mo25 (P. Moller et al., At. Data Nucl. Data Tables **66**, 131 (1997))

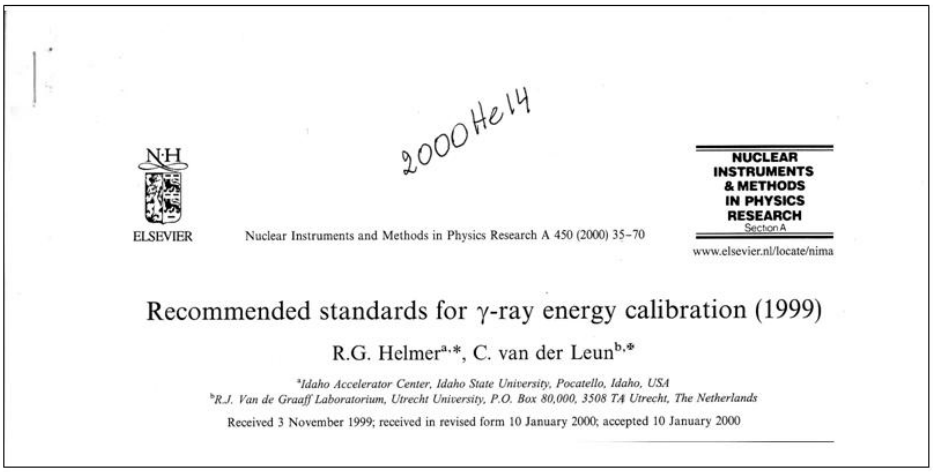
3. Gamma Rays

1. Energy (keV)

- Weighted average from radioactive decay
- Very precise measurements (e.g. bent crystal)
- Recommended standards for energy calibration:

  Helmer and Van der Leun (Nucl. Instrum. Methods Phys. Res. **A450**, 35 (2000)
- Not observed, but expected (from level energy difference)
- Deduced from conversion electron energies (give atomic electron binding energy)
- Multiplets:

  Broader peak in spectrum
  Known levels involved



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ELSEVIER

Nuclear Instruments and Methods in Physics Research A 450 (2000) 35–70

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

Recommended standards for γ-ray energy calibration (1999)

R.G. Helmer[a,*], C. van der Leun[b,*]

[a]Idaho Accelerator Center, Idaho State University, Pocatello, Idaho, USA
[b]R.J. Van de Graaff Laboratorium, Utrecht University, P.O. Box 80,000, 3508 TA Utrecht, The Netherlands

Received 3 November 1999; received in revised form 10 January 2000; accepted 10 January 2000

- Uncertainties: statistical

Give (in comments) estimate of systematic errors.

When uncertainties are known to include systematic errors, no result from weighted average should have an uncertainty smaller than the smallest input uncertainty.

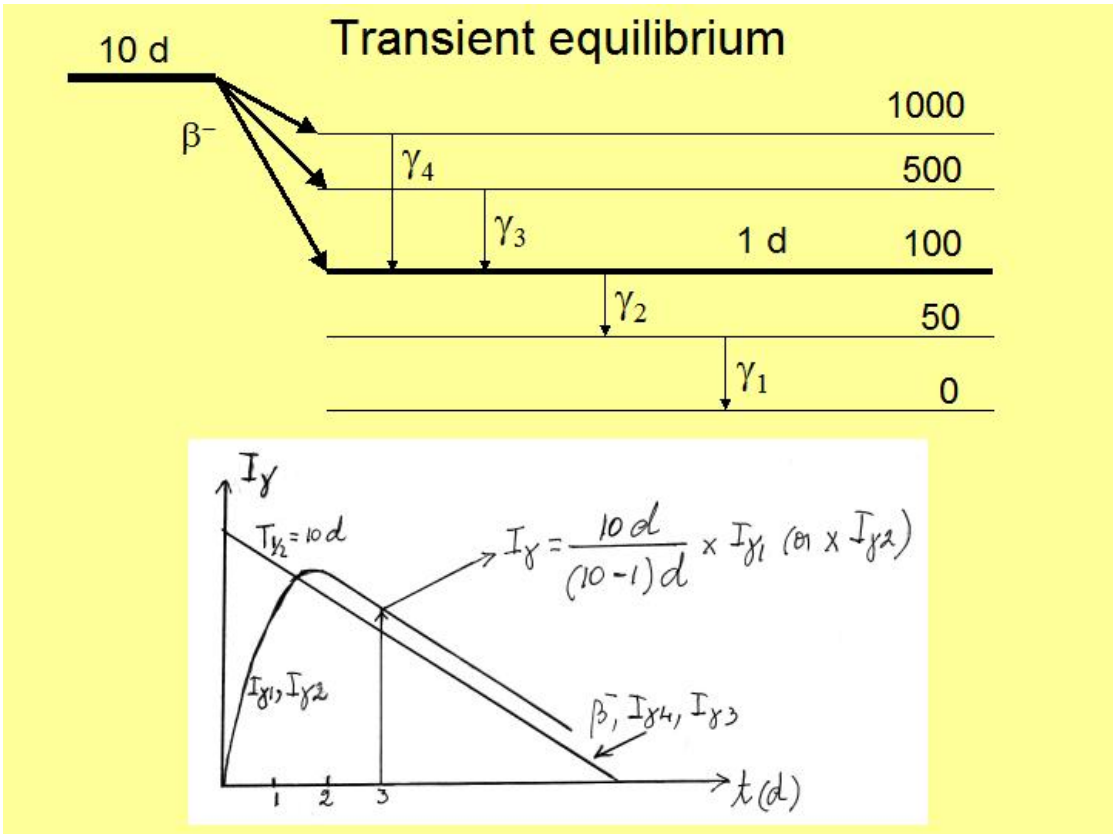
No uncertainty should be smaller than the uncertainty in the calibration standard.

Uncertainties larger than *25* should be rounded off.

Author	ENSDF
351.53 ± 0.25	351.53 *25*
351.53 ± 0.30	351.5 *3*
8346 ± 29	83.5E2 *3*

2. Relative intensity

- Weighted average from radioactive decay
- Use 100 for the most intense gamma ray
- Use a limit for an expected (but unobserved) γ ray
- Use total transition intensity (TI) if this is the only quantity measured, or deduced from transition intensity balance. If α_T is known, deduce and give I_γ
- Limits are acceptable (e.g. $I_\gamma < A$), but $I_\gamma = ½\ A \pm ½\ A$ is preferable (for calculating transition intensity balances)
- Intensity from an isomer in the daughter nucleus should not be given if such intensity is time dependent. Include a comment giving the percent feeding to the isomer, and explain the reason for not giving I_γ



3. Multipolarity and mixing ratio (δ).

- From conversion electron data. If I_K and I_γ were used to determine α_K, explain normalization between electron and photon intensity scales. Conversion electron sub-shell ratios.
- From γ-ray angular correlations ($\gamma(\theta)$). $\gamma(\theta)$ determines *only* the L component of the γ-ray character, thus mult.= D, D + Q, etc. $T_{1/2}$(exp.) may be used to rule out choices, for example, Q = M2 and D + Q = E1 + M2.

Multipolarity and mixing ratio (δ) from conversion electron data

- Using experimental conversion coefficients

δ^2 = E2 γ-ray intensity / M1 γ-ray intensity = $I_\gamma(E2)/I_\gamma(M1)$ .... (1)

$$I_\gamma(M1) + I_\gamma(E2) = I_\gamma \text{ .... (2)}$$

From equations (1) and (2) we obtain:

$$I_\gamma(M1) = I_\gamma / 1 + \delta^2, \text{ and } I_\gamma(E2) = I_\gamma\, \delta^2 / 1 + \delta^2$$

Conversion electron intensity: $I_e = I_e(M1) + I_e(E2)$

Experimental conversion coefficient

$$\alpha(\text{exp}) = I_e / I_\gamma = [I_\gamma(M1) \times \alpha(M1)^{th} + I_\gamma(E2) \times \alpha(E2)^{th}] / I_\gamma$$

$$\text{or, } \alpha(\text{exp}) = [I_\gamma / 1 + \delta^2 \times \alpha(M1)^{th} + I_\gamma\, \delta^2 / 1 + \delta^2 \times \alpha(E2)^{th}] / I_\gamma$$

$$\boxed{\delta^2 = (\alpha(M1)^{th} - \alpha(\text{exp})) / (\alpha(\text{exp}) - \alpha(E2)^{th})}$$

$$\%M1 = 100/1 + \delta^2, \quad \%E2 = 100\, \delta^2 / 1 + \delta^2$$

- Using experimental electron sub-shell ratios

$$R(\text{exp}) = I_e(L1) / I_e(L3)$$

Then

$$\boxed{\delta^2 / 1 + \delta^2 = A / [\alpha(E2,L1)^{th} - \alpha(M1,L1)^{th} + R(\text{exp})\, (\alpha(M1,L3)^{th} - \alpha(E2,L3)^{th})]}$$

where

$$\boxed{A = R(\text{exp})\, \alpha(M1,L3)^{th} - \alpha(M1,L1)^{th}}$$

- Consistency of entries for α and δ:

For a single multipolarity, the δ field should be blank

For $\delta < V$:

give *only* dominant multipolarity and corresponding α. Give $\delta < V$ in a comment, or

give both multipolarities and $\delta < V$ in the δ field Calculate α from $\delta = ½\ V \pm ½\ V$

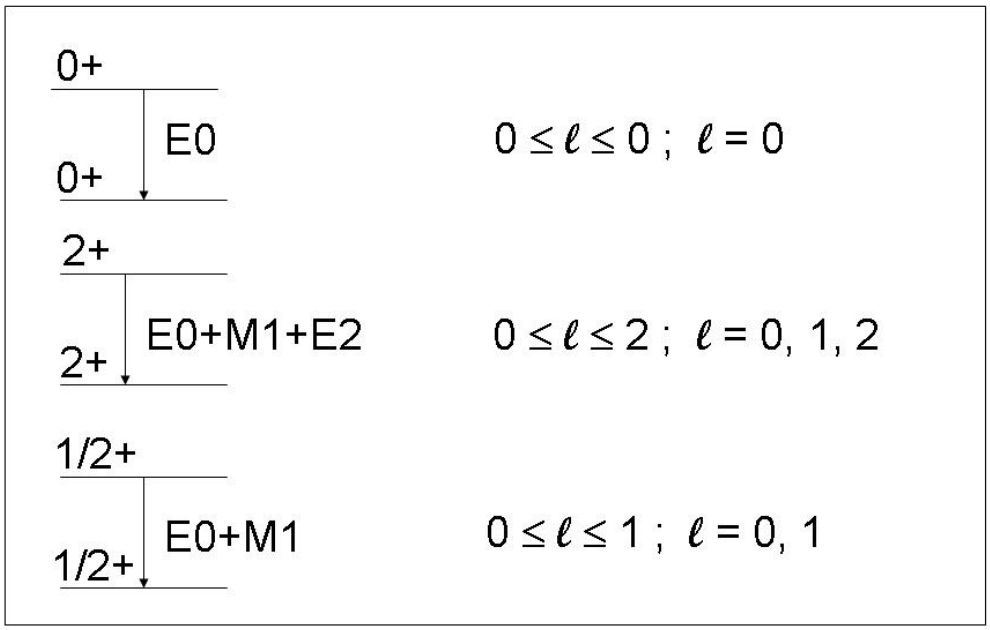
Examples: E2+M3 with $\delta < 0.5$ should preferably be entered as E2, whereas M1+E2 with $\delta < 0.5$, as M1+E2 ($\delta = 0.25 \pm 0.25$)

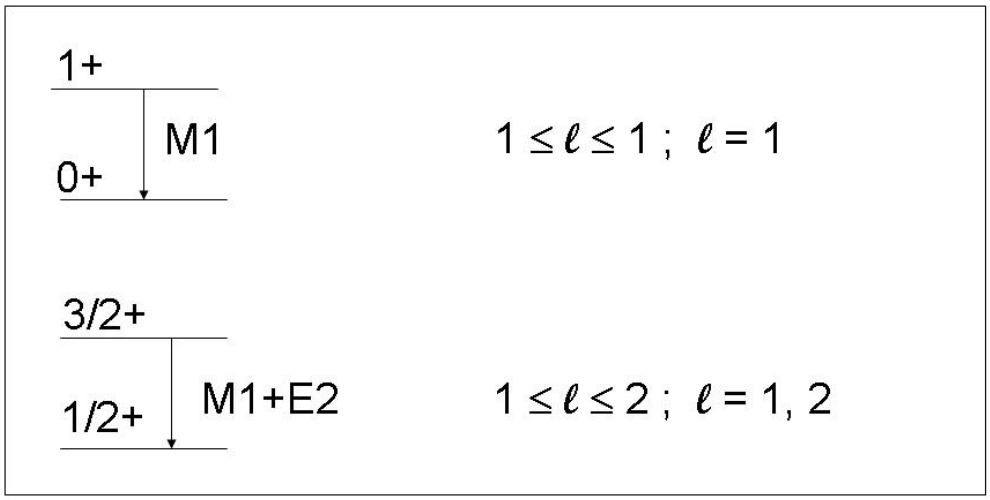
M1, E2 is not the same as M1+E2

- Assumed multipolarity

[M1], [E2], [M1+E2], [M4], etc.

More about multipolarities





4. Internal Conversion Coefficients

Theoretical Values

New Calculation of Internal Conversion Coefficients
Dirac-Fock Internal Conversion Coefficients

I.M. Band, M.B. Trzhaskovskaya, C.W. Nestor, Jr., P.O. Tikkanen and S. Raman

Atomic Data and Nuclear Data Tables **81**, 1 (2002)

To be discussed by Tibor Kibedi

Experimental values:

Very precise values ($\leq$ 1.5% uncertainty)

E_γ = 661 keV ; ^{137}Cs (α_K=0.0902 $\pm$ 0.0008, M4)

Nuclear penetration effects

^{233}Pa β^- decay to ^{233}U

E_γ = 312 keV almost pure M1 from electron sub-shell ratios

However α_K(exp) = 0.64 $\pm$ 0.02

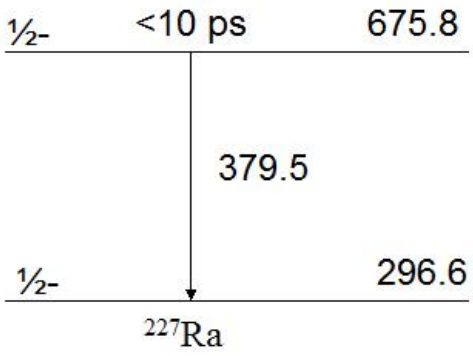
($\alpha_K{}^{th}$(M1)=0.72, $\alpha_K{}^{th}$(E2)=0.070)

Mixed E0 transitions (e.g., M1+E0).

^{227}Fr β^- ^{227}Ra

E_γ = 379.1 keV (M1+E0); α(exp) = 2.4 $\pm$ 0.8

α^{th}(M1) = 0.37; α^{th}(E2) = 0.078



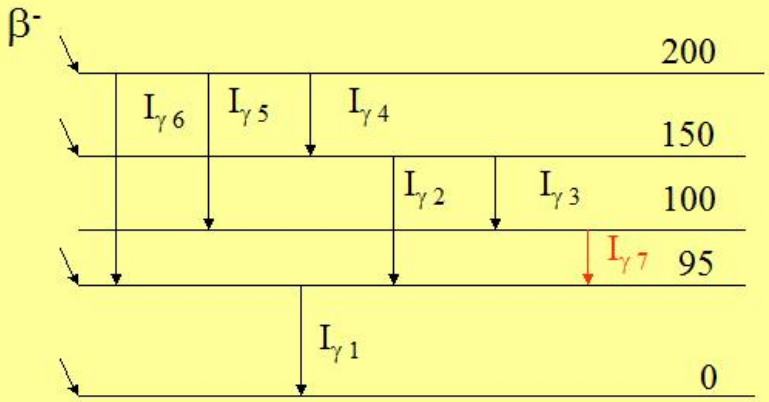
Total transition intensity

TI field should be used *only* if TI (rather than I_γ) is the measured or deduced quantity. Usual cases are:

TI deduced from transition intensity balance

TI = Σ I_i(ce), if I_γ is known to be negligible. If not negligible, but conversion coefficient is known, then deduced and give I_γ

Total intensity from transition-intensity balance



$TI(\gamma_7) = TI(\gamma_5) + TI(\gamma_3)$

If $\alpha(\gamma_7)$ is known:

$I\gamma_7 = TI(\gamma_7) / [1 + \alpha(\gamma_7)]$

5. Absolute intensities

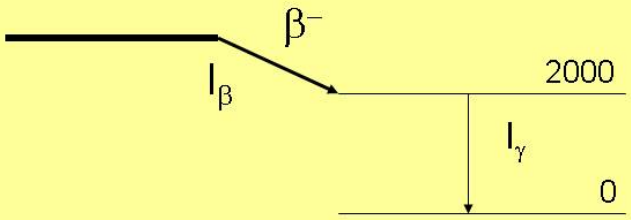
Intensities per 100 disintegrations of the parent nucleus

Measured (Photons from β^-, $\varepsilon+\beta^+$, and α decay)

Simultaneous singles measurements

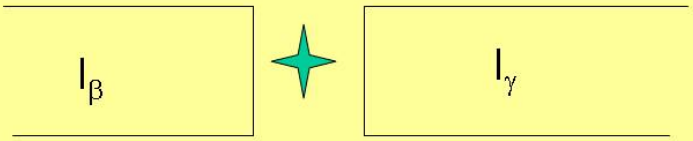
Coincidence measurements

Absolute γ-ray Intensity



$\gamma(\%) = I_\gamma / I_\beta = 100\%$

Simultaneous Singles Measurement



I_β: β^- intensity corrected for detector efficiency

I_γ: γ-ray intensity corrected for detector efficiency

I_γ / I_β = absolute γ-ray intensity

Units: photons per β^- (or per 100 β^-) disintegrations

4. Decay Scheme Normalization

Rel. Int.	Norm. Factor	Abs. Int.
I_γ	NR × BR	$\%I_\gamma$
I_t	NT × BR	$\%I_t$
I_β	NB × BR	$\%I_\beta$
I_ε	NB × BR	$\%I_\varepsilon$
I_α	NB × BR	$\%I_\alpha$

NR: factor for converting Relative I_γ to I_γ per 100 decays through this decay branch

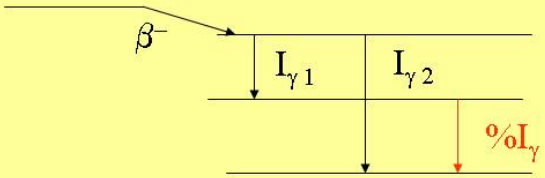
NT: factor for converting Relative TI to TI per 100 decays through this decay branch.

NB: factor for converting Relative β^- and ε intensities to intensities per 100 decays of this decay branch.

BR: factor for converting Intensity per 100 decays through this decay branch, to intensity per 100 decays of the parent nucleus

Normalization Procedures

1. Absolute intensity of one gamma ray is known ($\%I_\gamma$)



2. Relative intensity $I_\gamma \pm \Delta I_\gamma$

   Absolute intensity $\%I_\gamma \pm \Delta\%I_\gamma$

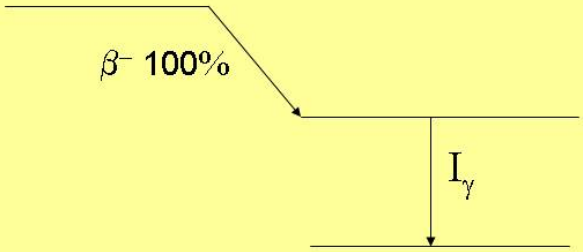
   Normalization factor $N = \%I_\gamma / I_\gamma$

   Uncertainty $\Delta N = [(\Delta\%I_\gamma / \%I_\gamma)^2 + (\Delta I_\gamma / I_\gamma)^2]^{1/2} \times N$

   then $\%I_{\gamma 1} = N \times I_{\gamma 1}$

   $\Delta\%I_{\gamma 1} = [(\Delta N/N)^2 + (\Delta I_{\gamma 1} / I_{\gamma 1})^2]^{1/2} \times I_{\gamma 1}$

2. From Decay Scheme



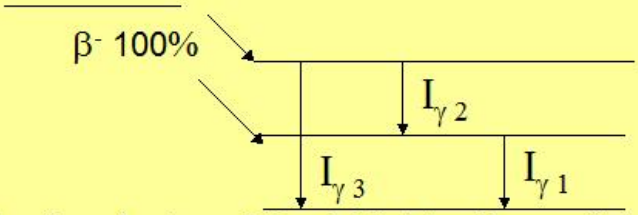
$I\gamma$: Relative γ-ray intensity; α: total conversion coefficient

$$N \times I_\gamma \times (1 + \alpha) = 100\%$$

Normalization factor $N = 100 / I_\gamma \times (1 + \alpha)$

Absolute γ-ray intensity $\% I_\gamma = N \times I_\gamma = 100 / (1 + \alpha)$

Uncertainty $\Delta\% I_\gamma = 100 \times \Delta\alpha/(1 + \alpha)^2$



Normalization factor $N = 100 / I_{\gamma 1}(1 + \alpha_1) + I_{\gamma 3}(1 + \alpha_3)$

$\% I_{\gamma 1} = N \times I_{\gamma 1} = 100 \times I_{\gamma 1} / I_{\gamma 1}(1 + \alpha_1) + I_{\gamma 3}(1 + \alpha_3)$

$\% I_{\gamma 3} = N \times I_{\gamma 3} = 100 \times I_{\gamma 3} / I_{\gamma 1}(1 + \alpha_1) + I_{\gamma 3}(1 + \alpha_3)$

$\% I_{\gamma 2} = N \times I_{\gamma 2} = 100 \times I_{\gamma 2} / I_{\gamma 1}(1 + \alpha_1) + I_{\gamma 3}(1 + \alpha_3)$

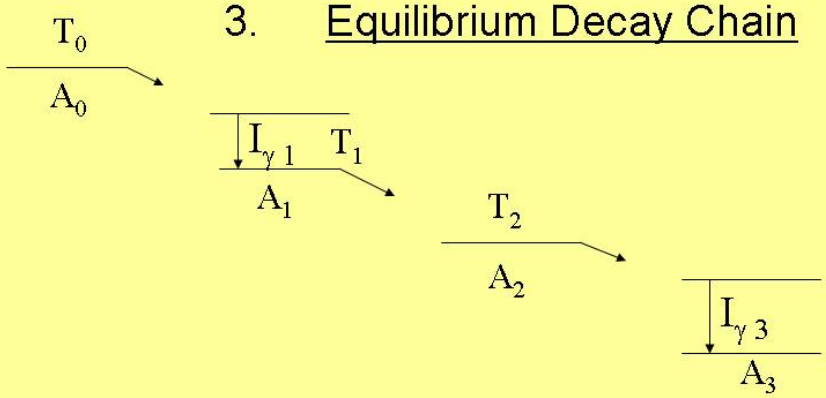
Calculate uncertainties in $\%I_{\gamma 1}$, $\% I_{\gamma 2}$, and $\% I_{\gamma 3}$.

Use 1.5% fractional uncertainty in α_1 and α_3.

See Nucl. Instrum. Methods Phys.Rev. **A249**, 461(1986).

Use computer program GABS to save time

3. Equilibrium Decay Chain



$T_0 > T_1, T_2$ are the radionuclide half-lives

For $t = 0$ only radionuclide A_0 exists

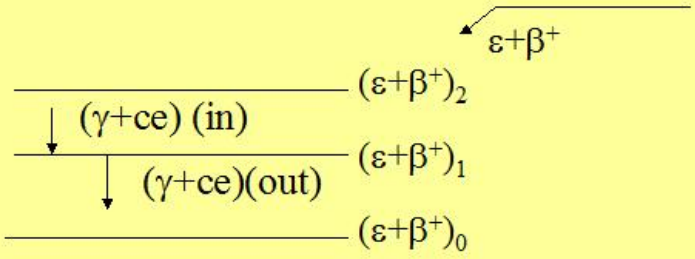
% $I_{\gamma 3}$, $I_{\gamma 3}$, and $I_{\gamma 1}$ are known

Then, at equilibrium

$$\% I_{\gamma 1} = (\% I_{\gamma 3}/I_{\gamma 3}) \times I_{\gamma 1} \times (T_0/(T_0 - T_1) \times (T_0/(T_0 - T_2)$$

Normalization factor $N = \% I_{\gamma 3} / I_{\gamma 3}$

4. Annihilation radiation intensity is known



$I(\gamma\pm)$ = Relative annihilation radiation intensity

X_i = Intensity imbalance at ith level = (γ+ce) (out) – (γ+ce) (in)

$r_i = \varepsilon_i / \beta^+_i$ theoretical ratio to ith level

$X_i = \varepsilon_i + \beta^+_i = \beta^+_i\ (1 + r_i)$, therefore $\beta^+_i = X_i / 1 + r_i$

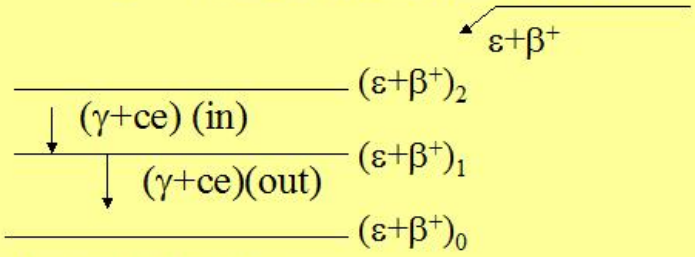
$$2\ [X_0 / (1 + r_0) + \Sigma\ X_i / (1 + r_i)] = I(\gamma\pm) \ldots\ldots\ (1)$$

$$[X_0 + \Sigma\ I_{\gamma i}\ (\gamma + ce) \text{ to gs }]\ N \quad = 100 \ldots\ldots\ (2)$$

Solve equation (1) for X_0 (rel. gs feeding)

Solve equation (2) for N (normalization factor)

5. X-ray intensity is known



I_K = Relative Kx-ray intensity

X_i = Intensity imbalance at ith level = (γ+ce) (out) – (γ+ce) (in)

$r_i = \varepsilon_i / \beta^+_i$ theoretical ratio to ith level

$X_i = \varepsilon_i + \beta^+_i$, so $\varepsilon_i = X_i r_i / 1 + r_i$ (atomic vacancies); ω_K=K-fluorsc. yield

P_{Ki} = Fraction of electron-capture decay from K shell

$I_K = \omega_K [\varepsilon_0 \times P_{K0} + \Sigma \varepsilon_i \times P_{Ki}]$

$$I_K = \omega_K [P_{K0} \times X_0 r_0 / (1 + r_0) + \Sigma P_{Ki} \times X_i r_i / 1 + r_i] \ldots (1)$$

$$[X_0 + \Sigma I_i(\gamma + ce) \text{ to gs}] N = 100 \ldots . (2)$$

Solve equation (1) for X_0, equation (2) for N.

5. Beta Particles

1. Energy (keV)

- Give E_β(max) *only* if experimental value is so accurate that this value could be used as input to mass adjustment
- Do not give E_β(avg.), program LOGFT calculates the value

2. Absolute intensity (%I_β, per 100 decays of the parent nucleus)

- Give experimental value, if used for normalizing the decay scheme
- Give absolute value deduced from γ-ray transition intensity balance (Program GTOL)

3. Log*ft*

Usually authors assign spins and parities. Nevertheless, verify that the relevant log*ft* values are consistent with their assignments

6. Electron Capture

- Give ($I_{\varepsilon}+I_{\beta+}$) feedings deduced from γ-ray transition intensity balance. Program LOGFT calculates ε and β^+ probabilities from theory.
- Program LOGFT calculates sub-shell (P_K, P_L, P_M, ...) probabilities from theory.
- Give x-ray intensities In comments.These data are useful for normalizing or testing the decay scheme.

7. Alpha Particles

• Energy (keV)

Most measurements are relative to a line from a standard radionuclide - include this information in a comment.

Use Ritz (At. Data Nucl. Data Tables **47**, 205 (1991)) evaluated E_α and I_α when no new values are available.

• Intensity

Give intensities preferably "per 100 α decays" (NB = 1), and a branching factor BR to convert them to "per 100 decays of the parent nucleus"

• Hindrance factor

HF = experimental $T_{1/2}(\alpha)$/theoretical $T_{1/2}(\alpha)$ - theoretical value is from 1947Pr17 (M.A. Preston). Assumed that 0^+ to 0^+ α transitions from even-even nuclei are the fastest (HF = 1). These transitions are used to determine the radius parameter r_0 (see 1998Ak04, Y.A. Akovali). Use ALPHAD program.

Favored Alpha-particle Transition

- HF < 4
- Takes place between levels with the same spin and parity

Radius Parameter r_0
(Y. Akovali, Oak Ridge National Laboratory)

- Odd-N nucleus (Z, A)

  $r_0(Z, N) = [r_0(Z, N-1) + r_0(Z, N+1)]/2$

- Odd-Z nucleus (Z, A)

  $r_0(Z, N) = [r_0(Z-1, N) + r_0(Z+1, N)]/2$

- Odd-Odd nucleus (Z, A)

  $r_0(Z, N) = [r_0(Z, N-1) + r_0(Z, N+1)]/2 =$
  $[r_0(Z-1, N+1)+r_0(Z-1, N-1)+r_0(Z+1, N+1) +r_0(Z+1, N-1)]/4$

Example

$^{219}Rn \Rightarrow ^{215}Po$ (Odd-N)

r_0 (Z=84, N=131) = [r_0(84, 130) + r_0(84, 132)] /2

From 1998Ak04:

r_0(84,214) = 1.559 *8*

r_0(84,216) = 1.5555 *2*, therefore

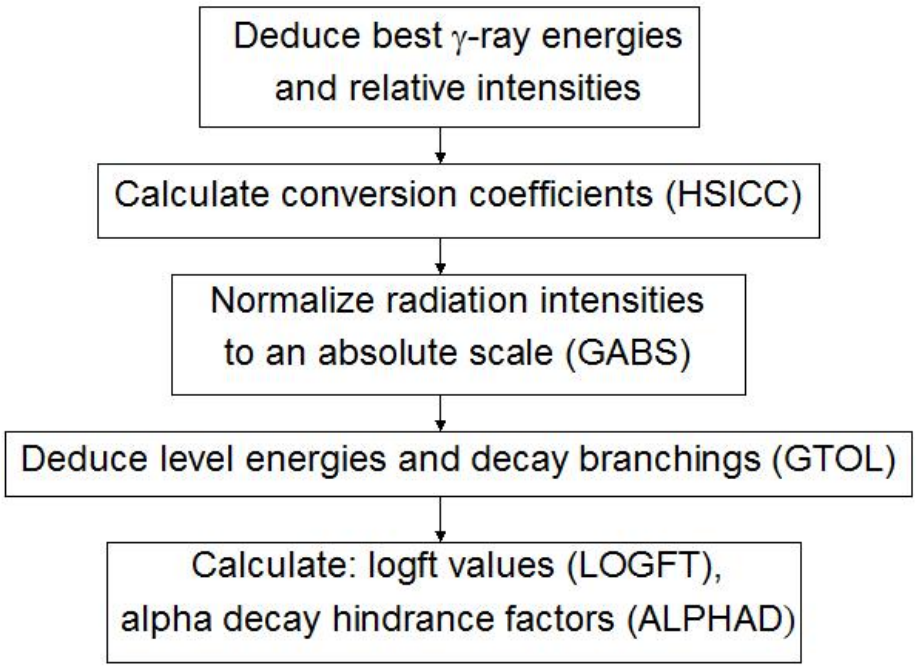
r_0 (Z=84, N=131) = 1.557

Use Table 1 – "Calculated r_0 for even-even nuclei" (1998Ak04). Insert R0 = … in *comment* record:

CA HF R0 =…

Run ALPHAD program to calculate hindrance factors

8. Level Structure and Decay Scheme



ENSDF – Evaluations: Methodology and Worked Examples

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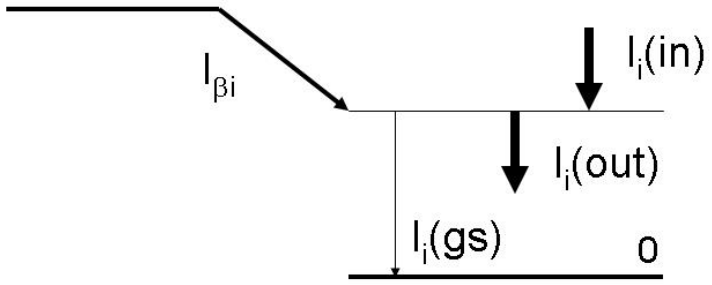
Workshop on
NUCLEAR STRUCTURE AND DECAY DATA EVALUATION
Model exercise

Edgardo Browne

γ-ray transition intensity balance



The corresponding normalization factor is

$N = 100 / \Sigma[I_i(out) + I_i(gs) - I_i(in)] =$
$100 / \Sigma[I_i(out) - I_i(in)] + \Sigma I_i(gs)$, but
$\Sigma[I_i(out) - I_i(in)] = 0$, therefore
$N = 100 / \Sigma I_i(gs)$

^{233}Pa β^- decay

$I_\gamma(312)$ = 38.6 (5) % (experimental value, Gehrke et al.)
$\Sigma I(\gamma+ce)$ (gs) = 102 (2) %

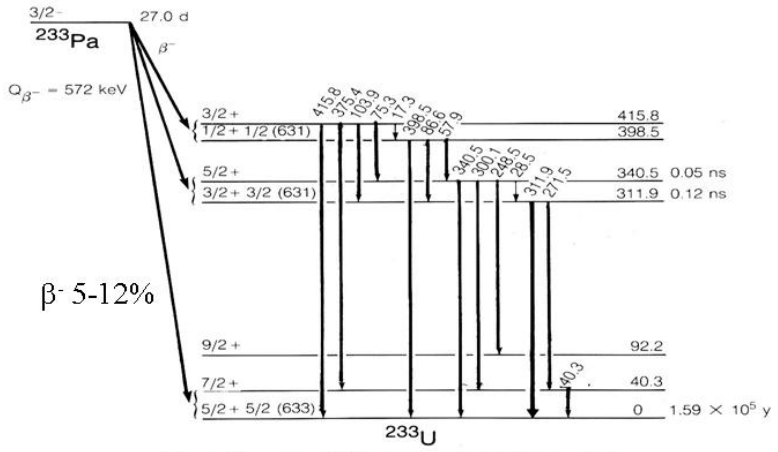


Fig. 1. Simplified ^{233}Pa decay scheme from ref. [1]).

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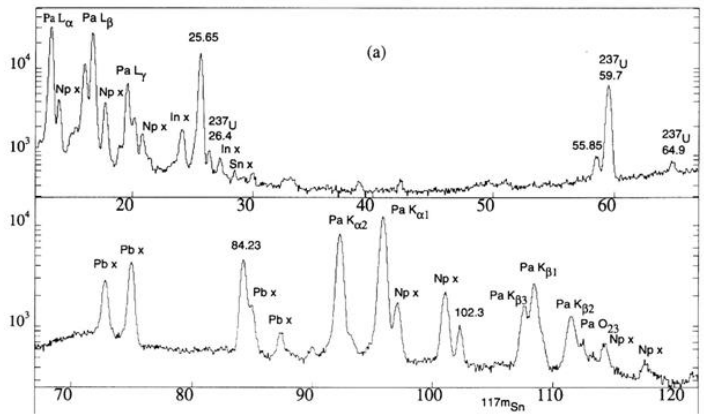
What went wrong?

E_γ(keV)	α_T(exp.)	α_T(theo. M1)
300	0.83 (2)	1.04
312	0.79 (2)	0.96
340	0.61 (2)	0.75

Answer: Nuclear penetration effects

Using X rays to normalize a decay scheme

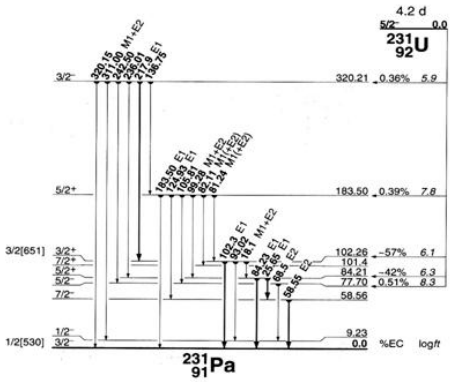
^{231}U γ-ray spectrum



I_γ(25)=100 (6)

I_γ(84)=50 (3)

I_{KX}=390 (14)



EC(K)/EC(Total) = 0.59

ω_K = 0.972

Fig. 4. ^{231}U electron-capture decay scheme. Gamma rays measured in this work are shown with thicker arrows; other data are from refs. [3,11]. Electron-capture branches per 100 decays of ^{231}U and log *ft* values are from gamma-ray transition probability balances (see Table 3).

B_K = 115.6 keV, thus most K-x rays originate from vacancies produced by the electron-capture process

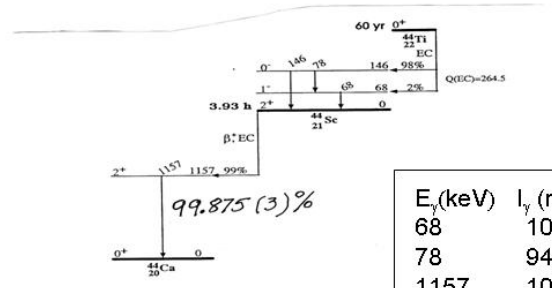
Total vacancies = I_{KX} EC(Total) / ω_K EC(K) = 680 (33)

Normalization factor N = 100 / 680 (33) = 0.147 (7)

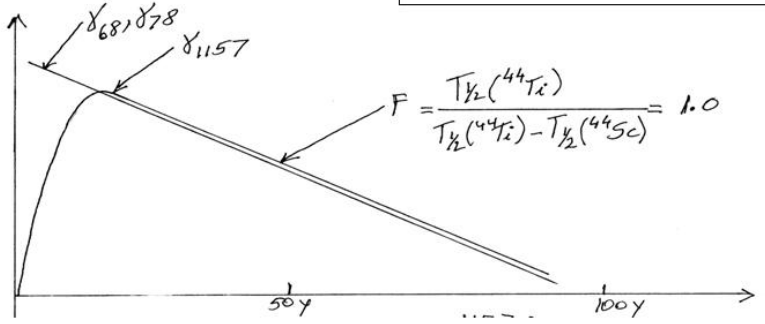
I_γ(25) = 100 (6) x 0.147 (7) = 15 (1)%

I_γ(84) = 50 (3) x 0.147 (7) = 7.5 (6)%

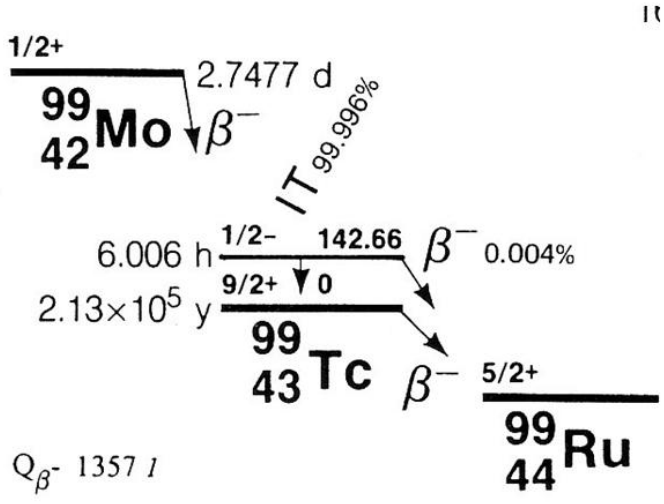
^{44}Ti electron capture decay

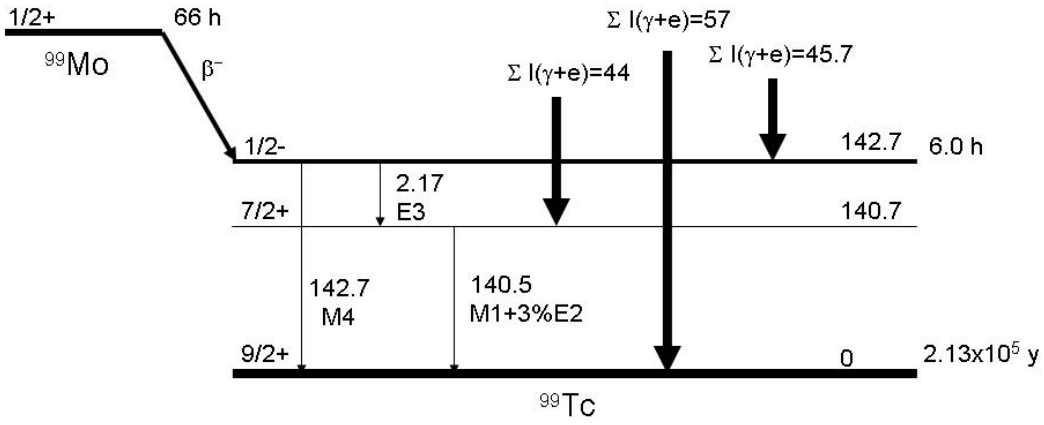


E_γ(keV)	I_γ (rel)	I_γ(%)
68	100 (1)	96.6 (10)
78	94.2 (8)	91.0 (8)
1157	103.4 (10)	99.875 (3)



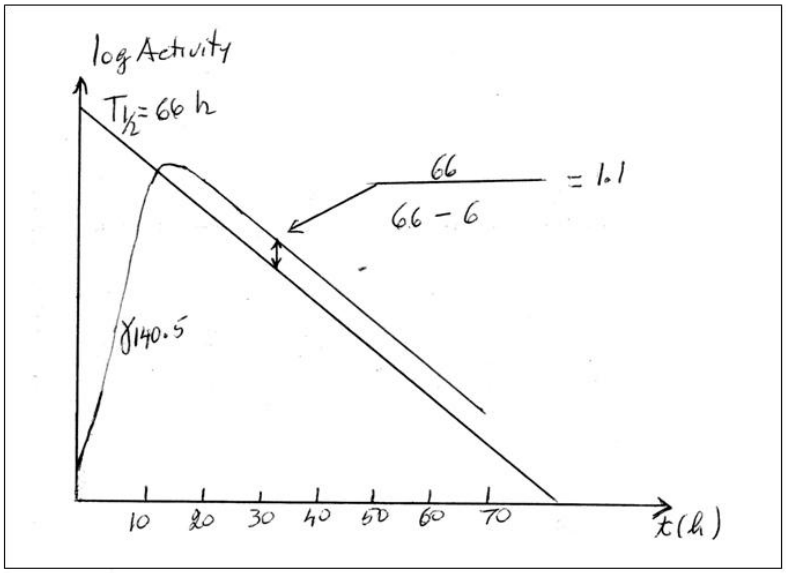
^{99}Mo(2.75 d) $\xrightarrow{\beta^-}$ ^{99m}Tc(6.0 h) $\xrightarrow{IT}$ ^{99}Tc(2.1x10^5 y)

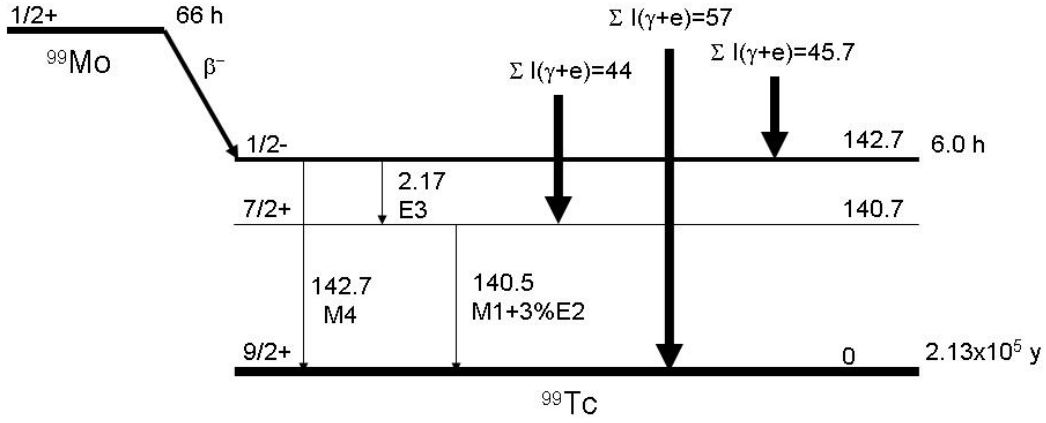




Equilibrium Intensities

E_γ(keV)	I_γ	α	$I_{\gamma+ce}$
140.5	742 (11)	0.114 (3)	827 (12)
142.7	0.17 (2)	40.9 (12)	7.3 (7)





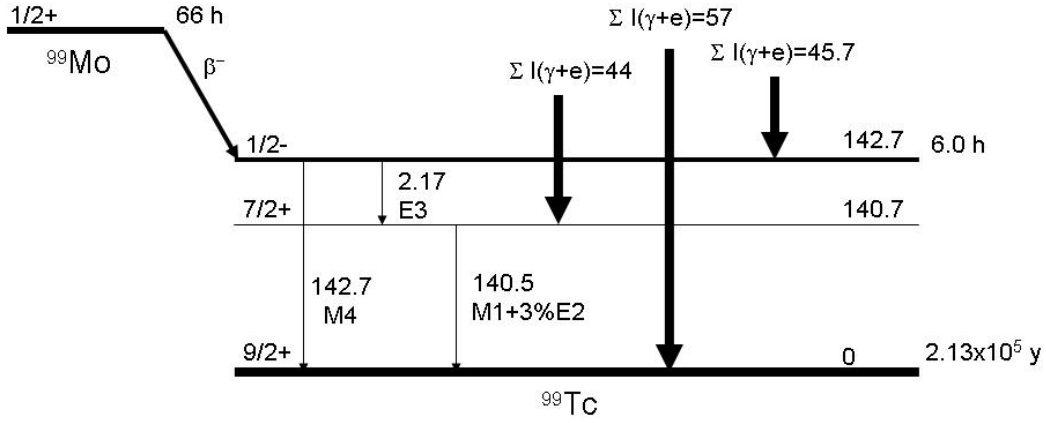
Decay Scheme Normalization

$$[I(\gamma+ce)(142.7)/1.1 + I(\gamma+ce)(140.5)/1.1 + \Sigma I(\gamma+ce)_{gs}] \times N = 100$$

$$[7.3\ (7)/1.1 + 827\ (12)/1.1 + 57.0\ (8)] \times N = 100$$

$$N = 100/816\ (11) = 0.1226\ (17)$$

So, $I_\gamma(\%)(140.5) = 742\ (11) \times 0.1226\ (7) = 91.0\ (\mathbf{3})\%$



β^- feeding to 142.7-keV level

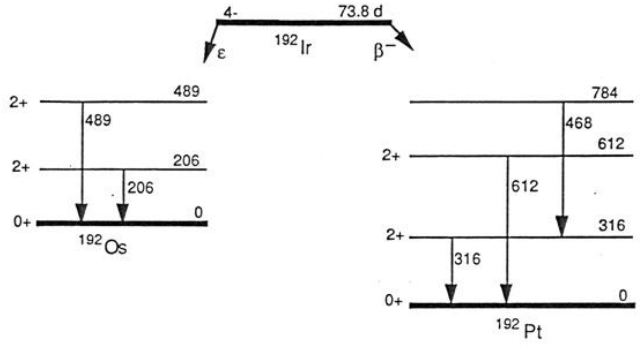
$$I_{\beta-} = I(\gamma+ce)(142.7)/1.1 + I(\gamma+ce)(2.17)/1.1 - \Sigma I(\gamma+ce)_{142.7}$$

$$I(\gamma+ce)(140.5)/1.1 - I(\gamma+ce)(2.17)/1.1 - \Sigma I(\gamma+ce)_{140.5} = 0$$

$$I_{\beta-} = 668$$

So, $I_{\beta-}(\%) = 668 \times 0.1226 = 82.0\%$

^{192}Ir β^- and electron capture decay



E_γ(keV)	I_γ	α	$I_\gamma(1+\alpha)$	
206	4.01 (6)	0.305 (9)	5.23 (8)	
489	0.527 (9)	0.0242 (7)	0.540 (9)	Σ= 5.77 (8)
316	100.0 (5)	0.085 (3)	108.5 (6)	
468	57.76 (20)	0.0294 (9)	58.43 (20)	
612	6.365 (25)	0.0155 (5)	6.464 (25)	Σ= 114.9 (6)

The normalization factor is:

$N = 100 / [I_\gamma(489)(1+\alpha_{489}) + I_\gamma(206)(1+\alpha_{206}) + I_\gamma(316)(1+\alpha_{316}) + I_\gamma(612)(1+\alpha_{612})]$

$= 100 / 120.7\ (7) = 0.828\ (5)$

$$N = 0.828\ (5)$$

Electron capture (ε) and β^- decay branchings are:

$\varepsilon = 100\ [I_\gamma(489)(1+\alpha_{489}) + I_\gamma(206)(1+\alpha_{206})] / 120.7\ (7)$

$= 100 / [1 + (I_\gamma(316)(1+\alpha_{316}) + I_\gamma(612)(1+\alpha_{612})/(I_\gamma(489)(1+\alpha_{489}) + I_\gamma(206)(1+\alpha_{206}))$

$= 100 / [1 + 114.9\ (6)/5.77\ (8)] = 100 / 20.9\ (3) = 4.78\ (7)\%$

$\beta^- = 100 - EC = 100 - 4.78\ (7) = 95.22\ (7)\%$

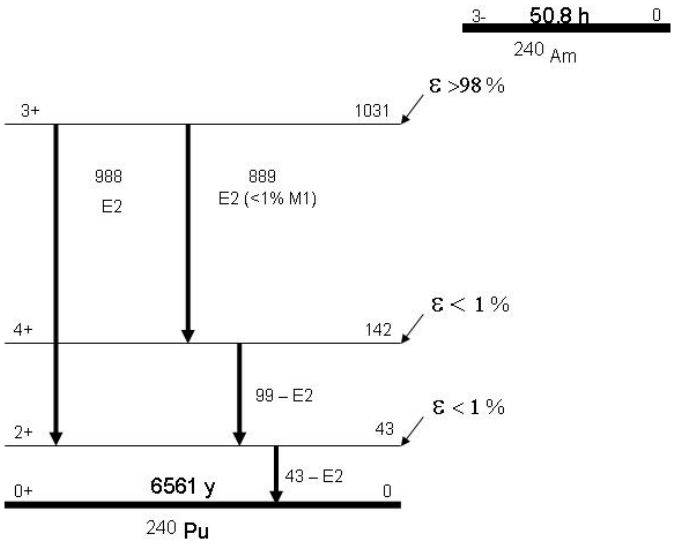
$$\beta^- = 95.22\ (7)\%$$

$$\varepsilon = 4.78\ (7)\%$$

988-keV γ ray from ^{240}Am Electron-Capture Decay

$$^{241}\mathrm{Am(n,2n)}^{240}\mathrm{Am} \xrightarrow{\mathrm{EC}} {}^{240}\mathrm{Pu}$$

Simplified ^{240}Am Decay Scheme



^{240}Am Relative γ-ray Intensities

Eγ(keV)	1971LeZO	1972Ah07	Weighted Average
889	25.1±0.4	25.1±0.0	25.1±0.4
988	73.2±1.0	73.3±2.5	73.2±1.0

Decay Scheme Normalization and Absolute γ-ray Intensity

$$\{I\gamma(988)\,[1 + \alpha_{988}] + I\gamma(889)\,[1 + \alpha_{889}]\}\,N = 99\,(1)\,\%$$

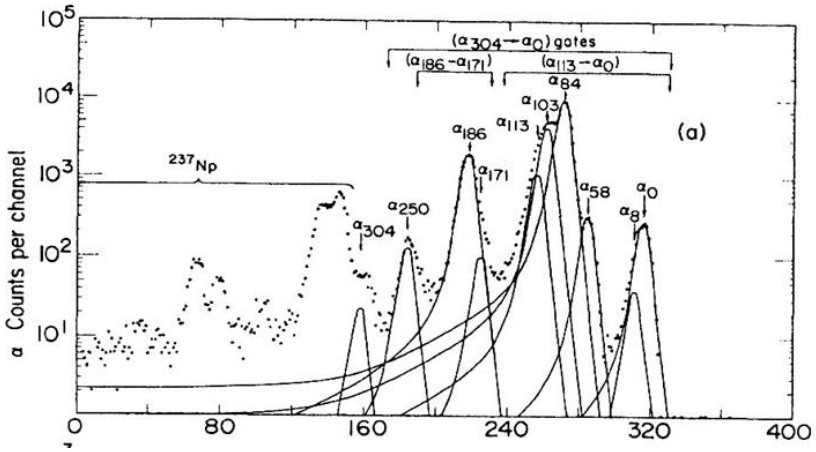
$$N = 0.994\,(15)$$

$$I\gamma(988)(\text{abs}) = I\gamma(988) \times N$$

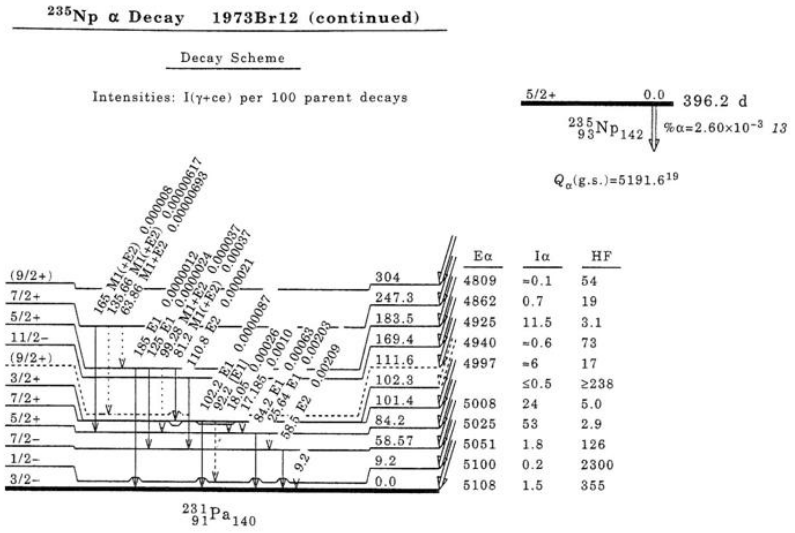
$$= \frac{99\,(1)\,\%}{[1 + \alpha_{988}] + \dfrac{I\gamma(889)\,[1 + \alpha_{889}]}{I\gamma(988)\,[1 + \alpha_{988}]}}$$

$$= \frac{99\,(1)\,\%}{1.0128\,(2) + 0.3438\,(70)} = 73.0\,(7)\,\%$$

^{235}Np Alpha-particle Spectrum



^{235}Np Alpha Decay Scheme



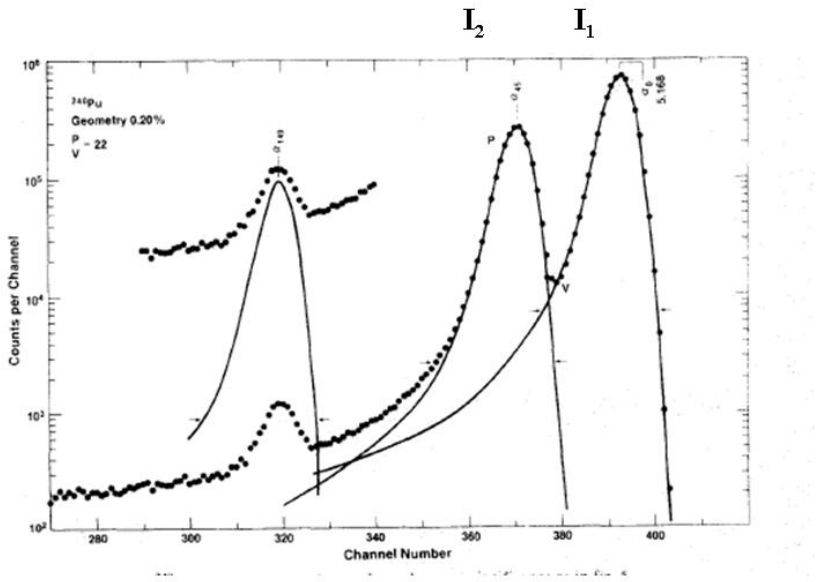
^{235}Np Alpha-particle intensities

E_α(keV)	E_{lev}(keV)	I_α(spec.)	I_α(bal.)
4809	304	~0.1	
4862	247	0.7 (1)	0.8 (2)
4925	183	11.5 (5)	16 (3)
4940	169	~0.6	0.8 (3)
4997	112	~6	
5008	101	24 (8)	33 (10)
5025	84	53 (8)	51 (12)
5051	58	1.8 (3)	~2
5100	9	0.2	
5108	0	1.5 (2)	

Particle Emission Probabilities

- Directly measured
- Deduced from γ-ray intensity balance

^{240}Pu Alpha Spectrum



α-particle emission probabilities are:

$p_1(\%) = I_1 \times 100/(I_1 + I_2)$, and

$p_2(\%) = I_2 \times 100/(I_1 + I_2)$

I_1 and I_2 are spectral areas

Uncertainties assuming uncorrelated spectral areas (I_1, I_2) and small values of dI_1 and dI_2

$$p_1(\%) = I_1 \times 100/(I_1 + I_2)$$

$$p_2(\%) = I_2 \times 100/(I_1 + I_2)$$

$$dp_1^2 = (dp_1/dI_1)^2\, dI_1^2 + (dp_1/dI_2)^2\, dI_2^2$$
$$dp_2^2 = (dp_2/dI_1)^2\, dI_1^2 + (dp_2/dI_2)^2\, dI_2^2$$

$$= \frac{100^2 \times}{(I_1 + I_2)^2} \left[(I_1^2\, dI_2^2 + I_2^2\, dI_1^2)\right]^2$$

if $I_1 = I_2 = I$, and $dI_1 = dI_2$, then

$$dp_1/p_1 = dp_2/p_2 = (2)^{1/2}/2\ dI/I$$

Surprising??

Of course NOT!

p_1 and p_2 are correlated!

$$p_1 = I_1 \times 100/(I_1 + I_2) = 100 \times 1/(1 + I_2/I_1)$$

$$p_2 = I_2 \times 100/(I_1 + I_2) = 100 \times 1/(1 + I_1/I_2)$$

Back to ^{240}Pu

Table 1
^{240}Pu alpha decay

Alpha energy [keV]	Intensity (relative)
5168.17 ± 0.15	73.51 ± 0.36
5123.62 ± 0.25	26.39 ± 0.21
5021.5 ± 0.5	0.071 ± 0.001

$$dp_1^2 = dp_2^2 = \frac{100^2 \text{ x}}{(I_1+I_2)^4} \quad [I_1^2\, dI_2^2 + I_2^2\, dI_1^2], \text{ so}$$

$$dp_1^2 = dp_2^2 = \frac{[73.51^2 \text{ x } 0.21^2 + 26.39^2 + 0.36^2]}{100^2} = \frac{328.56}{100^2}$$

$$dp_1 = dp_2 = \frac{(328.56)^{1/2}}{100} = 0.18$$

Finally,

$p_1 = 73.51 \pm 0.18$ % $p_2 = 26.39 \pm 0.18$ %

General Case

Nucl. Instrum. Methods Phys. Res. A265, 541 (1988)

The emission probability of the ith particle group is given by

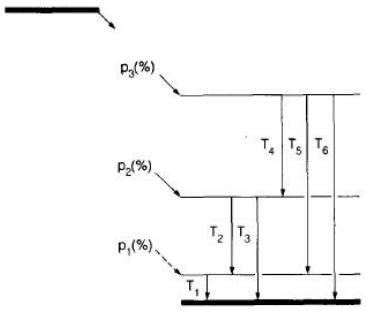
$$p_i(\%) = \frac{BI_i}{\sum_k I_k}, \tag{1}$$

where I_i is the relative spectral intensity of the ith particle group (with statistical uncertainty dI_i), B is the percentage particle branching (with statistical uncertainty dB), and the summation is over all particle groups k.

The fractional uncertainty of $p_i(\%)$, calculated in first order approximation in a Taylor series expansion,

$$\frac{dp_i(\%)}{p_i(\%)} = \left[\left(\frac{dI_i}{I_i} \right)^2 \left(1 - \frac{2I_i}{\sum_k I_k} \right) + \frac{\sum_k dI_k^2}{\left(\sum_k I_k \right)^2} + \left(\frac{dB}{B} \right)^2 \right]^{1/2}. \tag{2}$$

Particle Emission Probabilities Deduced from Decay Scheme



$$p_1(\%) = \frac{T_1 - T_2 - T_5}{T_1 + T_3 + T_6} \times 100, \quad p_2(\%) = \frac{T_2 + T_3 - T_4}{T_1 + T_3 + T_6} \times 100, \quad p_3(\%) = \frac{T_4 + T_5 + T_6}{T_1 + T_3 + T_6} \times 100.$$

$$\mathrm{d}p_i^2(\%) = \sum_{k=1}^{6} \left(\frac{\partial p_i}{\partial T_k} \mathrm{d}T_k \right)^2,$$

Uncertainties become

$$\mathrm{d}p_1(\%) = \frac{100}{(T_1 + T_3 + T_6)^2} \Big(\mathrm{d}T_1^2 (T_2 + T_3 + T_5 + T_6)^2 + (\mathrm{d}T_2^2 + \mathrm{d}T_5^2)(T_1 + T_3 + T_6)^2 + (\mathrm{d}T_3^2 + \mathrm{d}T_6^2)(T_1 - T_2 - T_5)^2 \Big)^{1/2},$$

$$\mathrm{d}p_2(\%) = \frac{100}{(T_1 + T_3 + T_6)^2} \Big(\mathrm{d}T_3^2 (T_1 - T_2 + T_4 + T_6)^2 + (\mathrm{d}T_2^2 + \mathrm{d}T_4^2)(T_1 + T_3 + T_6)^2 + (\mathrm{d}T_1^2 + \mathrm{d}T_6^2)(T_2 + T_3 - T_4)^2 \Big)^{1/2},$$

$$\mathrm{d}p_3(\%) = \frac{100}{(T_1 + T_3 + T_6)^2} \Big(\mathrm{d}T_6^2 (T_1 + T_3 - T_4 - T_5)^2 + (\mathrm{d}T_4^2 + \mathrm{d}T_5^2)(T_1 + T_3 + T_6)^2 + (\mathrm{d}T_1^2 + \mathrm{d}T_3^2)(T_4 + T_5 + T_6)^2 \Big)^{1/2}.$$

If $p_1(\%) = 0$, then $T_1 = T_2 + T_5$

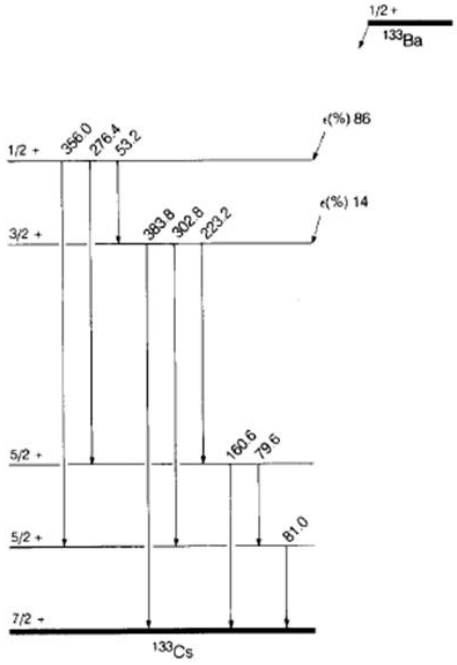
The particle emission probabilities then become

$$p_2(\%) = \frac{T_2 + T_3 - T_4}{T_2 + T_3 + T_5 + T_6} \times 100 \quad \text{and} \quad p_3(\%) = \frac{T_4 + T_5 + T_6}{T_2 + T_3 + T_5 + T_6} \times 100,$$

and their corresponding uncertainties become equal, i.e.,

$$\mathrm{d}p_2(\%) = \mathrm{d}p_3(\%) = \frac{100}{(T_2 + T_3 + T_5 + T_6)^2}\Big(\mathrm{d}T_4^2(T_2 + T_3 + T_5 + T_6)^2 + (\mathrm{d}T_2^2 + \mathrm{d}T_3^2)(T_4 + T_5 + T_6)^2 + (\mathrm{d}T_5^2 + \mathrm{d}T_6^2)(T_2 + T_3 - T_4)^2\Big)^{1/2}.$$

^{133}Ba EC Decay to ^{133}Cs



^{133}Ba EC Decay to ^{133}Cs

Normalization factor $N = 100/(T_{81} + T_{161} + T_{384}) = 1.0044$

uncertainties become:

$d\varepsilon_{384} = 0.74$, $d\varepsilon_{437} = 2.0$ (they are not equal).

$\varepsilon 437 = 86 \pm 2$ % and $\varepsilon 384 = 14.00 \pm 0.74$ %

^{133}Ba EC Decay to ^{133}Cs

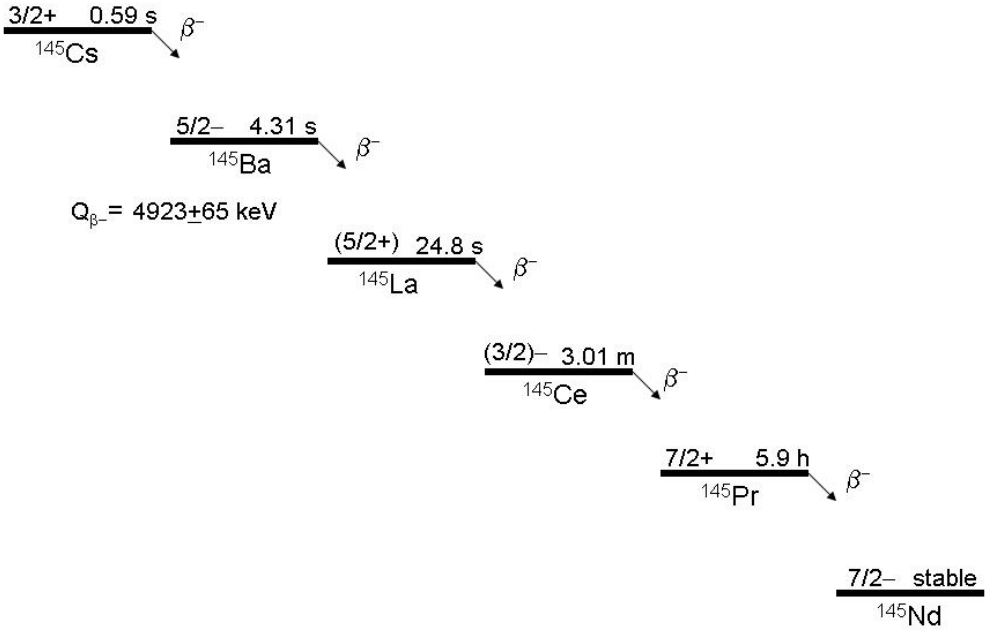
If we assume $\varepsilon_{81} = \varepsilon_{162} = 0$%, then

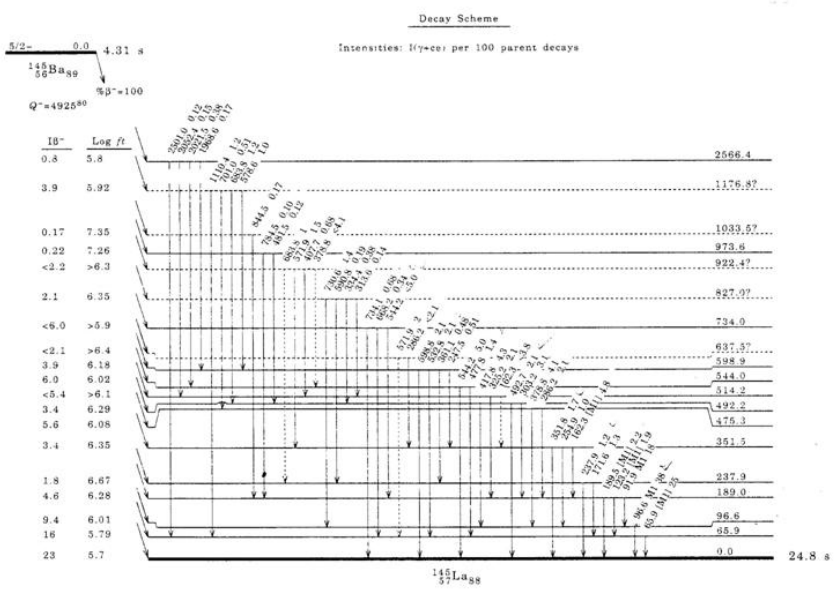
$N = 100/(T_{356}+T_{276}+T_{384}+T_{223}) = 1.00090$, and

$\varepsilon_{437} = 86.00 \pm 0.67$ %, and $\varepsilon_{384} = 14.00 \pm 0.67$ %

For the general case see

Nucl. Instrum. Methods Phys. Res. A265, 541 (1988)





Decay scheme is from NDS 68, 997 (1963)
Absolute γ-ray intensities are based on a measured value of γ(96) = 17.1 +2.1%.
β- feeding intensities are from γ-ray intensity balances

Nuclear Instruments and Methods in Physics Research A 390 (1997) 95–154

ELSEVIER

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Measurement of β^--decay intensity distributions of several fission-product isotopes using a total absorption γ-ray spectrometer

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[b]*Retired, Idaho National Engineering Laboratory, Idaho Falls, ID 83415-2114, USA*
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Received 6 June 1996

Abstract

A total absorption γ-ray spectrometer coupled to the ^{252}Cf-based INEL ISOL facility has been used in a program of systematic study of the distributions of β^--decay intensities of fission-product radionuclides. Cascade-summed γ-ray spectra measured with the system have been compared with the spectrum simulated from the corresponding decay schemes, as a test of the completeness and correctness of these schemes. New β^--decay intensity distributions have been deduced for the decay of these radionuclides. Radionuclides which have been studied in this manner include ^{89}Rb, ^{90g}Rb, ^{90m}Rb, ^{91}Rb, ^{93}Rb, ^{93}Sr, ^{94}Sr, ^{94}Y, ^{95}Sr, ^{95}Y, ^{138g}Cs, ^{138m}Cs, ^{139}Cs, ^{140}Cs, ^{141}Cs, ^{141}Ba, ^{142}Ba, ^{142}La, ^{143}Ba, ^{143}La, ^{144}Ba, ^{144}La, ^{145}Ba, ^{145}La, ^{145}Ce, ^{146}Ce, ^{146}Pr, ^{147}Ce, ^{147}Pr, ^{148}Ce, ^{148}Pr (2.0 min), ^{148}Pr (2.27 min), ^{149}Pr, ^{149}Nd, ^{151}Pr, ^{151}Nd, ^{152}Nd - ^{152}Pm (4.1 min.), ^{153}Nd, ^{153}Pm, ^{154}Nd, ^{154}Pm (1.7 min), ^{155}Nd, ^{155}Pm, ^{156}Pm, ^{157}Pm, ^{157}Sm, ^{158}Sm, and ^{158}Eu.

^{145}Ba Total Absorption γ-Ray Spectrum (1997Gr09)

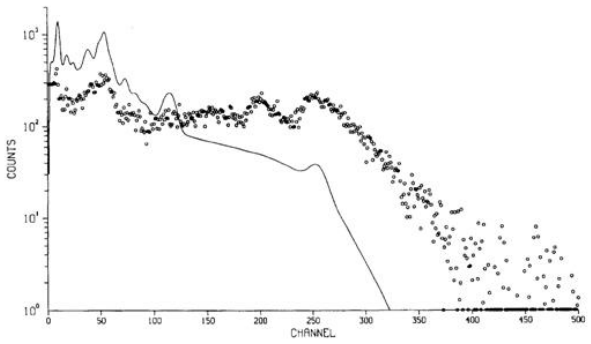
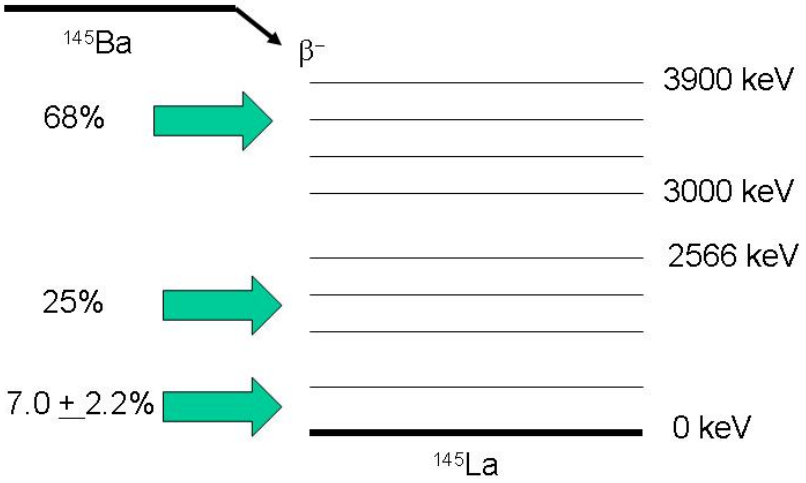


Fig. 25. Comparison of measured singles spectrum for ^{145}Ba with the simulated spectrum for the NDS decay scheme [32].

^{145}Ba Decay Scheme Based on Total Absorption γ-Ray Spectrum
1997Gr09

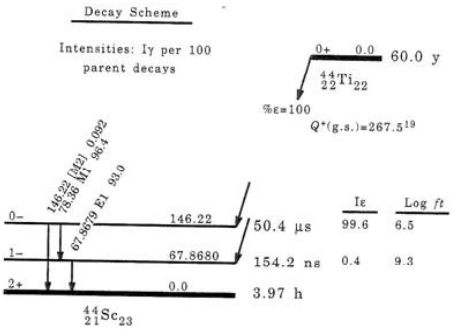


^{145}Ba β$^-$-decay intensities

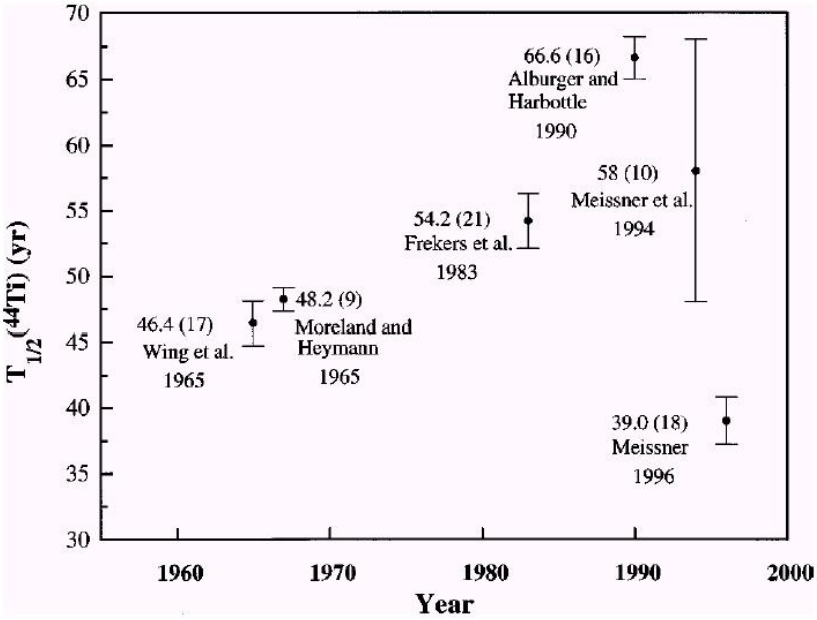
Level energy (keV)	I_β (%)	
	NDS [32]	TAGS
0.0	23.0	7.0 ± 2.2
65.9	16.0	
96.6	9.4	4.39
189.0	4.6	2.15
237.9	1.8	0.65
351.5	3.4	3.4
475.3	5.6	0.84
492.2	3.4	0.51
514.2	< 5.4	4.84
544.0	6.0	1.94
598.9	3.9	1.89
637.5	< 2.1	1.02
734.0	< 6.0	0.54
827.0	2.1	1.02
922.4	< 2.2	0.0
973.6	0.22	0.22
1033.5	0.17	0.17
1176.8	3.9	1.83
1300. P		0.38
1400. P		0.81
1500. P		1.35
1600. P		2.69
1700. P		1.61
1800. P		0.54
2000. P		7.53
2100. P		4.30
2200. P		1.40

Preparing ENSDF Data Sets

^{44}Sc ENSDF Data Set




```
44SC    44TI EC DECAY
44TI  P 0            0+              60.0 Y    11            267.5     19
44SC  N 0.964      13         1.0
44SC  L 0            2+              3.97 H    4
44SC  L 67           1-              154.2 NS  8
44SC  G 67.8679   14   96.5 16    E1                   0.0845
44SCS G KC=   0.0766  $LC=   0.00664
44SC  L 146          0-              50.4 US   7
44SC  G 78.36      3  100.0 11    M1                   0.0302
44SCS G KC=   0.0273  $LC=   0.00243
44SC  G 146.22     3  0.095 3    [M2]                 0.0460
44SCS G KC=   0.0414  $LC=   0.00385
```



Summary of previously reported values for the half-life of ^{44}Ti. Numbers in parentheses represent the lσ uncertainties in the Least significant digit(s).

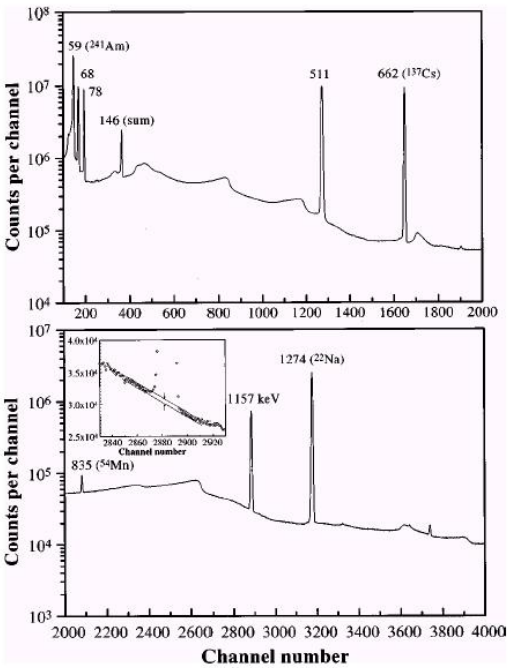
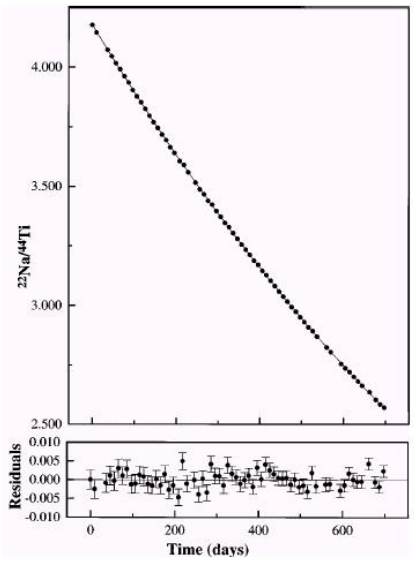


Fig. 4. γ-ray spectrum accumulated in 10 days of counting the source of ^{44}Ti, ^{241}Am, ^{137}Cs and ^{22}Na. All energies are in keV. Peaks labelled only by energy are from the decay of ^{44}Ti. Inset illustrates the background under the 1157-keV peak, and arrows indicate a ± 1% systematic background uncertainty.



The upper part of this figure shows the decrease in the ratio between the peak areas of the 1274-keV (^{22}Na) and 1157-keV (^{44}Ti) γ-rays as a function of time. The curve through the data is the result of a least-squares fit of an exponentially decreasing function of time. The ^{44}Ti half-life determined from this fit is 61.5(9) yr and $\chi^{2/\nu}$ = 1.1. Lower panel shows residuals to this fit.

^{44}Ti Half-life (LWEIGHT)

44Ti Half-life Measurements

INP. VALUE	INP. UNC.	R. WGHT	chi**2/N-1	REFERENCE
.607000E+02	.120E+01	.141E+00	.826E-01	99Wi01
.590000E+02	.600E+00 MIN	*.563E+00*	.479E+00	98Ah03
.603000E+02	.130E+01	.120E+00	.163E-01	98Go05
.620000E+02	.200E+01	.507E-01	.214E+00	98No06
.666000E+02	.160E+01	.792E-01	.348E+01	90Al11
.542000E+02	.210E+01	.460E-01	.149E+01	83Fr27

No. of Input Values N= 6 CHI**2/N-1= 5.76 CHI**2/N-1(critical)= 3.00

UWM :.604667E+02 .164796E+01
WM :.599288E+02 .450317E+00(INT.) .108057E+01(EXT.)

INP. VALUE	INP. UNC.	R. WGHT	chi**2/N-1	REFERENCE
.607000E+02	.120E+01	.161E+00	.563E-01	99Wi01
.590000E+02	.681E+00	*.500E+00*	.487E+00	98Ah03
* Input uncertainty increased .114E+01 times *				
.603000E+02	.130E+01	.137E+00	.663E-02	98Go05
.620000E+02	.200E+01	.580E-01	.188E+00	98No06
.666000E+02	.160E+01	.907E-01	.334E+01	90Al11
.542000E+02	.210E+01	.526E-01	.156E+01	83Fr27

No. of Input Values N= 6 CHI**2/N-1= 5.63 CHI**2/N-1(critical)= 3.00
UWM :.604667E+02 .164796E+01
WM :.600634E+02 .481846E+00(INT.) .114378E+01(EXT.)
LWM :.600634E+02 .114378E+01 Min. Inp. Unc.=.600000E+00
LWM has used weighted average and external uncertainty

Recommended value: 60.0 (11) y

^{44}Sc ENSDF Data Set (GTOL)

LEVEL	TI (OUT)	TI (IN)	TI (NET)	NET FEEDING (CALC)	(USE)
0.0	0.000	104.8 18	-104.8 18	-1.0 17	0.0
67.8679 14	104.7 18	103.0 12	1.6 21	1.6 21	0.6 11
146.224 22	103.1 12	0.000	103.1 12	99.4 11	99.4 11

```
44SC    44TI EC DECAY
44TI  P 0             0+              60.0 Y    11            267.5     19
44SC  N 0.964      13         1.0
44SC  L 0             2+              3.97 H    4
44SC  L 67.8679   141-               154.2 NS  8
44SC  E                           0.6      11
44SC  G 67.8679   14   96.5 16     E1                  0.0845
44SCS G KC=   0.0766  $LC=   0.00664
44SC  L 146.224   220-               50.4 US   7
44SC  E                           99.4     11
44SC  G 78.36      3   100.0 11    M1                  0.0302
44SCS G KC=   0.0273  $LC=   0.00243
44SC  G 146.22     3   0.095 3     [M2]                0.0460
44SCS G KC=   0.0414  $LC=   0.00385
```

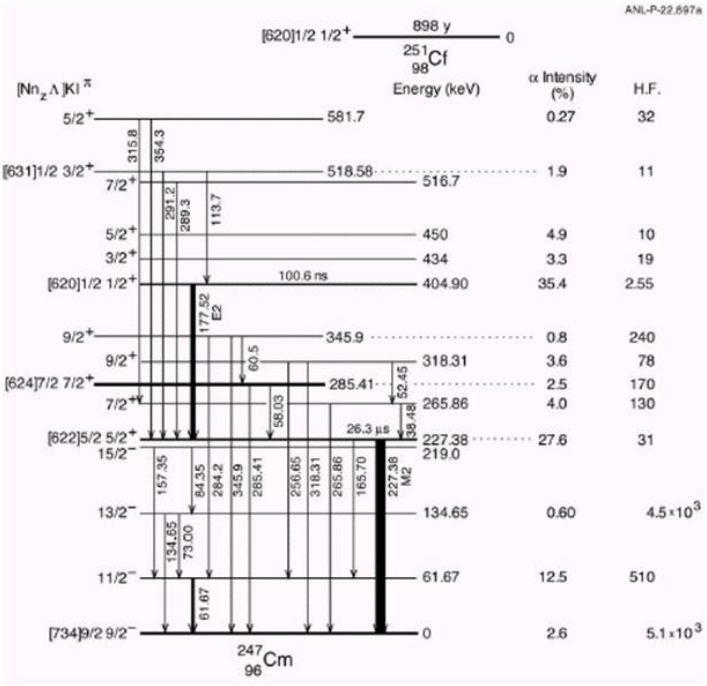
^{44}Sc ENSDF Data Set (LOGFT)

```
44SC    44TI EC DECAY
44TI  P 0             0+              60.0 Y    11            267.5     19
44SC  N 0.964      13         1.0
44SC  L 0             2+              3.97 H    4
44SC  L 67.8679   141-               154.2 NS  8
44SC  E                           0.6   11   9.2   8
44SCS E  CK=0.8910 $CL=0.09309 $CM+=0.01592
44SC  G 67.8679   14   96.5 16     E1                  0.0845
44SCS G KC=   0.0766  $LC=   0.00664
44SC  L 146.224   220-               50.4 US   7
44SC  E                           99.4  11  6.509 17
44SCS E  CK=0.8883 $CL=0.09533 $CM+=0.016352 18
44SC  G 78.36      3   100.0 11    M1                  0.0302
44SCS G KC=   0.0273  $LC=   0.00243
44SC  G 146.22     3   0.095 3     [M2]                0.0460
44SCS G KC=   0.0414  $LC=   0.00385
```

New Exercise
Trieste, 28 April – 9 May 2008

PHYSICAL REVIEW C **68**, 044306 (2003)

Energy levels of ^{247}Cm populated in the α decay of $^{251}_{98}$Cf



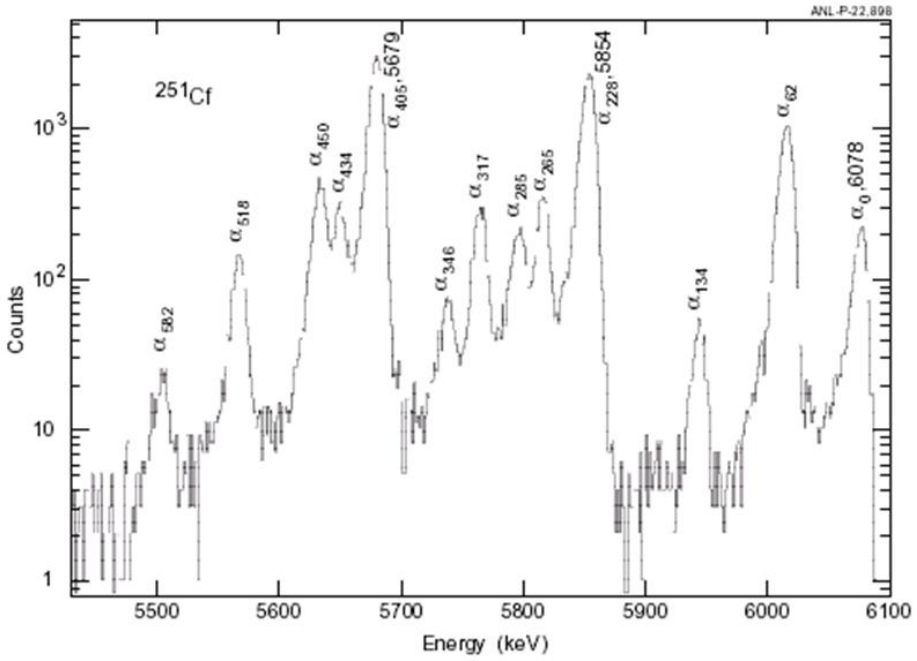


TABLE I. ^{251}Cf α groups.

Energy (MeV)	Excited state energy (keV)	Intensity (%)	Hindrance factor[a]
6.078±0.002	0	2.6±0.1	5.1×10^3
6.017±0.002	62	12.5±0.3	5.1×10^2
5.946±0.002	134	0.60±0.06	4.5×10^3
5.854±0.002	228	27.6±0.5	31
5.817±0.002	265	4.0±0.2	1.3×10^2
5.798±0.002	285	2.5±0.2	1.7×10^2
5.766±0.002	317	3.6±0.2	78
5.738±0.002	346	0.8±0.1	2.4×10^2
5.679±0.002	405	35.4±0.5	2.55
5.651±0.002	434	3.3±0.2	19
5.635±0.002	450	4.9±0.2	10
5.568±0.002	518	1.9±0.1	11
5.505±0.002	582	0.27±0.05	32

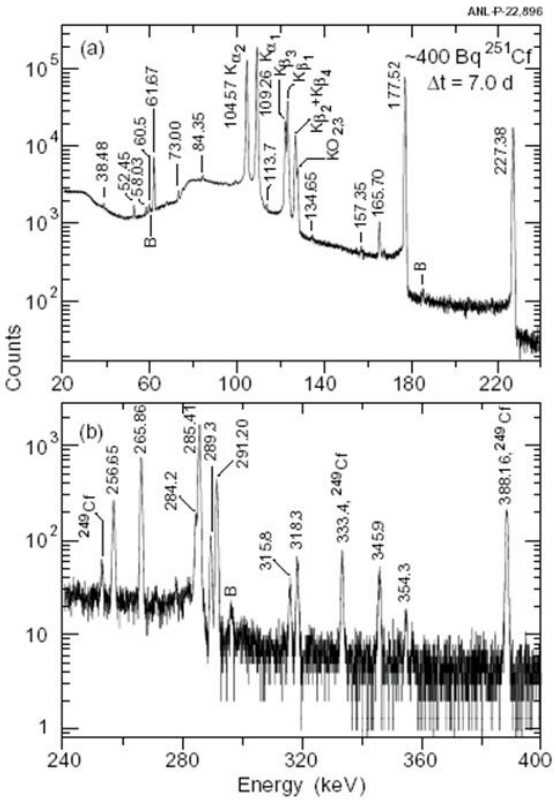


TABLE III. ^{251}Cf γ rays.

Energy (keV)	Intensity (%)	Transitions Initial→Final
38.48±0.05	0.038±0.006	265.86→227.38
52.45±0.05	0.048±0.005	318.31→265.86
58.03±0.05	0.024±0.005	285.41→227.38
60.5±0.1	0.010±0.003	345.9→285.41
61.67±0.05	0.40±0.03	61.67→0
73.00±0.08	0.040±0.005	134.65→61.67
84.35±0.08	0.040±0.005	219.0→134.65
104.57±0.02	12.6±0.7	Cm $K\alpha_2$
109.26±0.02	19.8±1.0	Cm $K\alpha_1$
113.7±0.1	0.024±0.005	518.58→404.90
122.31±0.02+		Cm $K\beta_3$
123.40±0.02	7.7±0.5	Cm $K\beta_1$
127.01±0.04+		Cm $K\beta_2$+$K\beta_4$
128.00±0.05	2.6±0.2	Cm $KO_{2,3}$
134.65±0.08	0.014±0.003	134.65→0
157.35±0.08	0.020±0.004	219.0→61.67
165.70±0.05	0.12±0.01	227.38→61.67
177.52±0.02	17.3±0.9	404.90→227.38
227.38±0.02	6.8±0.3	227.38→0
256.65±0.08	0.13±0.01	318.31→61.67
265.86±0.08	0.43±0.03	265.86→0
284.2±0.1	0.12±0.01	345.9→61.67
285.41±0.08	1.13±0.09	285.41→0
289.3±0.1	0.070±0.007	516.7→227.38
291.20±0.08	0.30±0.03	518.58→227.38
315.8±0.1	0.024±0.003	581.7→265.86
318.3±0.1	0.050±0.005	318.31→0
345.9±0.1	0.043±0.004	345.9→0
354.3±0.1	0.013±0.002	581.7→227.38

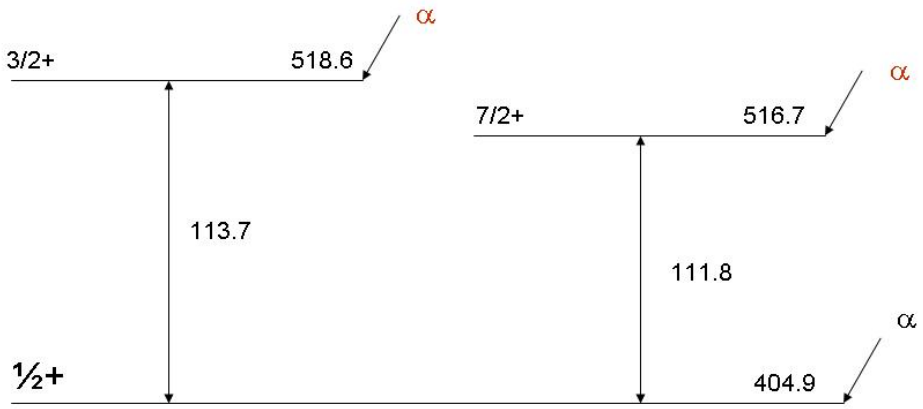
TABLE II. ^{251}Cf conversion electron data.

Transition energy (keV)	Shell	Energy (keV)	Intensity (%)	Conversion coefficient	Theory	Mixing ratio δ	Multipolarity
38.48	$L+M+\cdots$			183±31[a]	122($M1$), 1833($E2$)	0.19±0.05	$M1$+3.6%$E2$
52.45	$L+M+\cdots$			70±10[a]	49.3($M1$), 410($E2$)	0.25±0.06	$M1$+5.7%$E2$
58.03	$L+M+\cdots$			80±19[a]	36.7($M1$), 256($E2$)	0.50±0.08	$M1$+20%$E2$
60.5	$L+M+\cdots$			62±21[a]	32.6($M1$), 208($E2$)	0.45±0.12	$M1$+17%$E2$
61.67	L_1+L_2	37.4	9.4±1.0	23.5±3.1	22.8($M1$), 78.7($E2$)	0.11±0.025	
	L_3	43.0	1.3±0.3	3.3±0.8	0.096($M1$), 56.7($E2$)	0.24±0.03	
	$M+N$	55.5	4.5±0.6	11.0±1.7	7.7($M1$), 53($E2$)	0.28±0.07	$M1$+7%$E2$
73.00	$L+M+\cdots$			40±16[a]	18.7($M1$), 84.3($E2$)	0.69±0.14	$M1$+32%$E2$
165.7	L_1+L_2	141.7	1.8±0.3	15±3	15.6($E3$)		$E3$
	L_3	146.6	0.8±0.3	6.7±2.6	5.6($E3$)		
177.52	K	49.3	3.3±0.5	0.19±0.03	0.17($E2$)		
	L_1+L_2	153.7	12.3±1.2	0.71±0.08	0.73($E2$)		$E2$
	L_3	158.6	5.3±0.5	0.31±0.03	0.31($E2$)		
	$M+N$	171.8	7.1±0.7	0.41±0.05	0.40($E2$)		
227.38	K	99.1	41±3	6.0±0.5	7.9($M2$), 0.27($E3$)	0.58±0.05	$M2$+25%$E3$
	L_1+L_2	202.9	18.4±1.9	2.7±0.3	2.76($M2$), 3.26($E3$)		
	L_3	208.2	2.8±0.3	0.41±0.05	0.28($M2$), 0.91($E3$)		
	$M+N$	221.1	10.4±1.1	1.53±0.17	1.13($M2$), 1.73($E3$)		

[a]Deduced from decay scheme γ-ray and α-particle intensity balance.

ENSDF Dataset (1)

```
247CM    251CF A DECAY                  2003AH07
251CF  P 0.0          1/2+              898 Y     44            6175.8    10
247CM  N 1.0          1.0       1.0
247CM  L 0.0          9/2-              1.56E+7 Y 5
247CM  A 6078      2  2.6    1
247CM  L 62           11/2-
247CM  A 6017      2 12.5    3
247CM  G 61.67     5  0.40   3 M1+E2     0.24    3
247CM  L 135          13/2-
247CM  A 5946      2  0.60   6
247CM  G 73.00     8 0.040   5 M1+E2     0.69     14
247CM  G 134.65    8  0.014  3   [E2]
247CM  L 219          15/2-
247CM  G 84.35     8 0.040   5 [M1+E2]
247CM  G 157.35    8 0.020   4 [E2]
247CM  L 227          5/2+              26.3 US   3
247CM  A 5854      2 27.6    5
247CM  G 165.70    5 0.12    1  E3
247CM  G 227.38    2  6.8    3  M2+E3    0.58    5
247CM  L 266          (7/2+)
247CM  A 5817      2  4.0    2
247CM  G 38.48     5 0.038   6 (M1+E2)   0.19    5
247CM  G 265.86    8  0.43   3 [E1]
247CM  L 285          (7/2+)
247CM  A 5798      2  2.5    2
247CM  G 58.03     5 0.024   5 (M1+E2)   0.50    8
247CM  G 285.41    8  1.13   9   [E1]
247CM  L 318          9/2+
247CM  A 5766      2  3.6    2
247CM  G 52.45     5 0.048   5 (M1+E2)   0.25    6
247CM  G 256.65    8 0.13    1 [E1]
247CM  G 318.3     1 0.050   5 [E1]
247CM  L 346          (9/2+)
247CM  A 5738      2 0.8     1
247CM  G 60.5      1 0.010   3 (M1+E2)   0.45    12
247CM  G 284.2     1 0.12    1 [E1]
247CM  G 345.9     1 0.043   4 [E1]
```



516.7 - 404.9 = 111.8 keV
518.6 - 404.9 = 113.7 keV
E_{α}(516.7 + 518.6) = 5568 keV

E_{α}(404.9) = 5679.3 keV

Q(516.7) = 5679.3 x 251/247 – 111.8 = 5659.5 keV
E_{α}(516.7) = 5659.5 x 247/251 = 5569 keV

Q(518.6) = 5679.3 x 251/247 – 113.7 = 5657.6 keV
E_{α}(518.6) = 5657.6 x 247/251 = 5567 keV

ENSDF Dataset (2)

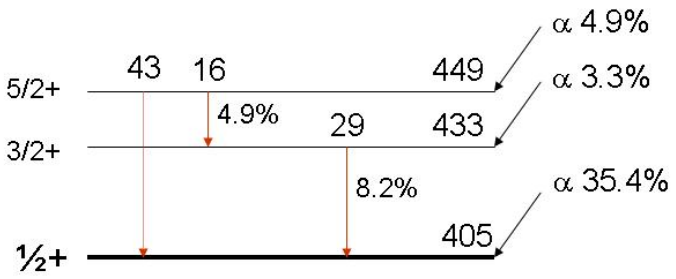
```
247CM  L 405          1/2+             100.6 NS  6
247CM  A 5679.3    1635.4    5
247CM  G 177.52    2  17.3   9  E2
247CM  L 434          (3/2+)
247CM  A 5651      2   3.3   2
247CM  G 28        5           [M1+E2]                          8.2       3
247CM  L 450       2 (5/2+)
247CM  A 5635      2   4.9   2
247CM  G 16        5           [M1+E2]                          4.9       2
247CM  G 44                                                                    S
247CM  L 517          (7/2+)
247CM  A 5569      2   1.9   LE
247CM cA E         from E|a(404.9 level)=5679.3 {I16} and the energy difference
247CM2cA between 516.7 and 404.9 levels (recoil energy is taken into account).
247CM3cA E|a=5568 {I2}, measured by 2003Ah07, is assumed by the evaluator to be
247CM4cA a doublet, feeding the 516.7- and 518.58-keV levels.
247CM cA IA        1.9 {I1} was measured by 2003Ah07 for the doublet.
247CM  G 289.3     1 0.070   7 [M1+E2]
247CM  L 519          (3/2+)
247CM  A 5567      2   1.9   LE
247CM cA E         from E|a(404.9 level)=5679.3 {I16} and the energy difference
247CM2cA between 518.6 and 404.9 levels (recoil energy is taken into account).
247CM  G 113.7     1 0.024   5 [M1+E2]
247CM  G 291.20    8 0.30    3 [M1+E2]
247CM  L 582          (5/2+)
247CM  A 5505      2  0.27   5
247CM  G 63        5           [M1+E2]                          0.21      5
247CM  G 315.8     1 0.024   3 [M1+E2]
247CM  G 354.3     1 0.013   2 [M1+E2]
```

HSICC Program (1)

```
247CM    251CF A DECAY                  2003AH07
251CF  P 0.0          1/2+              898 Y     44              6175.8    10
247CM  N 1.0         1.0       1.0
247CM  L 0.0          9/2-              1.56E+7 Y 5
247CM  A 6078      2  2.6    1
247CM  L 62           11/2-
247CM  A 6017      2 12.5    3
247CM  G 61.67     5  0.40   3 M1+E2     0.24    3       39.2 22
247CMS G LC=29.0 16$MC=7.4 5$NC+=2.82 18
247CM  L 135          13/2-
247CM  A 5946      2  0.60   6
247CM  G 73.00     8 0.040   5 M1+E2     0.69     14      40   6
247CMS G LC=29 5$MC=7.8 13$NC+=3.0 5
247CM  G 134.65    8  0.014  3   [E2]                     5.06
247CMS G KC=0.156$LC=3.52$MC=0.99$NC+=0.389
247CM  L 219           15/2-
247CM  G 84.35     8 0.040   5 [M1+E2]                    27
247CMS G LC=20 11$MC=5 4$NC+=2.1 13
247CM  G 157.35    8 0.020   4 [E2]                     2.62
247CMS G KC=0.178$LC=1.76$MC=0.495$NC+=0.193
247CM  L 227           5/2+              26.3 US   3
247CM  A 5854      2 27.6    5
247CM  G 165.70    5 0.12    1  E3                      31.2
247CMS G KC=0.243$LC=21.7$MC=6.60$NC+=2.65
247CM  G 227.38    2  6.8    3  M2+E3    0.58    5       10.6  2
247CMS G KC=6.0 3$LC=3.35 4$MC=0.93 2$NC+=0.364 6
247CM  L 266          (7/2+)
247CM  A 5817      2  4.0    2
247CM  G 38.48     5 0.038   6 (M1+E2)   0.19    5      1.8E2  4
247CMS G LC=135 25$MC=35 7
247CM  G 265.86    8  0.43   3 [E1]                    0.0571
247CMS G KC=0.0446$LC=0.0094$MC=0.00229$NC+=0.00084
247CM  L 285          (7/2+)
247CM  A 5798      2  2.5    2
247CM  G 58.03     5 0.024   5 (M1+E2)   0.50    8        80  12
247CMS G LC=58 8$MC=15.6 23$NC+=6.0 9
247CM  G 285.41    8  1.13   9   [E1]                   0.0489
247CMS G KC=0.0383$LC=0.00795$MC=0.00194$NC+=0.00071
247CM  L 318           9/2+
247CM  A 5766      2  3.6    2
247CM  G 52.45     5 0.048   5 (M1+E2)   0.25    6        71  11
```

HSICC Program (2)

```
247CM  L 346          (9/2+)
247CM  A 5738      2 0.8     1
247CM  G 60.5      1 0.010   3 (M1+E2)   0.45    12       62  14
247CMS G LC=45 10$MC=12 3$NC+=4.6 11
247CM  G 284.2     1 0.12    1 [E1]                   0.0494
247CMS G KC=0.0386$LC=0.00803$MC=0.00196$NC+=0.00072
247CM  G 345.9     1 0.043   4 [E1]                   0.0324
247CMS G KC=0.0256$LC=0.00515$MC=0.00125$NC+=0.00046
247CM  L 405           1/2+              100.6 NS  6
247CM  A 5679.3    1635.4    5
247CM  G 177.52    2  17.3   9  E2                     1.61
247CMS G KC=0.168$LC=1.04$MC=0.291$NC+=0.113
247CM  L 434          (3/2+)
247CM  A 5651      2   3.3   2
247CM  G 28        5            [M1+E2]                4.E3  58.2       3
247CMS G L/T=0.73 23$M/T=0.20 21
247CM  L 450       2 (5/2+)
247CM  A 5635      2   4.9   2
247CM  G 16        5            [M1+E2]               1.9E4 194.9       2
247CMS G M/T=0.75 19
247CM  G 44                                                                S
247CM  L 517          (7/2+)
247CM  A 5569      2   1.9   LE
247CM cA E         from E|a(404.9 level)=5679.3 {I16} and the energy difference
247CM2cA between 516.7 and 404.9 levels (recoil energy is taken into account).
247CM3cA E|a=5568 {I2}, measured by 2003Ah07, is assumed by the evaluator to be
247CM4cA a doublet, feeding the 516.7- and 518.58-keV levels.
247CM cA IA        1.9 {I1} was measured by 2003Ah07 for the doublet.
247CM  G 289.3     1 0.070   7 [M1+E2]                 1.0   8
247CMS G KC=0.7 7$LC=0.21 7$MC=0.052 15$NC+=0.020 6
247CM  L 519          (3/2+)
247CM  A 5567      2   1.9   LE
247CM cA E         from E|a(404.9 level)=5679.3 {I16} and the energy difference
247CM2cA between 518.6 and 404.9 levels (recoil energy is taken into account).
247CM  G 113.7     1 0.024   5 [M1+E2]                  8    3
247CMS G LC=5.7 19$MC=1.5 6$NC+=0.60 25
247CM  G 291.20    8 0.30    3 [M1+E2]                 1.0   7
247CMS G KC=0.7 7$LC=0.20 7$MC=0.051 15$NC+=0.020 6
247CM  L 582          (5/2+)
247CM  A 5505      2  0.27   5
247CM  G 63        5            [M1+E2]               1.0E2  70.21      5
247CMS G L/T=0.72 19$M/T=0.20 16$N/T=0.08 7
```



Report from GTOL

LEVEL	RI (OUT)	RI (IN)	RI (NET)	TI (OUT)	TI (IN)	TI (NET)	NET FEEDING (CALC)	(INPUT)
0.0	0.000	8.9 4	-8.9 4	0.000	97 5	-97 5	3 5	2.6 1
	Upper limit (90% C.L.) estimates:							
	Method 1: 9.80							
	Method 2: 9.10							
61.67 4	0.40 3	0.430 19	-0.03 4	16.1 16	5.8 5	10.2 17	10.2 17 12.5	3
134.66 6	0.054 6	0.040 5	0.014 8	1.7 4	1.1 7	0.6 8	0.6 8 0.60	6
	Upper limit (90% C.L.) estimates:							
	Method 1: 1.63							
	Method 2: 1.54							
219.02 7	0.060 7	0.000	0.060 7	1.2 7	0.000	1.2 7	1.2 7	
	Upper limit (90% C.L.) estimates:							
	Method 1: 2.05							
	Method 2: 2.03							
227.379 19	6.9 3	17.7 9	-10.8 10	83 5	55 4	28 6	28 6 27.6	5
265.86 4	0.47 3	0.072 6	0.40 4	7.3 19	3.5 7	3.8 20	3.8 20 4.0	2
	Upper limit (90% C.L.) estimates:							
	Method 1: 6.40							
	Method 2: 6.38							
285.41 5	1.15 9	0.010 3	1.14 9	3.1 5	0.63 24	2.5 6	2.5 6 2.5	2
318.31 5	0.228 13	0.000	0.228 13	3.6 7	0.000	3.6 7	3.6 7 3.6	2
345.89 6	0.173 12	0.000	0.173 12	0.80 24	0.000	0.80 24	0.80 24 0.8	1
404.90 3	17.3 9	0.024 5	17.3 9	45.2 25	8.4 4	37 3	37 3 35.4	5
433 4	0.000	0.000	0.000	8.2 3	4.90 20	3.3 4	3.3 4 3.3	2
448.9 10	0.000	0.000	0.000	4.90 20	0.000	4.90 20	4.90 20 4.9	2
516.68 11	0.070 7	0.000	0.070 7	0.14 6	0.000	0.14 6	0.14 6 1.9	LE
518.59 7	0.32 3	0.000	0.32 3	0.82 24	0.21 5	0.61 24	0.61 24 1.9	LE
581.67 8	0.037 4	0.000	0.037 4	0.27 6	0.000	0.27 6	0.27 6 0.27	5

GTOL Program (1)

```
247CM    251CF A DECAY                  2003AH07
251CF  P 0.0           1/2+             898 Y     44              6175.8    10
247CM  N 1.0          1.0       1.0
247CM  L 0.0           9/2-             1.56E+7 Y 5
247CM  A 6078       2  2.6    1 5080
247CM  L      61.67 4 11/2-
247CM  A 6017       2 12.5    3 512
247CM  G 61.67      5  0.40   3 M1+E2     0.24    3       39.2 22
247CMS G LC=29.0 16$MC=7.4 5$NC+=2.82 18
247CM  L     134.66 6 13/2-
247CM  A 5946       2  0.60   6 4460
247CM  G 73.00      8 0.040   5 M1+E2     0.69     14      40   6
247CMS G LC=29 5$MC=7.8 13$NC+=3.0 5
247CM  G 134.65     8  0.014  3   [E2]                     5.06
247CMS G KC=0.156$LC=3.52$MC=0.99$NC+=0.389
247CM  L     219.02 7  15/2-
247CM  G 84.35      8 0.040   5 [M1+E2]                    27  16
247CMS G LC=20 11$MC=5 4$NC+=2.1 13
247CM  G 157.35     8 0.020   4 [E2]                     2.62
247CMS G KC=0.178$LC=1.76$MC=0.495$NC+=0.193
247CM  L    227.37919 5/2+             26.3 US   3
247CM  A 5854       2 27.6    5 31.3
247CM  G 165.70     5 0.12    1  E3                      31.2
247CMS G KC=0.243$LC=21.7$MC=6.60$NC+=2.65
247CM  G 227.38     2  6.8    3  M2+E3    0.58    5      10.6  2
247CMS G KC=6.0 3$LC=3.35 4$MC=0.93 2$NC+=0.364 6
247CM  L     265.86 4(7/2+)
247CM  A 5817       2  4.0    2 134
247CM  G 38.48      5 0.038   6 (M1+E2)   0.19    5     1.8E2  4
247CMS G LC=135 25$MC=35 7
247CM  G 265.86     8  0.43   3 [E1]                    0.0571
247CMS G KC=0.0446$LC=0.0094$MC=0.00229$NC+=0.00084
247CM  L     285.41 5(7/2+)
247CM  A 5798       2  2.5    2 168
247CM  G 58.03      5 0.024   5 (M1+E2)   0.50    8       80  12
247CMS G LC=58 8$MC=15.6 23$NC+=6.0 9
247CM  G 285.41     8  1.13   9   [E1]                   0.0489
247CMS G KC=0.0383$LC=0.00795$MC=0.00194$NC+=0.00071
247CM  L     318.31 5 9/2+
247CM  A 5766       2  3.6    2 77
247CM  G 52.45      5 0.048   5 (M1+E2)   0.25    6       71  11
```

GTOL Program (2)

```
247CM  L     345.89 6(9/2+)
247CM  A 5738       2 0.8     1 244
247CM  G 60.5       1 0.010   3 (M1+E2)   0.45    12      62  14
247CMS G LC=45 10$MC=12 3$NC+=4.6 11
247CM  G 284.2      1 0.12    1 [E1]                    0.0494
247CMS G KC=0.0386$LC=0.00803$MC=0.00196$NC+=0.00072
247CM  G 345.9      1 0.043   4 [E1]                    0.0324
247CMS G KC=0.0256$LC=0.00515$MC=0.00125$NC+=0.00046
247CM  L     404.90 3 1/2+             100.6 NS  6
247CM  A 5679.3     1635.4    5 2.6
247CM  G 177.52     2  17.3   9  E2                     1.61
247CMS G KC=0.168$LC=1.04$MC=0.291$NC+=0.113
247CM  L        433 4(3/2+)
247CM  A 5651       2   3.3   2 19.2
247CM  G 28         5           [M1+E2]                 4.E3  58.2       3
247CMS G L/T=0.73 23$M/T=0.20 21
247CM  L      448.910(5/2+)
247CM  A 5635       2   4.9   2 10.5
247CM  G 16         5           [M1+E2]                1.9E4 194.9       2
247CMS G M/T=0.75 19
247CM  G 44                                                                    S
247CM  L     516.6811 (7/2+)
247CM  A 5569       2   1.9   LE11      GE
247CM cA E          from E|a(404.9 level)=5679.3 {I16} and the energy difference
247CM2cA between 516.7 and 404.9 levels (recoil energy is taken into account).
247CM3cA E|a=5568 {I2}, measured by 2003Ah07, is assumed by the evaluator to be
247CM4cA a doublet, feeding the 516.7- and 518.58-keV levels.
247CM cA IA         1.9 {I1} was measured by 2003Ah07 for the doublet.
247CM  G 289.3      1 0.070   7 [M1+E2]                 1.0   8
247CMS G KC=0.7 7$LC=0.21 7$MC=0.052 15$NC+=0.020 6
247CM  L     518.59 7 (3/2+)
247CM  A 5567       2   1.9   LE11      GE
247CM cA E          from E|a(404.9 level)=5679.3 {I16} and the energy difference
247CM2cA between 518.6 and 404.9 levels (recoil energy is taken into account).
247CM  G 113.7      1 0.024   5 [M1+E2]                  8    3
247CMS G LC=5.7 19$MC=1.5 6$NC+=0.60 25
247CM  G 291.20     8 0.30    3 [M1+E2]                 1.0   7
247CMS G KC=0.7 7$LC=0.20 7$MC=0.051 15$NC+=0.020 6
247CM  L     581.67 8(5/2+)
247CM  A 5505       2  0.27   5 32
247CM  G 63         5           [M1+E2]                1.0E2  70.21      5
247CMS G L/T=0.72 19$M/T=0.20 16$N/T=0.08 7
```

AlphaD Program (Alpha Hindrance factors)

98 251. DATE RUN 23-FEB- 5

Q ALPHA	E TOTAL	ALPHA HALF LIFE	RADIUS	RZERO	TOTAL HALF LIFE	ALPHA BRANCH
6.1758	6.2154	3.280E+05 D	9.3638E-13	1.4924	8.980E+02 Y	1.000E+00

ENERGY LEVEL	ABUNDANCE	CALC. HALF LIFE	HINDRANCE FACTOR
0.00	2.60E-02	2.48E+03	5.08E+03
61.67	1.25E-01	5.13E+03	5.12E+02
134.66	6.00E-03	1.23E+04	4.46E+03
227.38	2.76E-01	3.80E+04	3.13E+01
265.86	4.00E-02	6.13E+04	1.34E+02
285.41	2.50E-02	7.83E+04	1.68E+02
318.31	3.60E-02	1.18E+05	7.69E+01
345.89	8.00E-03	1.68E+05	2.44E+02
404.90	3.54E-01	3.59E+05	2.58E+00
433.00	3.30E-02	5.17E+05	1.92E+01
448.90	4.90E-02	6.36E+05	1.05E+01
516.68	1.90E-02	1.56E+06	1.11E+01
518.59	1.90E-02	1.60E+06	1.08E+01
581.67	2.70E-03	3.74E+06	3.25E+01

ENSDF – Evaluations: Methodology and Worked Examples

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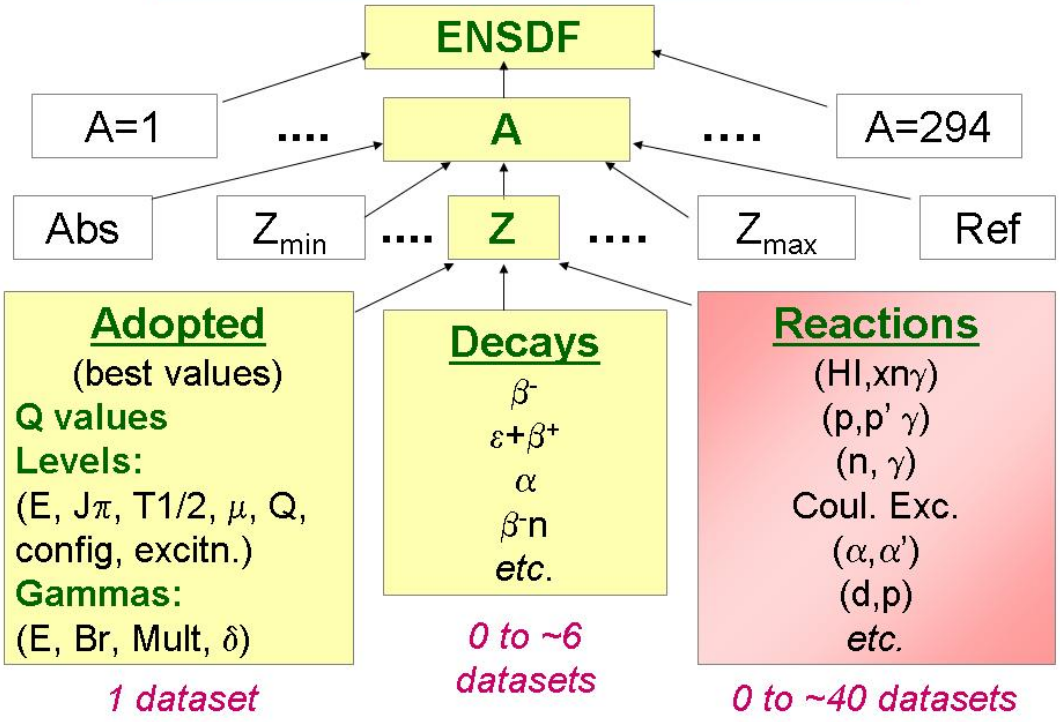
ENSDF – Reaction Data

Coral Baglin

Workshop on *Nuclear Structure and Decay Data: Theory and Evaluation*
ICTP, Trieste, 28 April – 9 May 2008

LAWRENCE BERKELEY NATIONAL LABORATORY

ENSDF Database Structure



Summary

Principal Categories of Reactions.

• *Reactions in which gammas are not detected:*

- Stripping and pickup reactions
- Multi-particle transfer reactions
- Charge-exchange reactions
- Inelastic scattering
- Coulomb excitation (particles detected)
- Resonance reactions …

• *Reactions in which gammas are detected:*

- Summary of information available from γ-ray measurements
- Inelastic scattering
- Nuclear resonance fluorescence
- (light ion,xnypγ)
- (heavy ion,xnypγ)
- Particle capture
- Coulomb excitation (γs detected)

Gammas not detected

Measured Quantities of Interest:

- E(level) from particle energy spectrum or excitation function
- L – angular momentum transfer
- S, C^2S - spectroscopic factors
- β_2, β_4 - deformation parameters (if model independent)
- Γ, Γ_i – total or partial widths for level
- B(Eλ), B(M λ) – transition probabilities
- J^π, T – spin, parity, isospin

Stripping and Pickup

Examples:

Stripping: (d,p), (α,^{3}He), (pol d,p), (^{3}He,d), *etc.*

Pickup: (p,d), (^{3}He,α), (t,α), *etc.*

Quantities to Record:

• **E(level),** deduced by authors from charged particle spectrum.

• **L** and **S** or **C^{2}S** from authors' DWBA analysis:

$(d\sigma/d\omega(\theta))_{exp} = (d\sigma/d\omega(\theta))_{DWBA} \times N \times C^2S'$

where $S' = S$ (pickup) or

$S' = S \times (2J_f+1)/(2J_i+1)$ (stripping)

(**$d\sigma/d\omega$** for one angle should be given in suitably relabelled S field when spectroscopic-factor information is not provided by authors)

• **J** from L±1/2 for polarised beam if vector analysing power shows clear preference between L+1/2 and L-1/2

Relevant Documentation:

Target J^π (unless 0^+)

Spectrum resolution (FWHM, keV)

Normalisation factor for DWBA analysis

Range of angles measured, laboratory or c. m . (but specify)

Stripping and Pickup, ctd.

Deformed Nuclides; α and lighter beams:

$(d\sigma/d\omega(\theta))_{exp} / [(d\sigma/d\omega(\theta))_{DWBA} \times 2N] = c^2(jl)\, V^2$,

where c is amplitude of Nilsson state wavefunction for transferred nucleon, V is fullness factor describing partial filling of target nucleus orbitals

• Pattern of cross sections among rotational-band members may provide a characteristic **fingerprint** for a specific Nilsson configuration**,** enabling a set of levels to be assigned as specific J members of a band with that configuration if:

(i) experimental fingerprint agrees well with that predicted by Nilsson-model wave functions, and

(ii) fingerprint differs distinctly from those for other plausible configurations.

Example: $(d\sigma/d\omega(60°))$ calculated (1997Bu03) for ^{226}Ra(t,α)^{225}Fr:

Orbital:	1/2[400]	1/2[530]	**1/2[541]**	3/2[402]	3/2[651]	**3/2[532]**	Expt.	Mixed
J=3/2	23	14	1.5	103	0.0	0.7	~1.5	0.9
J=5/2	7.6	0.2	13	4.6	0.03	6.2	14	10
J=7/2	0.4	39	2.0	1.2	0.0	3.3	20	4.1
J=9/2	0.05	0.4	33	0.05	2.0	26	~45	49

Reality (not so simple!): 3/2[532] Coriolis mixed with 1/2[541] fits σ, energy

Multi-particle Transfer

Examples:

(p,t), (α,d), (t,p), (α,p), (^{6}Li,d) …

Quantities to Record:

• E(level)

• L – if angular distribution can be fitted by a unique value

Deduced Quantities:

J^π- from J(target)+L (vector sum) and $\pi_i\pi_f=(-1)^{Jf}$, for strong groups only in two-neutron, two-proton or α–particle transfer

(*i.e.*, pairs of identical particles can be assumed to be transferred in relative s state for **strong** groups)

Charge-Exchange Reactions

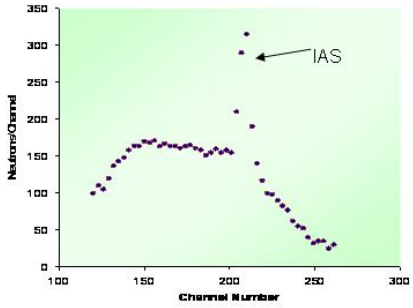
Examples:

(p,n), (^{3}He,t)

Quantities of interest:

• E(level)

• Isobaric analog state information



Inelastic Scattering

Examples:

(e,e'), (p,p'), (d,d'), (α,α') (at projectile energies **above** the Coulomb barrier)

Quantities to Record:

• E(level)

• L – if angular distribution is fitted by unique L value

• β2, β4 … - deformation parameters (if model independent); specify whether 'charge' or 'nuclear', if relevant (typically from (α,α') or (e,e'))

• B(Eλ), B(M λ) – transition probabilities (typically from (e,e'))

Coulomb Excitation
(particles detected)

Examples:
(p,p'), (d,d'), (α,α') with projectile energy **below** Coulomb barrier.

Quantities to Record:

• E(level)

• J^{π}:

  • determined if the excitation probability agrees with that calculated by Alder (1960Al23).

  • low energy Coulomb excitation is predominantly E2

• B(Eλ) – for excitation (*i.e.*, B(Eλ)↑)

Resonance Reactions

Examples:

(p,p), (p,X), (γ,n) … (excitation function data, σ(E), dσ/dω(θ,E))

Quantities of interest:

• E(level) – calculate from SP+E(p)(c.m.) or give as 'SP+976.3', *etc.*, where 976.3 is E(p)(lab) for resonance; do not use both notations within the same dataset

• Ep at resonance - can be given in relabeled 'S' or 'L' field.

• Partial widths – can be given in comments or relabeled 'S' field.

• Is this an isobaric analog state? (if so, specify state of which it is the analog)

• Is this a giant resonance? (if so, which one?)

• Any J^{π} information that can be deduced

Note:

ENSDF is primarily concerned with bound levels, but includes all isobaric analog states, giant resonances, and unbound levels which overlap or give information on bound levels

Reactions with Gammas Detected

Measured Quantities of Interest:

• E_γ - photon energy
• Iγ - relative intensity (or photon branching)
• α, α_K, … - electron conversion coefficients, usually from I(ce)/Iγ; and sometimes from intensity balance (gives α_{exp})
• K/L, L1/ L3 … - ce subshell ratios
• A_2, A_4 … - Legendre polynomial coefficients characterizing angular distribution (γ(θ)) or angular correlation (γγ(θ))
• DCO ratio – directional correlation of gammas from oriented nuclei
• Asymmetry ratio - *e.g.*, $I\gamma(\theta_1)/I\gamma(\theta_2)$
• Linear polarization
• Level $T_{1/2}$ – from γ(t), DSAM, RDM, centroid-shift, delayed coincidence, *etc.*, if measured in that reaction (state method used)
• g-factor – include if measured in that reaction

Reactions with Gammas Detected – ctd.

Deduced Quantities of Interest:

• E(level) – from least-squares adjustment of Eγ (GTOL), avoiding Eγ for lines that have uncertain or multiple placements whenever possible but serious misfits

• Band structure – indicate via band flags for levels. (easier if a given band has the same band-flag character in each dataset in the nuclide!)

• Band configurations – justify when possible; band parameters may be informative, especially for K=1/2 bands

• J^{π} - may be desirable to indicate authors' values in the reaction dataset and add parentheses in *Adopted Levels* if insufficient (or no!) supporting arguments are available (but major discrepancies exist)

•Transition quadrupole moment (if authors give it; include on level comment record or in band description)

• M - transition multipolarity

• δ – mixing ratio (√((L+1)-pole/(L-pole)), Krane-Steffen sign convention

Gamma-ray Energies

• Give measured energy and uncertainty (*i.e.*, do not correct for recoil energy loss)

• State source of data (unless obvious, *e.g.*, if only one keynumber)

• Uncertainties: if authors give uncertainty as:

(i) "0.3 keV for strong lines, 1 keV for weak or poorly resolved lines"; assign 0.3 to those which could be reasonably considered 'strong' and 1 to all others, but give authors' statement in general comment on Eγ and define Iγ that you consider 'strong' (or assign 1 keV to all)

(ii) "do not exceed 0.5 keV"; 0.5 could be assigned for all lines

(iii) If no uncertainty is stated, point this out in a general comment [for the purpose of deducing E(level) using GTOL, a default of 1 keV (adjustable by user via control record at head of dataset) will be used and this should be noted in a comment on level energy]

• If measured Eγ not available but G record is needed in order to give other information, deduce from level energy difference and remove recoil energy loss; give no ΔEγ and state where Eγ came from

Gamma-ray Intensities

• Give relative intensities, if available (do not renormalise so strongest is 100)

• Do not mix data from different reactions, or data from same reaction at different energies, when entering RI on G records (use different datasets instead, or include in comments or tabulation)

• If branching ratios are measured independently (*e.g.*, from $\gamma\gamma$ coincidences), also quote these (*e.g.*, in a comment); one set of data may be more precise than the other

• Give uncertainties whenever authors state them; if authors give both statistical and systematic uncertainties, show statistical on G record but state systematic in comment (so that uncertainty in $I\gamma$ ratios is not distorted)

• If both prompt and delayed $I\gamma$ are given, adopt separate datasets, or give one set under comments

• For multiply-placed lines, specify whether quoted $I\gamma$ has been suitably divided between placements (& (undivided) or @ (divided) in column 77)

Conversion Coefficients

• Give measured α_K, α_L, *etc.*, and subshell ratios (in comments or on continuation of G record); state how photon and ce intensity scales were normalised

• Quote experimental coefficients (usually α) obtained using intensity balance arguments (these are frequently buried in the text of a paper); specify as "from intensity balance at xxxx level", where relevant

• Include α(theory) on G record (from BrIcc) when needed for calculation or argument (or α(theory)+α(pair) if $E\gamma > 1022$ keV)

γ Linear Polarisation

γ linear polarisation data may be available from Compton polarimeter measurements of relative $I\gamma$ in planes perpendicular and parallel to reaction plane
Such data may distinguish between electric and magnetic radiations

Angular Distributions

I_γ as a function of angle θ with respect to beam direction:

$$W(\theta) = 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta) + \ldots$$

- Include A_2, A_4 … ; these data are very important to evaluators and readers alike, as they provide information vital to transition multipolarity assignments
- Remember that these are signed quantities
- A_2, A_4 … depend on ΔJ, mixing ratio and degree of alignment σ/J, where σ is half-width of Gaussian describing the magnetic substate population
- σ/J is usually determined from measurements of $W(\theta)$ for known $\Delta J=2$ transitions-however, many authors assume $\sigma/J=0.3$ for practical purposes
- σ/J affects only the magnitudes of A_2, A_4
- $W(\theta)$ is largely independent of J for high spin states
- Alignment is reduced if level lifetime is not small
- **$W(\theta)$ can determine ΔJ, but <u>not</u> $\Delta\pi$**

Angular Distributions – ctd.

Typical values of A_2, A_4 for θ relative to beam direction if $\sigma/J = 0.3$
(from B. Singh, McMaster University)

ΔJ	Multipolarity	Sign of A_2	Sign of A_4	Typical A_2	Typical A_4
2	Q	+	-	+0.3	-0.1
1	D	-		-0.2	0.0
1	Q	-	+	-0.1	+0.2
1	D+Q	+ or -	+	+0.5 to -0.8	0.0 to +0.2
0	D	+		+0.35	0.0
0	Q	-	-	-0.25	-0.25
0	D+Q	+ or -	-	+0.35 to - 0.25	0.0 to -0.25

DCO Ratios

Directional **C**orrelations of γ rays from **O**riented states of nuclei

• If γ_K (known multipolarity) and γ_U (unknown multipolarity) are measured in coincidence using detectors at angles θ_1 and θ_2 to the beam:

DCO = I(γ_U(at θ_1) gated by γ_K(at θ_2))/I(γ_U(at θ_2) gated by γ_K(at θ_1))

• Sensitive to ΔJ, multipolarity and mixing ratio; **independent of $\Delta\pi$**

• Gating transitions are frequently stretched Q, but stretched D may also be used - so specify which was used

• Authors frequently indicate expected DCO values for stretched Q and stretched D transitions for the geometry used - helpful to state these values

• Remember that identical values are expected for stretched Q and for D, $\Delta J = 0$ transitions (although the latter are less common)

DCO Ratios – ctd.

Typical DCO values for $\theta_1 = 37°$, $\theta_2 = 79°$, $\sigma/J = 0.3$ (B. Singh, McMaster University.)

ΔJ_γ ^{gate}, Mult	ΔJ_γ	Mult	Typical DCO
2, Q	2	Q	1.0
2, Q	1	D	0.56
2, Q	1	D+Q	0.2 to 1.3
2, Q	0	D	1.0
2, Q	0	D+Q	0.6 to 1.0
1, D	2	Q	1/0.56
1, D	1	D	1.0
1, D	0	D	1/0.56

Multipolarity

• L and $\Delta\pi$ may be determined from measured subshell ratios or conversion coefficients

• L alone can be determined by angular distributions or DCO ratios or γ asymmetry ratios

• $\Delta\pi$ may be determined by γ linear polarisation measurements

• When transition strengths are calculable ($T_{1/2}$ and branching known), **R**ecommended **U**pper **L**imits (RUL) can be used to rule out some multipolarities (*e.g.*, stretched Q transition for which $B(M2)_W$ exceeds 1 can be assigned as E2). Similarly, for a D+Q transition with large mixing, RUL may enable the rejection of E1+M2

• Assign Multi when measured information indicates a clear preference for that assignment; otherwise, let $\gamma(\theta)$ or DCO data speak for themselves (exception: if no measurement exists but multi. is needed for some reason, use the [M1+E2], *etc.*, type of entry)

• Mult determined for a doublet will be not reliable - can be given in comment (with disclaimer), but not on G record

Mixing Ratios

• Include on G record whenever available.

• Calculate from conversion electron data or $\gamma\gamma(\theta)$ using the DELTA program, or from subshell ratios

• Rely on authors' deductions from $\gamma(\theta)$, DCO or nuclear orientation data

• (HI,xnγ) studies: model-dependent values of δ are sometimes deduced from in-band cascade to crossover transition intensity ratios; these could be given in comments (stating relevant K) if considered really important, but should not be entered on G record

• Check that correct sign convention was used by authors - convert to Krane-Steffen if not, and take special care if uncertainties are asymmetric (-2.3 +4-2 becomes +2.3 +2-4 upon sign reversal)

Inelastic Scattering

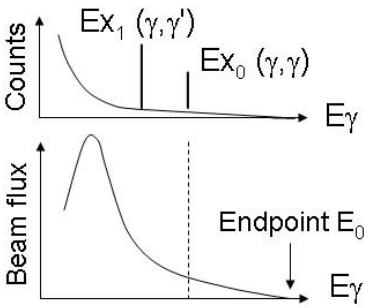
(p,p'γ), (n,n'γ), *etc.*; beam energies > Coulomb barrier

Separate these datasets from those for (p,p'), (n,n') … and from that for Coulomb excitation

Information of interest: typically Eγ, Iγ, $\gamma(\theta)$; maybe γ linear polarisation

Nuclear Resonance Fluorescence

(γ,γ) and (γ,γ') measurements with Bremsstrahlung spectrum; low momentum transfer excite low-spin states (mainly E1 and M1, but also some E2 excitation)



- γ spectrum measured; areas of γ peaks at Ex_0 and Ex_1, combined with knowledge of $N\gamma(Ex_0)$, yields scattering cross sections from which width and branching information may be obtained
- γ asymmetry differentiates D and Q excitation
- γ linear polarization differentiates M and E

Nuclear Resonance Fluorescence – ctd.

Integrated scattering cross section I_s (eV b) is often given:

$$I_s = ((2J+1)/(2J_0+1))\ (\Gamma\gamma_0\Gamma\gamma_f/\Gamma\gamma)\ (\pi\hbar c/E\gamma)^2\ W(\theta)/4\pi$$

where J is g.s. spin, J_0 is spin of excited level, $\Gamma\gamma \cong \Gamma$ is total width and $\Gamma\gamma_0$, $\Gamma\gamma_f$ decay widths for γ decay to the g.s. and the final state f (for elastic scattering, $\Gamma\gamma_0=\Gamma\gamma_f$); $W(\theta)$ represents the normalised angular distribution - data are often taken at 127° where W = 1 for D transitions

- Give $\Gamma\gamma_0^2/\Gamma$ values (extract if necessary) on L record (col. 65 (value), 75 (uncertainty)); relabel field.
- If $\Gamma\gamma_f/\Gamma\gamma_0$ is measured, include relative branching on G records

Γ can be calculated from:

$$(\Gamma\gamma_0^2/\Gamma)\ /\ (\Gamma\gamma_0/\Gamma)^2$$

using known branching, or under the assumption $\Gamma = \Gamma\gamma_0 + \Gamma\gamma_f$ (which needs to be stated)

- Then: $T_{1/2}$ (ps)= 0.456 /Γ (meV); include on L record

Propagate uncertainties with care!

(Light Ion,xnypγ)

(p,xnγ), (^{3}He, xnγ), (α,pγ), *etc.*

• Separate from (HI,xnγ) studies, whenever practical

• Separate from datasets in which gammas are not measured (*e.g.*, do not combine (d,pγ) and (d,p))

(Heavy Ion,xnypγ)

• Relative intensities will differ for different reactions and also for a given reaction measured at different beam energies; best to use separate datasets for each study that provides significant Iγ or branching data

• (HI,xnγ) reactions tend to populate yrast levels (lowest energy for given J) or near-yrast levels; populated states tend to have spins that increase as the excitation energy increases

• Use band flags to delineate deduced band structure - if authors give configuration for band, include in band description

(Heavy Ion,xnypγ) – ctd.

• Inconsistencies in γ order, postulated J^π, configuration, *etc.*, compared with other studies and especially with those in *Adopted Levels, Gammas*

• Beware of multipolarity and J^π assignments for which no supporting measurements exist - sometimes, unmeasured values inserted in order to generate a RADWARE band drawing live on in the published table of data; they do not qualify as 'measured data'!

• Multipolarities determined as D, Q, D+Q, *etc*, by γ(θ) or DCO are best left this way in the reaction dataset unless definite arguments exist (*e.g.*, from RUL) to establish Δπ; otherwise 'D' (strong J^π argument) and '(D)' (weak J^π argument) become indistinguishable when written as, for example, (M1)

• Watch for and report statements of coincidence resolving time (or equivalent) since they might place a limit on level lifetime, thereby enabling RUL to be used to reject Δπ = yes for a transition multipolarity

• K = 1/2 rotational bands: the decoupling parameter may give a clear indication of the Nilsson orbital involved in the band configuration

(Heavy Ion,xnypγ) – ctd.

• Deformed nucleus: if a cascade including $\Delta J = 2$ and/or $\Delta J = 1$ transitions is observed at high spin with regular energy progression, they can be assigned to a band with definite J^{π} assignments if at least one level J^{π} and one in-band transition with multipolarity E2 or M1(+E2) can be assigned independently

• Near-spherical nuclei: if a cascade of $\Delta J=1$ transitions is observed at high spin with regular energy progression, those transitions may be assigned as (M1) transitions within a common band. Exception: rare cases - nuclei can have alternating parity bands (reflection asymmetry), for which $\Delta J = 1$, $\Delta\pi$ = yes cascades occur.

• However, octupole-deformed nuclei may exhibit an apparent band structure which is really two $\Delta J = 2$ rotational sequences of opposite parity, connected by cascading E1 transitions

Special Case:

Superdeformed band data are updated continuously in ENSDF by Balraj Singh (McMaster University). One should check ENSDF at the end of a mass chain evaluation to be sure no SD-band data were added since the chain was downloaded for revision

Capture Reactions

(p,γ), (n,γ) E = thermal, (n,γ) E = res, *etc.*

• Use separate datasets for thermal and resonance n-capture data

• Primary and secondary transitions usually appear in the same dataset even if their intensities require different normalisations.

• The J^{π} of the thermal neutron capture state(s) is J^{π}(target)±1/2 (*i.e.*, s-wave capture is assumed)

• Thermal neutron capture: the multipolarity of a primary γ is E1, M1, M1+E2 or E2

• Resonance n capture: ENSDF does not include the resonances and their properties; adequate to list the bound states fed, their interconnecting gammas and any conclusions concerning level J^{π}

• Average resonance n capture: inclusion of primary gammas and their reduced intensities (which carry information on final state J^{π}) is optional; a list of final level E and deduced J^{π} would suffice

Coulomb Excitation

• If authors determine matrix element values, give them in comments and calculate B(Eλ) using

$$B(E\lambda) = |\langle M(E\lambda)\rangle|^2 / (2J_0+1)$$ where J_0 is g.s. spin

• If authors give B(Eλ)↓, convert to B(Eλ)↑ and include with level information $(B(E\lambda; i\rightarrow f)) = B(E\lambda: f\rightarrow i) \times (2J_f+1)/(2J_i+1))$

• Strongly-deformed region: a cascade of E2 transitions with enhanced transition probabilities $(B(E2)_W > 10)$ provides definitive evidence for a rotational band and for the sequence of J^π values, provided the J^π of one level is known independently

• Calculate level $T_{1/2}$ from B(Eλ) and adopted γ-ray properties when possible

• Occasionally, mixing ratio or nuclear moment information can be extracted from matrix elements

•Clearly indicate the direction for any given B(Eλ) values

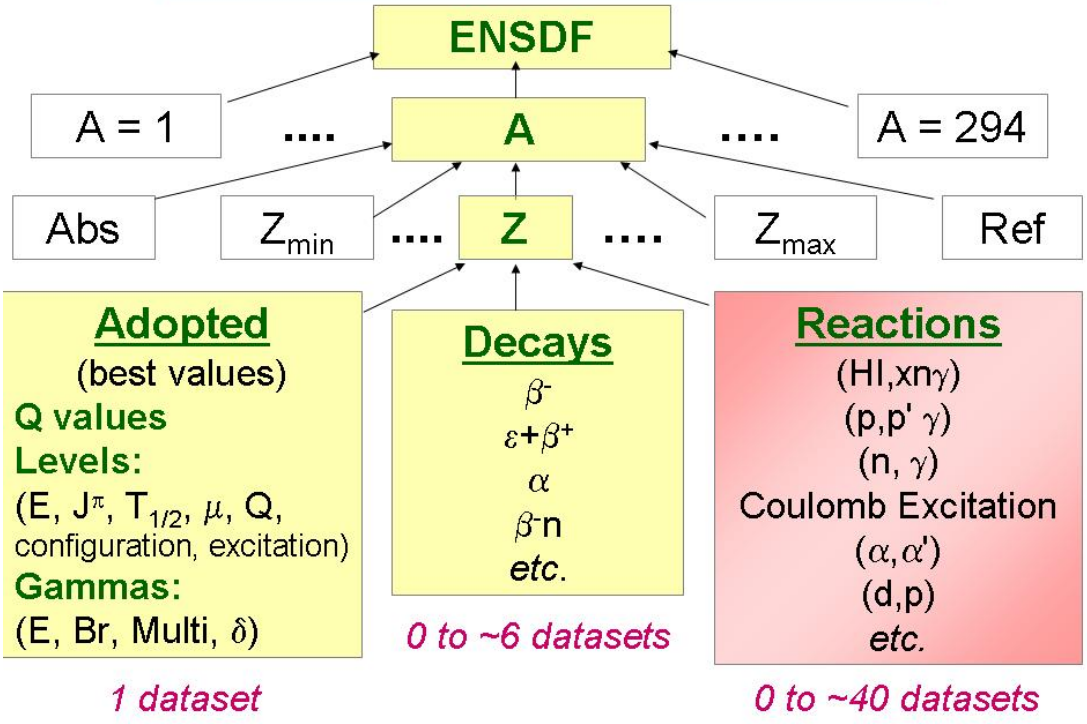
ENSDF – Adopted Levels and Gammas

Coral Baglin

Workshop on *Nuclear Structure and Decay Data: Theory and Evaluation*
ICTP, Trieste, 28 April – 9 May 2008

LAWRENCE BERKELEY NATIONAL LABORATORY

ENSDF Database Structure



Adopted Levels, Gammas

This dataset is the heart of any nuclide evaluation !

- Condensation of all the information in all the other datasets and provides the **best values** known at the time of the evaluation
- Provides information that goes into the summary database NUDAT
- May be the **only** dataset that some readers will ever look at
- The source of all data appearing here must be made transparent to the reader and easily traceable

General Information

Q values:

- Usually rounded values from latest mass table (presently 2003Au03)
- Add new S(p), Q(α), *etc.*, (with keynumber) if available; compare with 2003Au03 value
- Optional: Comment on uncertainties in 'SY' values; note newly-measured masses if significantly different from Audi's prediction

General Comments:

e.g., Production/Identification, keynumber lists for major shell model calculations or isotope shift/hfs references (all optional)

Other Reactions:

Give reaction and keynumber if wanted for completeness, even though no data have been used and no reaction dataset has been created, *e.g.*, continuum gamma study (optional)

Define XREF Symbols:

Every DSID in nuclide must be listed here, even if not associated with any specific level

Example 1 →

```
167IR     ADOPTED LEVELS
167IR  C  Production: 92MO(78KR,p2n) E=357, 384 MEV (1997DA07).
167IR  C  Identification: 1981HO10 unambiguously assign a new |a group to 167IR
167IR2C  by relating it to known transitions through a multi-dimensional
167IR3C  analysis correlating parent energies, daughter energies, and the
167IR4C  timing of events. The production reactions involved 58NI on
167IR5C  molybdenum-tin targets and 107AG on vanadium-nickel targets
167IR  C  For calculation of proton decay widths for 167IR GS and isomer see
167IR2C  2000DA11.
167IR   Q          11760   SY-1070   6 6507    5    1995AU04,1997DA07
167IR  CQ         |DS(n)=300 (1995AU04).
167IR  CQ QA$from measured EA=6351 5 (1997DA07) for GS to GS transition; 1995AU04
167IR2CQ give QA=6495 50, reflecting lack of information concerning daughter
167IR3CQ state at that time.
167IR  CQ SP       From measured EP=1064 6 (1997DA07) for GS to GS transition;
167IR2CQ SP=-1110 10 in 1995AU04.
167IR    XA171AU A DECAY (1.02 MS)
167IR    XB78KR(92MO,2NPG)
167IR    L 0          (1/2+)          35.2 MS   20
167IR2   L %A=48 6 (1997DA07)$%P=32 4 (1997DA07)$%EC+%B+=?
167IRX   L XREF=B
167IR   CL J        comparison of calculated and measured partial lifetimes for
167IR 2CL p decay rule out d{-3/2} and h{-11/2} transitions, so 1997DA07 conclude
167IR 3CL that an L=0 p is emitted to the 0+ GS of 166OS.
167IR   CL %A,%P     From relative intensities of |a and p decay from level,
```

Level and Gamma Properties - General

- Assignments are definite (no parentheses.) if based on 'strong' arguments but indefinite (in parentheses.) if justification includes a 'weak' argument; see Nuclear Data Sheets (NDS) introductory material for specific rules
- Every nuclide must have at least 1 level
- Document sources of all data (**dataset name**, not just keynumber)
- Comment on serious discrepancies
- Specify whether 'average' is weighted or unweighted (use larger of internal and external uncertainties for weighted averages)
- Remember to round off so uncertainty <26
- Remember that 'level' and 'gamma' data appear in different tables in NDS; unhelpful to say "Jpi for levels with γ to 8+ isomer are based on …" (in level table) or "multi for γs observed in low spin reactions is from …" (in γ table)
- Do not include:
  - continuation G records that give CC, KC, *etc*;
  - primary γ rays from n capture;
  - neutron capture state(s);
  - coincidence 'C' from col. 78 of G records;
  - unplaced γ rays listed in source datasets

Level Properties

Level Energy:

- Use GTOL to calculate from adopted Eγ (in most cases)
- Include all discrete levels and giant resonances; identify analog resonances
- Adopt minimum number of levels consistent with source datasets.**T1/2 (or Γ):**
- Specify source, *e.g.*, "from B(E2)↑ in Coulomb excitation", *etc.*
- Give bare-atom half-lives in comment (*e.g.*, "$T_{1/2}$(52Fe26+)= …")
- Remember Γ = Γγ + Γp +… for resonance, so note any assumptions made, such as '**Γ = Γγ_0 + Γγ_1**' or '**Γ = Γp**'.

Band Flag: (if relevant)

Give rotational band parameters in comment (if meaningful) from:

$E_K(J) = E_0+A(J(J+1)-K^2)+B(J(J+1)-K^2)^2+(-)^{(J+K)}(J+K)!/(J-K)!(A_{2K}+B_{2K}(J(J+1)-K^2))$

Isospin: very important for low A nuclides!

Level Decay Branches: for g.s. and $T_{1/2} \geq 0.1$ s levels, include all modes that might reasonably be expected, even if not yet observed

```
 92RB   Q 8096       6  5098    10 10750   60 -6460   40     2003AU03
 92RB   L 0.0           0-                 4.492 S    20
 92RB2  L %B-=100 $ %B-N=0.0107 5 (1993RU01)$
 92RBX  L XREF=AB
--------------
192PO   Q                11.0E3 SY 2.2E3   SY 7320     7     1995AU04
192PO  CQ              |DS(n)=360, |DS(p)=450 (1995AU04).
192PO   L 0.0            0+                 33.2 MS    14
192POX  L XREF=AB
192PO2  L %A AP 100$ %EC+%B+=?$
192PO  CL              %A: only A DECAY observed. %(EC+B+) AP 0.4 can be
192PO2CL estimated from gross B decay theory (partial T AP 8 S)
192PO3CL (1973TA30), or AP 0.54 from partial BETA T of 6.1 S
192PO4CL calculated by 1997MO25.
-------------
168RE   Q -5800      SY8960     SY830      SY5063     13     1995AU04
168RE  CQ              |DQ(|b)=400, |DS(n)=420, |DS(p)=510 (1995Au04).
168RE   L  0.0           (5+,6+,7+)         4.4 S      1
168RE2  L %EC+%B+=100$ %A AP 5E-3 (1992Me10)$
168REX  L XREF=AB
168RE  CL              %A: deduced from IA/RI(199.3G in 168W) and EC decay
168RE2CL scheme for 168RE (1992Me10).
```

Example 2: decay branches

XREF Flags:

• Use 'X(*)' if level from dataset X cannot be uniquely identified with level in question

• Use 'X(energy)' to resolve any ambiguity due to poor energy match between adopted level and dataset X level

Example 3: XREF's

```
59NI    L 5821      10
59NIX   L XREF= BN(*5830)
59NI  CL          JPI=3/2+ FROM (POL P,D) AND L(P,D)=2 FOR 5821 AND/OR
59NI2CL 5844 LEVEL(S).
59NI    L 5844      10 (3/2+,5/2+)
59NIX   L XREF=BN(*5830)
59NI  CL  J       L(D,P)=(2). JPI=3/2+ FROM (POL P,D) AND L(P,D)=2 FOR 5821
59NI2CL AND/OR 5844 LEVEL(S).
```

• Watch out for systematic energy scale deviations between various reaction studies

• Avoid associating a transfer reaction level with an adopted level whose configuration would not be excited

Example 4

^{169}Tm(d,p) Target: π 1/2[411] g.s.

n stripped from d

^{170}Tm states populated must be π 1/2[411] $\otimes$ ν Ω[xxx]

Populated:

π 1/2[411] $\pm$ ν 1/2[521]
π 1/2[411] $\pm$ ν 5/2[512]
π 1/2[411] $\pm$ ν 7/2[633]
π 1/2[411] $\pm$ ν 3/2[521]

Not populated:

π 7/2[404] $\pm$ ν 7/2[633]
π 1/2[541] $\pm$ ν 5/2[512]
π 1/2[541] $\pm$ ν 7/2[633]

B(Lλ)↑:

Include with level information **only** when value measured, but photon branching or $T_{1/2}$ unknown (*e.g.*, E3 Coulomb excitation measured, but no E3 transition observed)

Moments (μ, Q): static, model-independent values

- Summarized in 1989Ra17 (evaluation) and 2005St24 (compilation); add any new measurements
- Specify method used
- Mention standards used, corrections applied (*e.g.*, Sternheimer)
- Signs matter
- Convert g-factor data to μ

Δ<r2> (DAVRSQ): include data in comment on g.s. (or isomer), if available

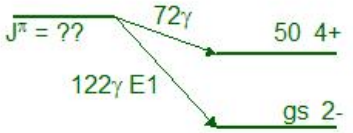
Example 5: μ, Δ<r2>, *etc.*

```
167LU  L     0.0+X  1/2(+)          1 M      GE                    CM
167LUX L XREF=B
167LU2 L %EC+%B+=?$%IT=?
167LU3 L MOMM1=-0.0999 13 (1998GE13)$
167LU CL          DAVRSQ(170LU,167LU)=-0.291 (1998GE13); 10%
167LU2CL systematic uncertainty.
167LU CL          J,MOMM1: from collinear fast beam laser spectroscopy
167LU2CL (1998GE13). PI based on proximity of MOMM1 to value expected for
167LU3CL 1/2[411] orbital (-0.05) cf. that for the only other nearby J=1/2
167LU4CL orbital (viz. 1/2[541], |m AP +0.7).
167LU CL T        estimated by 1998GE13; based on known rare-earth diffusion …
```

Spin and Parity:

- An argument must be provided for every J^{π} that is given
- Use fewest and best strong arguments for definite J^{π}; the more arguments the better if J or π is uncertain. Try to convince reader: enable a quick check on the impact of any new data that may become available later
- Use flagged comments for long, repetitive arguments (*e.g.*, "Jpi based on presence of primary γ from ½+ capture state in (n, γ) E = thermal and log$f^{1u}t$<8.5 from 1/2- in … EC decay")
- If J is directly measured (*e.g.*, atomic beam), state the method
- Note that μ no longer provides a strong J^{π} argument (used to)
- Avoid using multiply-placed γs in "γ to J^{π} =…" type arguments
- Note that "γs to 3/2+ and 5/2-" (2 levels) differs from "γs to 3/2+, 5/2-" (1 level) – avoid ambiguities
- "γ to J^{π}" is a weak argument
- "γ to …" arguments: level J^{π} matters, not E(level)
- Use "log*ft*=…from J^{π}=1/2-" and L(d,p)=2 for 9/2+ target" type arguments; parent/target J^{π} is part of the argument

Sample J^{π} Arguments:



Argument(s)	J^{π}
E2 737γ to 7/2+ g.s.; log*ft* < 5.9 from 1/2+	3/2+
Primary γ from 1/2+ in (n,γ) E = thermal; E1 438γ from 7/2- 832 level	5/2+
From (pol d,p) and L(d,p) = 2 for 0+ target	5/2+
Log$f^{1u}t$ < 8.5, log*ft* = 7.0 from 2-; M1 558γ from 4+ 1038 level	3+
M1+E2 78γ to 1/2- 132 level	3/2-
E1 122γ to 2- g.s.; 72γ to 4+ 50 level	(2,3)+
Probable analog of 3/2- 358 level in ^{AA}ZZ	(3/2-)
Unhindered (HF < 4) α decay from (10-) parent	(10-)
γ to 2- and γ to 4+	(2+,3,4-)

Gamma-Ray Properties

Energy:

If E_γ came from level-energy difference, say so and recalculate after GTOL has been run (without that E_γ included, of course)

Relative Branching:

• Scale I_γ so strongest branch is 100;

Exceptions:

strongest line is multiply placed (also in col. 77) (give as < (I+ΔI))
strongest line is given as a limit
transition is within a superdeformed band

• Omit uncertainty if only one branch

• Give TI for E0 or fully converted transitions (if known)

Multipolarity:

• [mult] means 'deduced solely from level scheme'; use [E2], *etc.*, only if <u>needed</u> to calculate transition probability or CC for a transition with no measured multipolarity

• Convert 'D' or 'Q' to '(E1)', '(E2)', *etc.*, if desired or if needed for calculation or J^{π} argument; specify how $\Delta\pi$ was deduced

• Remember that 'M1,E2' and 'M1+E2' are not equivalent

Mixing Ratio:

• Include sign, if known - absence of sign indicates modulus δ

• If two solutions: give both in comment and none in MR field

• Watch for cases where experiment gives higher limit than RUL allows; modify adopted δ if appropriate

Total Conversion Coefficient (CC):

Give whenever significant

E0 Transitions:

Quote ρ^2(E0) from 2005Ki02 or 1999Wo07 (or from authors of later papers who provide value)

Reduced Transition Probabilities:

• Give whenever calculable

• If δ overlaps 0 or ∞, calculate for pure D or pure Q, respectively

• Calculate for [E1], [E2], [ΔJ > 2]

• Watch out for δ, $T_{1/2}$ or I_γ data given as a limit

← Example 6

Reduced Transition Probability Calculations (Special Cases)

I: Data given as limit:

δ(M1,E2) < 0.3:

$B(E2)_W$: give as upper limit

$B(M1)_W$: give average of $B(M1)_W(\delta = 0)$ and $B(M1)_W(\delta = 0.3)$

TI < i for non-dominant branch:

Assign 1/2i ± 1/2i to this transition to enable calculation of $B(L\lambda)_W$ values for other branches.

$T_{1/2}$ < t:

Give resulting lower limits on $B(L\lambda)_W$ values

$T_{1/2}$ > t:

Typically, forget it !

However, $B(E2)_W$<0.005 or $B(E1)_W$< 2×10^{-10} might be worth mentioning, for example

II: When $T_{1/2}$ was calculated directly from B(Lλ):

Calculate $B(L\lambda)_W\downarrow$ from measured $B(L\lambda)\uparrow$ and single-particle value (available from RULER)

Example 6: B(Lλ)W's

Checking Your File

- Make sure that all data sets satisfy current ENSDF policies/practice
- Run FMTCHK and make the necessary corrections
- Read through file (ENSDAT output may be helpful); amazing what the eye can catch this way!
- Check band drawings – a typographical error in J^{π} or an incorrect band flag may be extremely easy to see there
- Run PANDORA
  - use PANDORA.ERR file to identify physics errors
  - use PANDORA.GLE file to check for:

(i) Inconsistencies in J^{π}, MULT, δ between adopted and decay datasets

(ii) Adopted photon branching that has not been renormalised so the strongest photon branch is 100

(iii) Levels or transitions in decay or reaction datasets which were accidentally omitted from *Adopted Levels, Gammas* (or conversely)

ENSDF MODEL EXAMPLES: I

Reaction Datasets

Coral M. Baglin
Lawrence Berkeley National Laboratory

Workshop on Nuclear Structure and Decay Data: Theory and Evaluation, ICTP, Trieste, 28 Apr. - 9 May 2008

^{192}Pt: from ^{190}Os(α,2nγ), ^{192}Os(α,4nγ)
^{91}Nb: from ^{89}Y(α,2nγ), ^{93}Nb(α,α'2nγ)
^{166}Os: from ^{106}Cd(^{64}Zn,2p2nγ)
^{186}W: from Coulomb Excitation
^{169}Ho: from ^{170}Er(pol t,α)
^{59}Fe: from ^{58}Fe(d,p), (pol d,p)
^{59}Fe: from ^{58}Fe(d,pγ)
^{59}Fe: from ^{59}Co(n,p)
^{166}Ho: from ^{165}Ho(n,γ) E = thermal
^{170}Tm: from ^{169}Tm(n,γ) E = thermal: two-photon cascades
^{170}Tm: from ^{169}Tm(n,γ) E = 2, 24 keV
^{170}Tm: from ^{169}Tm(d,p)
^{170}Tm: from ^{170}Er(^{3}He,t)
^{92}Mo: from ^{92}Mo(d,d′), (pol d,d)
^{170}Tm: from ^{171}Yb(t,α)
^{170}Er: from ^{170}Er(γ,γ′), (γ, pol γ′) (resonance fluorescence)
^{59}Co: from ^{58}Fe(p,p′)
^{93}Nb: from ^{92}Zr(p,p′), (pol p,p) IAR

^{190}Os(α,2nγ), ^{192}Os(α,4nγ)

```
192PT     190OS(A,2NG), 192OS(A,4NG)     1976CU02,1976HJ01          98NDS     199809
192PT  H  TYP=FUL$AUT=Coral M. Baglin$CIT=NDS 84, 717 (1998)$CUT=1-Aug-1998$
192PT C   Others: 1965LA02, 1974YA03, 1975FU04, 1975PI02, 1978TI02, 1979FUZN,
192PT2C   1981HJ01.
192PT C   1976CU02: E(A)=28-50 MEV; osmium targets enriched to 95% in
192PT2C   190OS (for (A,2NG)), to 98% in 192OS (for (A,4NG));
192PT3C   measured EG, IG (GELI, FWHM=2.1 KEV at 1332 KEV; low-energy photon
192PT4C   spectrometer, FWHM=650 EV
192PT5C   at 122 KEV), prompt and delayed GG coin, three-parameter
192PT6C   GG(T) coin, G-ray angular distributions (90 DEG to 140 DEG
192PT7C   (5 angles)). See also 1975PI02.
192PT C   1976HJ01: E(A)=23-27 MEV, osmium targets enriched to 79% in
192PT2C   190OS (for (A,2NG)); E(A)=43-51 MEV, osmium targets enriched
192PT3C   to 98% in 192OS (for (A,4NG)); measured EG, IG (GELI,
192PT4C   including system with FWHM=550 EV at 100 KEV), ECE, ICE (magnet with
192PT5C   SILI), prompt and delayed GG coin, G-ray angular
192PT6C   distributions, relative G-ray yields for (A,2NG) at 27 MEV and (A,4NG)
192PT7C   at 48 MEV (see also 1975FU04).
192PT C   The level scheme and all data are from 1976CU02 and 1976HJ01,
192PT2C   except where noted. Additional data are available from 1974YA03,
192PT3C   1978TI02, and 1979FUZN. 1981HJ01 report average spin distributions and
192PT4C   deexcitation G multiplicities for quasicontinuum levels excited in
192PT5C   192OS(A,4NG) at EA=51-55 MEV.
192PT CG          See 1976CU02 and 1976HJ01 for RI (other conditions),
192PT2CG  additional angular distribution coefficients, and coincidence data.
192PT CG E        From 1976CU02, except where noted (192OS(A,4NG),
192PT2CG  E(A)=45.5 MEV, |q=125 DEG).
192PT CG RI       IG from 192OS(A,4NG), E(A)=45.5 MEV,
```

2

```
192PT2CG  THETA=125 DEG, except where noted (1976CU02); values are relative to
192PT3CG  I(316.5G)=100.
192PT CG M        From CE data (1976HJ01) and/or G-ray angular distributions,
192PT2CG  except where noted; the photon and CE intensity scales were
192PT3CG  normalized through KC=0.0539 (E2 theory) for 316.5G. Stretched Q
192PT4CG  assignments from G(|q) are based on large positive A2 and
192PT5CG  small negative A4.
192PT CL J        Authors' values from G-ray multipolarities, coincidence
192PT2CL  data, and band structure (from 1976HJ01, except as noted). See 192PT
192PT3CL  adopted levels for evaluator's assignments.
192PT CL BAND(A)  K=0 GS BAND.
192PT CL BAND(B)  K=2 QUASI-G VIBRATION BAND.
192PT CL BAND(D)  PI=+ BAND, YRAST FOR J GE 10.
192PT CL BAND(E)  SEMIDECOUPLED PI=- BAND.
192PT2CL  BUILT ON the 5- two-quasiparticle excitation.
192PT CL BAND(G)  PI=- BAND.
192PT2CL  Built on 10- isomer (probable
192PT3CL  configuration=((|n 9/2[505])+(|n 11/2[615])).
192PT CG E(A)     From 1976HJ01 (192OS(A,4NG), E(A)=46 MEV,
192PT2CG  THETA=125 DEG); uncertainties range from 0.1 to 0.3 KEV.
192PT CG E(B)     From 1974YA03 (190OS(A,2NG), E(A)=24 MEV).
192PT CG E(EF)    G-ray associated with GT 3-ns delay (1976HJ01).
192PT CG M(HI),MR(GI)$From G-ray angular distributions in 1979FUZN.
192PT CG MR(DF)   From CE data and G-ray angular distributions in
192PT2CG  1976HJ01.
192PT  N
192PT PN                                                              C5
192PT2PN  RELATIVE RI FOR 192OS(A,4NG), E(A)=45.5 MEV, THETA=125 DEG
192PT  G  388.4   3                                                   B
192PT  G  398.73  23 2.0   3
```

3

```
192PT  G 407.0                                                              A
192PT CG           Assignment to 192PT uncertain (1976HJ01); EG=407.23 10 in
192PT2CG 1974YA03.
---------------
192PT  G 886                                                                A
192PT CG           Deexcites E(level)>5000 (1976HJ01).
192PT  L 0.0          0+               STABLE                               A
192PT  L 316.50    5  2+                                                    A
192PT  G 316.50    5  100       E2                    0.085                 E
192PT CG M         K:L:M=20:10:3.6.
192PT2CG A2=+0.25 2, A4=-0.03 3 (1976HJ01).
--------------------------
192PT  L 920.88    14 3+                                                    B
192PT  G 308.44    12 3.4    3  M1+E2    +7       2     0.096  4           I
192PT CG M         adopted T and RUL exclude DPI=yes option from G(|q).
192PT2CG A2=+0.28 3, A4=-0.01 6 (1976HJ01).
192PT  G 604.34    20                                                       B
192PT CG E         604.4 (uncertainty LE 0.3) in 1976HJ01.
192PT  L 1201.07   16 4+                                                    B
192PT  G 416.8     5  1.1    4  M1+E2    +6       2     0.042  3           I
192PT CG M         MR unreasonably large for E1+M2.
192PT  G 588.67    20 2.8    3 Q                                           H
192PT CG           A2=+0.23 9, A4=-0.01 15 (1976HJ01).
192PT  G 884.5        0.23    8
192PT CG RI$deduced from
192PT2CG RI(416.8G):RI(588.7G):RI(884.5G)=18.0 11:100:7.1 15 (1979FUZN).
```

^{89}Y(α,2nγ), ^{93}Nb(α,α′2nγ)

```
 91NB     89Y(A,2NG), 93NB(A,A'2NG)      1979FI06,1975SC30,1974BE3699NDS     199902
```



```
91NB  H TYP=FUL$AUT=Coral M. Baglin$CIT=NDS 86, 1 (1999)$CUT=15-Dec-1998$
91NB D  1973BeYD UNAVAILABLE SO NOT CHECKED (Jul. '98)
91NB C  Others: 1979Pl05, 1977Ba34, 1976Ba50, 1976Ba02, 1973BeYD.
91NB C  1979Fi06: (A,2NG); E=24.0 MEV, 35.7 MEV; measured EG, IG,
91NB2C  G(|q), G(T).
91NB C  1976Ba50: (A,2NG); E=24.6 to 27.8 MEV; coaxial and planar GELI,
91NB2C  scin detectors; measured EG, IG, G(|q) at seven angles for
91NB3C  EA=24.7 MEV, G(T), GG coin at EA=26 MEV, particle-|g coin,
91NB4C  G excit; shell-model level-energy calculations.
91NB C  1976Ba02: (A,2NG); E=21 MEV; NAI(TL), GE(LI) detectors.
91NB2C  Measured |a-G(|q,H,T); deduced ^T{-1/2}, g-factor for 13/2-
91NB3C  1984 level.
91NB C  1975Sc30: (A,A'2NG); E=48 MEV, pulsed beam; measured |a-CE(T).
91NB C  1974Be36: (A,2NG); E=17 MEV to 25 MEV, pulsed beam; measured
91NB2C  EG, IG, I(x), G(|q), G(T), G excit.
91NB C  1973BeYD: (A,2NG); E=17.3 MEV to 19.8 MEV. The energy has been
91NB2C  chosen just above the threshold for each level.
91NB3C  GE(LI). Measured EG and DSA.
91NB CL E          From least-squares adjustment of EG, assigning |DE{-|g}=1
91NB2CL KEV whenever no G deexciting a given level has been assigned
91NB3CL an uncertainty by the authors.
91NB CL J          Authors' values, based primarily on G(|q); from 1976Ba50 for
91NB2CL E(level)<3500, and from 1979Fi06 for higher energy levels,
91NB3CL except as noted.
91NB CL T          For values from DOPPLER-shift attenuation, experimental
91NB2CL uncertainties only are quoted; an additional
91NB3CL uncertainty of 20% should be added to account for the error
91NB4CL in the slowing-down theory (1973BeYD). Additionally, T<4 NS
91NB5CL for all levels above 3500 KEV (1979Fi06).
91NB CG E          From 1979Fi06, except as noted. Values taken from fig. 3
```

```
91NB2CG of 1979Fi06 are of unknown precision.
91NB CG RI        Relative intensity at 35.7 MEV (1979Fi06), except as noted.
91NB2CG Data given without uncertainty are from fig. 3 of 1979Fi06.
91NB CG M,MR      From G(|q) (1979Fi06), if not indicated otherwise.
91NB CG M(A,E),MR(A,E)$Based on G(|q) from 1974Be36.
91NB CG E(B)      From 1974Be36.
91NB CG E(D,E)    From 1973BeYD.
91NB CG E(F)      Observed only by 1976Ba50.
91NB CG E(G)      180.0 5 in table 1 of 1979Fi06, but 185.0 in figs. 1 and 3;
91NB2CG the latter value is in accord with datum from (6LI,3NG).
91NB CL T(T)      From DOPPLER-shift attenuation (1973BeYD).
91NB PN                                                                  C5
91NB2PN RELATIVE RI FROM (A,2NG) AT 35.7 MEV
----------
91NB  G 2117.5    7                                                      B
91NB CG           Placed by 1974Be36 from 2119 level, but EG inconsistent with
91NB2CG adopted value; also, RI(328):RI(2120)=3:10 (1976Ba50) is inconsistent
91NB3CG with adopted branching from that level.
91NB  L        0    9/2+
91NB CL J         from adopted levels.
91NB  L    102.0   71/2-
91NB CL J         from adopted levels.
91NB  G 102.0     7                                                        S
91NB CG E         G not observed in this experiment. E from level energy
91NB2CG difference.
91NB  L   1184.4   7 5/2-            2.6 PS    +15-7                    T
91NB  G 1082.4    2 3          E2                                        E
91NB CG           A2=+0.23 3, A4=-0.03 3 (1976Ba50). Other: 1974Be36.
91NB CG M         Q from G(|q), not M2 from RUL.
91NB  L   1310.1   83/2-             0.166 PS  17                       T
```



```
91NB  G 1208.1    3                                                      D
91NB  L  1580.61  10 7/2+           0.33 PS   3                        T
91NB  G 1580.6    1          M1+E2    +0.24   +10-9                    D
91NB CG           A2=-0.38 6, A4=+0.03 5 (1976Ba50). Other: 1974Be36.
91NB CG M         ^D+Q from G(|q), not E1+M2 from RUL.
91NB  L   1609.6   83/2-            0.054 PS  12                       T
91NB CL J         from adopted levels.
91NB  G 1507.6    2                                                      D
-----------------
91NB  L  1983.95  17 13/2-          10.0 NS   4
91NB2 L G=+1.26 4
91NB CL G         From time-differential perturbed angular distribution
91NB2CL (1976Ba02).
91NB CL T         from |a-G(T) (1976Ba02). Other: 8 NS 2 (1976Ba50).
91NB  G 193.5     1 26.7    7 (E2)
91NB CG           A2=+0.19 2, A4=0.00 1 (1979Fi06). Other: 1976Ba50.
91NB CG M         (Q) from G(|q), not M2 from RUL.
91NB  G 1983.9    2 78.8    9 (M2)
91NB CG           A2=+0.15 4, A4=-0.03 3 (1979Fi06). Others: 1974Be36,
91NB2CG 1976Ba50.
91NB CG M         Q from G(|q), DPI=yes from level scheme.
```

^{106}Cd(^{64}Zn,2p2nγ)

```
166OS     106CD(64ZN,2P2NG)              2002AP03
166OS  H  TYP=FUL$AUT=C. M. BAGLIN$CIT=NDS 109, 1103 (2008)$
166OS C   2002AP03: E(64ZN)=334 MEV; 80% ENRICHED 106CD TARGET; ^JUROSPHERE
166OS2C   DETECTOR ARRAY (5 ^NORDBALL (AT 79 DEG), 5 ^TESSA (AT 101 DEG) AND 15
166OS3C   ^EUROGAM PHASE ^I (AT 134 DEG OR 158 DEG) Ge DETECTORS); ^RITU
166OS4C   GAS-FILLED SEPARATOR; RECOILS IMPLANTED INTO 16-STRIP
```

```
166OS5C  POSITION-SENSITIVE SI DETECTOR; RECOIL DECAY TAGGING TECHNIQUE;
166OS6C  MEASURED EG, IG, RECOIL-|a-G-G COIN, G ASYMMETRY.
166OS CG E,RI       FROM 2002AP03.
166OS CG M          BASED ON G ASYMMETRY IN RECOIL-|a-G DATA, EXCEPT AS NOTED.
166OS2CG VALUES FOR 165W TRANSITIONS OF KNOWN MULTIPOLARITY, ALSO OBSERVED IN
166OS3CG THIS EXPERIMENT, SERVED AS AN ASYMMETRY CALIBRATION.
166OS4CG VALUES EXPECTED FOR PURE STRETCHED ^D ARE
166OS5CG ~0.55 AND, FOR STRETCHED Q (OR ^D, DJ=0), ~1.0.
166OS CL E          FROM LEAST-SQUARES FIT TO EG.
166OS CL J          AUTHORS' VALUES, BASED ON DEDUCED BAND STRUCTURE, MEASURED
166OS2CL TRANSITION MULTIPOLARITIES AND ANALOGY TO STRUCTURES IN 168OS.
166OS CL BAND(A)    YRAST SEQUENCE.
166OS2CL GS BAND CROSSED AT ~h|w=0.30 MEV (WITH ~11 ~h GAIN IN ALIGNMENT) BY
166OS3CL (|n i{-13/2}{+2}) BAND (2002AP03).
166OS CL BAND(B)    KPI=(3-), |a=1 BAND.
166OS2CL BANDHEAD DEEXCITES TO J=2 AND 4 MEMBERS OF GS BAND; STRUCTURE OF BAND
166OS3CL APPEARS TO BE SIMILAR TO THAT OF A 3- BAND IN 168OS.
166OS4CL POSSIBLE CONFIGURATION: |n (i{-13/2})(h{-9/2},f{-7/2}).
166OS CL BAND(C)    PI=(-), |a=0 BAND.
166OS2CL VERY WEAK BAND DECAYING THROUGH THE (3-) BAND, ANALOGOUS TO A SIDE BAND
166OS3CL KNOWN IN 168OS; ON THIS BASIS, AUTHORS TENTATIVELY ASSIGN PI=- AND
166OS4CL EVEN SPIN.
166OS5CL POSSIBLE CONFIGURATION: |n (i{-13/2})(h{-9/2},f{-7/2}).
166OS PN                                                                    5
166OS  G  171.3     5 7       3
166OS CG            IG(158 DEG)/(IG(79 DEG)+IG(101 DEG))=0.74 8.
166OS CG            AUTHORS SUGGEST THAT THIS G MAY BELONG TO DECAY FROM (3-)
166OS2CG BAND TO YRAST BAND.
-------------------------
166OS  L 0.0          0+                                                    A
```

8

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166OS  L 432.0      3 2+                                                    A
166OS  G  432.0     3 100     2 E2                    0.0330
166OS CG            IG(158 DEG)/(IG(79 DEG)+IG(101 DEG))=0.90 3.
166OS CG M          Q FROM G ASYMMETRY; NOT M2 FROM INTENSITY BALANCE AT 432
166OS2CG LEVEL.
166OS  L 1021.0     5 4+                                                    A
166OS  G  589.2     4 78      2 Q
166OS CG            IG(158 DEG)/(IG(79 DEG)+IG(101 DEG))=0.92 6.
166OS  L 1562.3     7 (3-)                                                  B
166OS  G  541.6     7 17      6 D
166OS CG            IG(158 DEG)/(IG(79 DEG)+IG(101 DEG))=0.66 7.
166OS  G  1129.2    9 25      6
166OS  L 1725.0     7 6+                                                    A
166OS CL E          AN ALTERNATIVE VALUE (E=1647.3) IS POSSIBLE BECAUSE THE
166OS2CL ORDER OF THE 626G-704G CASCADE IS NOT ESTABLISHED.
166OS  G  704.0     5 33      9 Q
166OS CG            IG(158 DEG)/(IG(79 DEG)+IG(101 DEG))=0.88 8.
```

^{186}W: from Coulomb Excitation

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186W     COULOMB EXCITATION            1989KU04,1977MC11,1971MI08
186W   H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 99, 1 (2003)$CUT=4-Apr-2003$
186W   C Others: 1958Mc02, 1959Bi10 (EP=2.8 MEV), 1961Ha21 ((p,p') and (d,d')),
186W 2C  1962Bi05 (EA=3 MEV), 1967As03 (16O,16O'G), 1967Gi02 (16O,16O'G),
186W 3C  1967Ku07 (P,P'G), 1968St13 (EA=8 MEV), 1969Ch23 (EA=8 MEV), 1970Me09
186W 4C  (EA=6 MEV), 1971Ob02 (EA=6 MEV), 1972Hi14 (EP=3 MEV), 1974Ba81
186W 5C  (EA=11.5-13.5 MEV), 1974Br31 (EA=10-20 MEV), 1974Le16 (EA=12.5-19
186W 6C  MEV), 1975Le22 (EA=13.25-19 MEV), 1979Hu01, 1985St07 (E(63CU)=220 MEV),
186W 7C  1986Bi13 (E(32S)=100 MEV), 2000WHZZ(E(238U)=1600 MEV.
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9

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186W  C  For determinations of transient-field strength and precession, see,
186W 2C  e.g., 1991St04, 1988St16, 1987St14.
186W  C  1971Mi08: (X,X'G); x=p, E=5.0, 5.08 MEV; x=a, E=14, 15 MEV; x=16O,
186W 2C  E=45.1, 45.5 MEV.
186W  C  1977Mc11: (X,X'G); x=|a, E=15 MEV; x=16O, E=42 MEV.
186W  C  1979Hu01: (84KR,84KR'G) E=340 MEV, 98.5% 186W target.
186W  C  1989Ku04: (208PB,208PB'G), E(208PB)=4.9 MeV/u; AP 95% 186W target;
186W 2C  measured EG, yield at 12 angles;
186W 3C  observed multiple COULOMB excitation of GS band (J LE 14),
186W 4C  |g band (J LE 12) and quasi-|b band (J=0 and 2); extracted
186W 5C  electromagnetic matrix elements for PI=+ yrast band.
186W  C  See also 1996Wu10 for extraction and
186W 2C  discussion of intrinsic E2 matrix elements between |DK=2 bands.
186W  CG E          From 1977Mc11, unless noted otherwise.
186W  CG RI         Relative photon branching from 1971Mi08, except as noted.
186W  CG M          From 1971Mi08, based on G anisotropy, except as noted.
186W  CG E(J)       1989Ku04 give EG=264.2 in table 1; evaluator presumes this is
186W 2CG typographical error for EG=274.2 (based on spectrum of fig. 1 and
186W 3CG systematics of EG for analogous transitions in 182W, 184W, 186W).
186W 4CG EG=274 in both 1979Hu01 and 1977Mc11.
186W  CG E(K)       From 1989Ku04; uncertainty not stated by authors.
186W  CG E(L)       Approximate value read by evaluator from spectrum in fig.1
186W 2CG of 1989Ku04 (DE AP 5 KEV); authors do not quote EG or E(level).
186W  CG M(M)       From 1977Mc11.
186W  CL            Band assignments shown here are from Adopted Levels. Note
186W 2CL that 1989Ku04 assign the 1006 level as the J=4 member of the |g
186W 3CL band, whereas 1977Mc11 suggest that it is the J=2 member of the |b
186W 4CL band. The basis for the latter assignment is unclear; such an
186W 5CL assignment is inconsistent with adopted JPI(1006), so it is presumed
186W 6CL to be in error. The 1030 level is adopted as the J=2 member of the
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186W 7CL |b band.
186W  CL E          From least-squares adjustment of EG, allowing DE=1 KEV
186W 2CL for transitions for which authors do not quote DE.
186W  CL T          Calculated by the evaluator from measured BE2 and adopted
186W 2CL branching.
186W  CL J          From direct E2 COULOMB excitation (1977Mc11), except as
186W 2CL noted.
186W  CL E(L)       Reported to have been observed by 1989Ku04; E(level) is
186W 2CL rounded-off value from Adopted Levels.
186W  CL J(M)       From band structure deduced by 1989Ku04, based on GG coin
186W 2CL data and energy and intensity systematics.
186W  CL J(N)       E2 G to (J-2) member of same band in multiple COULOMB
186W 2CL excitation.
186W  CL BAND(A)    GS BAND (1989Ku04).
186W  CL BAND(B)    K=2 |g BAND (1989Ku04).
186W 2CL Note that the 1006 level, adopted here as the 4+ member of this band,
186W 3CL was presumed to be the 2+ member of the |b band in 1977Mc11.
186W  CL BAND(C)    K=0 |b BAND.
186W 2CL Only weakly populated (J=0 and 2 members) in 1989Ku04. Authors do not
186W 3CL indicate E(level) or deexciting transitions for either member.
186W  CL BAND(D)    KPI=2- BAND.
186W 2CL K=2 based on Alaga rules for transitions from the 3- member to
186W 3CL the J=2 and 3 members of the |g band (1977Mc11).
186W  PN                                                                  6
186W   L 0            0+                                                 A
186W  CL J          from Adopted Levels.
186W   L 122.6       7 2+                 1.05 NS 3                     A
186W B L BE2=3.42 5
186W  CL BE2        weighted average of 3.50 6 (1968St13), 3.37 8 (1974Br31) and
186W 2CL 3.35 7 (1975Le22). Others: 3.6 4 (1958Mc02), 3.57 25 (1961Ha21),
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186W 3CL 3.35 11 (1974Le16), 3.4 3 (1989Ku04) from coulomb excitation, and 3.46
186W 4CL 12 from muonic atom (1970Hi03)
186W  CL           g-factor=0.308 17 FROM g-factor/g-factor(184W, 111)=1.07 5
186W 2CL (1991ST04) IF g-factor(184W, 111)= 0.289 7.  Others: 0.350 35
186W 3CL (1967Gi02), 0.35 3 (1967Ku07).
186W  CL           Q/Q(2+ 182W)=0.908 24 (1969Ch23), 0.906 18 (1971Ob02).
186W  CL T         from BE2. Other values: 1.12 NS 7 (P,P'G) (1959Bi10); 1.01 NS 4
186W 2CL (A,A'G) (1962Bi05); 1.30 NS 21 (1967As03), 1.116 NS 21 pulsed beam
186W 3CL (1967Ku07); 1.38 NS 12 (1970Me09, MOSSBAUER); 1.39 NS 12 (1971Ob02,
186W 4CL MOSSBAUER); GE 1.15 NS 6 (1972Hi14, MOSSBAUER).
186W  CL           Static matrix element <2+ M(E2) 2+> =-2.19 +28-11 (1989Ku04).
186W   G 122.5                E2                                              K
186W   L 396.7     12 4+                  36.4 PS 25                           A
186W B L BE2=1.63 11 (1971MI08)$BE4=0.14 +15-10$
186W  CL           Static matrix element <4+ M(E2) 4+> =-2.89 +37-14 (1989Ku04).
186W  CL BE2       for 2+(123) to 4+(397) excitation. Other: 2.7 4 (1989Ku04).
186W  CL BE4       from <0+ M(E4) 4+> =-0.37 17, weighted average of -0.27 10
186W 2CL (1974Le16) and -0.64 16 (1974Br31). Other <0+ M(E4) 4+>: -0.25 25
186W 3CL (1975Le22).
186W  CL J         E2 G to 2+; J=0 inconsistent with measured T.
186W  CL           g-factor/g-factor(122, 2+)=1.04 7 (1985St07).
186W  CL           Other T: 38 PS 3 from nuclear deorientation for ions
186W 2CL recoiling in vacuum (1986Bi13).
186W   G 274.2                E2                                              J
186W   L 737.2      7 2+              4.78 PS   16                            B
186W B L BE2=0.140 4
186W  CL BE2       Weighted average of 0.146 8 (1977Mc11; supersedes 0.150 8
186W 2CL from 1971Mi08) and 0.139 4 (1974Ba81).
186W  CL           g-factor/g-factor(122, 2+)=0.63 13 (1985St07).
186W   G 615            94    3  M1+E2      -11  -4+3
```



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186W  CG MR        from 1971Mi08; A2=-0.140 15 (1971Mi08).
186W   G 737            100      E2
186W   L 810.1     16 6+                  4.0 PS 3                            A
186W B L BE2=1.70 12
186W F L FLAG=N
186W  CL           Static matrix element <6+ M(E2) 6+> =-3.25 +17-42 (1989Ku04).
186W  CL BE2       Weighted average of 1.89 29 (1971Mi08) and 1.66 13
186W 2CL (1979Hu01); for 4+(397) to 6+(810) excitation. Other: 1.21 +14-12
186W 3CL (1989Ku04).
186W  CL           g-factor/g-factor(122, 2+)=1.03 20 (1985St07).
186W   G 413.4              E2                                                K
186W   L 861.8      9 (3)+                                                    B
186W  CL J         E1 G from 3-; band structure.
186W   G 739
186W   L 884        (0+)                                                      C
186W F L FLAG=L
186W  CL J         from Adopted Levels.
186W   L 952.1     10  (2)-                                                  D
186W  CL J         anisotropies of G to 2+ and G from 3-.
186W   G 215               E1                                                M
186W  CG M         G(|q) corrected for contamination by 184W line (1977Mc11).
186W   L 1006.7    15  4+                                                    B
186W  CL BE2       1977Mc11 report BE2=0.0030 6 for 0+(GS) to 2+(1007)
186W 2CL excitation, based on 610G yield and the assumption that the 1007
186W 3CL level is the 2+ member of the |b band; however level is currently
186W 4CL designated as the J=4 member of the |g band.
186W  CL J         1989Ku04 observe the gammas known to deexcite this level, and
186W 2CL designate them as transitions from the 4+ member of the |g band
186W 3CL rather than from the 2+ member of the |b band (as supposed in
186W 4CL 1977Mc11). The J=4 assignment is consistent with expected strong
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186W 5CL excitation of |g band levels in 1989Ku04 and with band systematics in
186W 6CL nearby ^W and Os even-^A nuclei.
186W   G 269
186W  CG E          rounded-off value from Adopted Gammas; |g not evident in
186W 2CG spectrum shown in 1989Ku04 (possibly masked by intense 274G), but
186W 3CG authors imply that it was observed.
186W   G 610           100
186W   G 884          5  12    LT                                          L
186W  CG RI         from |g yields in 1977Mc11 (G not observed).
186W 2CG However, |g is prominent in spectrum in 1989Ku04.
186W   L 1030          2+                                                  C
186W F L FLAG=L
186W  CL J          from Adopted Levels.
186W   L 1045.0      7  3-                                               D
186W S L BE3=0.101 8
186W  CL BE3        From 1977Mc11 (based on yields of 308G, 183G and 215G).
186W   G 93                 M1+E2      1.3   5                           M
186W  CG            |d{+2}=1.8 +150-11 (1977Mc11), from analysis of
186W 2CG 0+(E3)3-(M1+E2 93G)2-(E1 215G)2+ sequence.
186W   G 183            33.5     E1                                       M
186W  CG RI         from G yield (relative to 308G) in 1977Mc11.
186W  CG            Anisotropy=1.29 6 (1977Mc11); consistent with 0+(E3)3-(E1)3+
186W 2CG sequence.
186W   G 308           100       E1                                       M
186W  CG            Anisotropy=0.761 14 (1977Mc11); consistent with
186W 2CG 0+(E3)3-(E1)2+ sequence.
186W   G 1045                [E3]                                          S
186W  CG M          1045 level directly populated by E3 COULOMB excitation
186W 2CG (1977Mc11).
```

14

^{170}Er(pol t,α)

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169HO    170ER(POL T,A)                1979LO02
169HO  H TYP=FUL$AUT=C. M. BAGLIN$CUT=1-Mar-2008$
169HO C  E(T)=17 MEV, polarization=0.78 (average value); metallic ER
169HO2C  targets enriched to 96.9% in 170ER; measured E(level) (Q3D
169HO3C  mag spect, FWHM AP 16 KEV), angular distributions (9 angles
169HO4C  from 10 DEG to 50 DEG), analyzing powers; interpreted levels
169HO5C  in terms of the NILSSON model, including pairing and CORIOLIS
169HO6C  coupling, aided by analogies with known levels in 165HO
169HO7C  and 167HO.
169HO CL J          From angular distributions and analyzing powers (authors'
169HO2CL values).
169HO CL L          From DWBA analysis of angular distributions.
169HO CL S          NUCLEAR STRUCTURE FACTOR CALCULATED FROM
169HO2CL DS/DW(exp)/(2N DS/DW(DWBA)) ASSUMING ^N=32.5.
169HO CL BAND(A)    7/2[523] band.
169HO CL BAND(B)    3/2[411] band.
169HO CL BAND(C)    1/2[411] band.
-------
169HO  L 0.0           7/2-                              3        0.054       A
169HO  L 97         4  9/2-                              5        0.19        A
169HO  L 215        4  11/2-                             5        1.90        A
169HO CL S          large value attributed to CORIOLIS MIXING WITH OTHER orbitals
169HO2CL FROM the h{-11/2} shell.
169HO  L 254        4  3/2+                              2        0.11        B
169HO  L 314        4  5/2+                              2        0.79        B
169HO  L 359        4  3/2+                              2        0.27        C
169HO  L 381        4  7/2+                              4        0.15      APB
169HO CL L          angular distribution not shown, but L=4 determination
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15

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169HO2CL implied in text.
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^{58}Fe(d,p), (pol d,p)

```
59FE    58FE(D,P), (POL D,P)          1964SP03,1972MC18,1980TA05
59FE  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 95,215 (2002)$CUT=8-Feb-2002$
59FE C  Others: 1968GR18, 1967KL03, 1964BJ01.
59FE C  1980TA05: E(POL D)=10 MEV, measured SIGMA(THETA) and analyzing
59FE2C  power, 12 angles from 25 DEG to 80 DEG (lab), enriched targets
59FE3C  (82.48%), 8 SI(LI)-detectors at 15 DEG intervals, FWHM=30-50 KEV for
59FE4C  15-MEV protons, |s(|q) and analyzing power compared with DWBA
59FE5C  calculations.
59FE C  1972MC18: E(D)=10 MEV and 12 MEV, measured SIGMA(THETA), THETA(c.m)
59FE2C  from AP 5 DEG to AP 90 DEG, enriched targets (85.4%), multigap
59FE3C  spectrograph, FWHM=16 KEV for 16-MEV protons.
59FE C  1968GR18: E(D)=6 MEV. DWBA analysis of SIGMA(THETA); levels at 730,
59FE2C  1020, 1230, 1910 and 3590; deduced (2JF+1)^S for each level.
59FE C  1967KL03: E(D)=10 MEV, measured SIGMA(THETA), 34 angles from 7.5 DEG to
59FE2C  165 DEG, surface-barrier detector for protons at 25 DEG to 165 DEG with
59FE3C  FWHM (GS)=44 KEV, magnetic spectrograph at 5 angles from 7.5 DEG to
59FE4C  35 DEG.
59FE C  1964SP03: E(D)=6.55 MEV, THETA=30 DEG and 45 DEG; for E(D)=7.0 MEV,
59FE2C  THETA=10 DEG. Measured EP, enriched target (75.1%), single-gap
59FE3C  spectrograph.
59FE C  1964BJ01: E(D)=3-4.3 MEV, THETA=145.5 DEG, levels at 0, 290, 477,
59FE2C  614, 639, 732 KEV, DE=8 KEV.
59FE C  Spectroscopic factors from 1967KL03 are in very poor agreement with
59FE2C  those from 1972MC18 and 1980TA05. The results of 1980TA05 and 1968GR18
59FE3C  are in fair agreement with 1972MC18.
59FE CL L,S       L values and spectroscopic factors are from 1972MC18, based
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16

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59FE2CL on comparison of 10 MEV data with DWBA calculations, except as noted.
59FE CL E         From 1964SP03, except as noted.
59FE CL J         From L value and measured analyzing power (1980TA05).
59FE CL S$LABEL=S'
59FE CL E(A),S(A) From 1972MC18. Value of ^S' shown assumes L=1.
59FE CL L(B),S(B)$From 1980TA05.
59FE CL E(D)      Doublet.
59FE CL E(E)      From 1964BJ01.
59FE CL J(F),L(F)$Weakly excited state; |s(|q) corrected for JPI=3/2- 58FE
59FE2CL contaminant nearby. Analyzing power compatible with 3/2- or 5/2-.
59FE3CL |s(|q) poorly fitted by L=1 or L=3 DWBA in 1980TA05, and deviates
59FE4CL significantly from |s(|q) for other levels at |q>60 DEG. Consequently,
59FE5CL evaluator considers authors' L=1 assignment to be uncertain; it also
59FE6CL conflicts with adopted JPI(574)=5/2-.
59FE  L 0                 3/2-                1       1.45
59FE  L 287       10      1/2-                1       0.09
59FE  L 473       10      5/2-                3       2.10
59FE  L 574             (3/2-,5/2-)           (1,3)   0.017      A
59FE3 L FLAG=F
59FE  L 614       8                                              E  ?
59FE  L 639       8                                              E  ?
59FE  L 728       10      3/2-                1       0.50
59FE  L 1026      10      (7/2)-              3       0.19
```

^{58}Fe(d,pγ)

Separated from (d,p) data set because γ rays observed

```
59FE    58FE(D,PG)                  1977PA18
59FE  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 95,215 (2002)$CUT=8-Feb-2002$
59FE C  E(D)=3.5 MEV. Measured EG, natural and enriched (83.5%) targets, GELI
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17

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59FE2C  (1977PA18).
59FE CL E          From EG.
59FE  L 0
59FE  L 287.3      10
59FE  G  287.3     10
59FE  L 472        3
59FE  G  472       3
59FE  L 570.9      10
59FE  G  570.9     10
```

No need to give source of E_γ data because only one keynumber.

^{59}Co(n,p)

```
59FE     59CO(N,P)                        1993AL21,1963MO13
59FE  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 95,215 (2002)$CUT=8-Feb-2002$
59FE C  1993AL21: EN=198 MEV, |q(lab)=0 DEG-20 DEG (4 DEG steps), 99.99% 59CO
59FE2C  targets, magnetic spectrometer, FWHM AP 900 KEV; measured energy
59FE3C  spectra at 6 angles for protons exciting levels with E<30 MEV; ^DWIA
59FE4C  analysis. Decomposed strength function into L=0,1,2,3 components;
59FE5C  ^GT resonance (L=0) observed with centroid at 4.1 MEV. See 2001LA12
59FE6C  and 1999CA29 for further discussion of these results.
59FE C  1963MO13: measured energy and angular distribution of protons emitted
59FE2C  from 59CO when bombarded by 14.8-MEV 3H(D,N) neutrons.
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Note: no data from this data set will be used in Adopted Levels, Gammas, but this reaction must still be assigned an XREF there

^{165}Ho(n,γ) E = thermal

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166HO    165HO(N,G) E=THERMAL          1967MO05,1984KE15,2000PR03
166HO  H TYP=FUL$AUT=C. M. BAGLIN$CIT=NDS 109, 1103 (2008)$
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18

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166HO2 H CUT=1-Mar-2008$
166HO C  Other measurements: 1958SK59, 1959DR75, 1959JO33, 1960AL27, 1961ES02,
166HO2C  1961KR01, 1963GI03, 1963OR02, 1973HE15, 1973PRZI,
166HO3C  1979BO08, 1988BA79, 1989DU03, 2003CHZS, 2007CHZX.
166HO C  INCLUDES (POL N,G) E=0.065 EV.
166HO C  JPI(TARGET)=7/2-.
166HO C  SIGMAN=61.2 11 (2006MUZX).  ABUNDANCE(165HO)=100%.
166HO C  2007CHZX: PROVIDES AN EVALUATION OF EXPERIMENTAL DATA INCLUDING NEW
166HO2C  EG AND ELEMENTAL CROSS SECTION MEASUREMENTS USING GELI DETECTOR FOR
166HO3C  148 PRIMARY AND 73 SECONDARY TRANSITIONS (HEREIN REFERRED TO AS
166HO4C  'Budapest data', and taken from the ^EGAF SECTION OF THE ^CD THAT IS
166HO5C  PART OF THIS PUBLICATION).  SUPERSEDES 2003CHZS.
166HO C  2000PR03: THREE-CRYSTAL PAIR SPECTROMETER, FWHM AP 5.5 KEV AT 6.5 MEV;
166HO2C  calibration based on SN AND PATTERN OF PRIMARY TRANSITIONS TO SEVERAL
166HO3C  WELL-ESTABLISHED LOW-LYING LEVELS; MEASURED EG, GG COIN; DEDUCED
166HO4C  BAND STRUCTURE.
166HO C  1984KE15: >99.9% HO TARGET; Ge DETECTOR INSIDE QUADRISECTED NaI(Tl)
166HO2C  ANNULUS (FWHM=3.1-4.5 KEV FOR EG=4000-6200); MEASURED EG, IG FOR 270
166HO3C  TRANSITIONS WITH EG>4050; 14N(N,G) REACTION USED FOR CALIBRATION.
166HO C  1979BO08: (POL N,G); POLARIZED E=0.065 EV NEUTRONS AND POLARIZED
166HO2C  SINGLE-CRYSTAL 165HO TARGET; MEASURED G(|q) FOR 15 PRIMARY GAMMAS;
166HO3C  DEDUCED J.
166HO C  1967MO05: 99.8% HO TARGET; MEASURED PRIMARY EG, IG USING GELI DETECTOR
166HO2C  AS TWO-ESCAPE PAIR SPECTROMETER (FWHM=8.0 KEV; EG=5000-6200); MEASURED
166HO3C  SECONDARY EG, IG USING Riso CURVED-CRYSTAL SPECTROMETER (EG=30-750) OR
166HO4C  IG USING GELI DETECTOR (EG=70-550); MEASURED CONVERSION ELECTRONS
166HO5C  (E=29-500) USING Elephant SPECTROMETER AT Munich (FWHM=0.6% AT 100 KEV,
166HO6C  0.3% AT 200 KEV; THICK SOURCE) AND THE Studsvik B- SPECTROMETER
166HO7C  (FWHM=0.2%; THIN SOURCE).
166HO C  The LEVEL SCHEME INCLUDES REFINEMENTS MADE BY 2000PR03 TO THE SCHEMES
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19

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166HO2C  PROPOSED BY 1967MO05 AND OTHERS, IN WHICH G placements were based on
166HO3C  THE RITZ PRINCIPLE (SOMEWHAT UNRELIABLE AT THIS LEVEL DENSITY); GG
166HO4C  COIN DATA FROM 2000PR03 LED TO THE PLACEMENT OR RELOCATION OF MANY
166HO5C  TRANSITIONS AND THE ELUCIDATION OF A NUMBER OF ADDITIONAL BANDS.
166HO CG E,RI      EG data are from 1984KE15 if E>4050, and E<4050 data are from
166HO2CG 1967MO05 (cryst.), EXCEPT AS NOTED. 1967MO05 also report two separate
166HO3CG GE(LI) detector measurements of EG and/or IG for a number of G rays.
166HO4CG EG DATA FROM 2007CHZX (Budapest DATA) ARE, IN GENERAL, LESS PRECISE
166HO5CG AND LESS EXTENSIVE, BUT IN reasonable AGREEMENT WITH THE CRYSTAL DATA;
166HO6CG IG DATA SHOW POOR TO FAIR AGREEMENT WITH THE CRYSTAL DATA. THE
166HO7CG EVALUATOR GIVES THE LATTER EG, IG DATA IN COMMENTS; THE POSSIBLE
166HO8CG EXISTENCE OF COMPLEX LINES (DUE TO POORER RESOLUTION OR PRESENCE OF
166HO9CG IMPURITIES) MAKES IT DIFFICULT TO COMBINE THESE DATA WITH THE CRYSTAL
166HOACG DATA. The EG DATA of 1967MO05 are from wavelength
166HOCCG measurements and probably need to be increased by about 9 ppm to
166HODCG correspond to a scale on which EG(198AU)=411.80205 17. ALSO, the
166HOECG uncertainties do not include an uncertainty of 0.3 ppm in the
166HOFCG conversion of wavelength to energy (SEE, e.g., 2000HE14).
166HO CG M          From CONVERSION ELECTRON DATA (1967MO05,1973PRZI), EXCEPT
166HO2CG AS NOTED. THE PHOTON AND ELECTRON INTENSITY SCALES WERE NORMALIZED
166HO3CG BY 1967MO05 ASSUMING KC(116G)=1.46, L1C(116)=0.18 (FROM M1 theory)
166HO4CG AND KC(137G)=0.117 (FROM E1 THEORY); CURRENT THEORETICAL VALUES ARE
166HO5CG 3.7% LOWER, 1.3% LOWER AND 5.4% HIGHER, RESPECTIVELY, BUT IN VIEW OF
166HO6CG THE RELATIVELY MUCH LARGER UNCERTAINTIES IN THE EXPERIMENTAL DATA, THE
166HO7CG EVALUATOR HAS CHOSEN NOT TO RENORMALIZE THOSE AUTHORS' VALUES.
166HO CG E(A)       Questionable transition.
166HO CG E(B)       Line is complex (1967MO05).
166HO CG E(D)       From 1989DU03 (SI(LI)).
166HO CG RI(D)      From 1989DU03; a calibration uncertainty of 6% has been
166HO2CG ADDED IN QUADRATURE WITH THE STATISTICAL UNCERTAINTY.
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20

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166HO CG E(E)       EG DEVIATES FROM LEAST-SQUARES PREDICTION BY AT LEAST 5|s.
166HO CG E(P)       PLACEMENT FROM 2000PR03.
166HO CL E          FROM LEAST-SQUARES FIT TO EG, EXCLUDING DATA FOR MULTIPLY
166HO2CL PLACED TRANSITIONS AND FOR THE 48.303G AND 232.286G, BOTH OF WHICH
166HO3CL FIT THEIR PLACEMENTS PARTICULARLY POORLY. HOWEVER, IT SHOULD BE NOTED
166HO4CL THAT 28 OF THE REMAINING 570 EG DATA DEVIATE BY AT LEAST 3|s FROM
166HO5CL THE LEAST-SQUARES PREDICTION AND, OF THOSE, 12 DEVIATE BY AT LEAST 5|s.
166HO6CL THE LATTER ARE NOTED IN COMMENTS ON THE RELEVANT G.
166HO CL J          RECOMMENDED VALUE FROM 2000PR03, unless otherwise noted;
166HO2CL BASED ON TRANSITION MULTIPOLARITY AND DEDUCED BAND STRUCTURE.
166HO CL T(h)       From 1978SC10.
166HO CL J(u)       Spin from the angular distribution measurements of the
166HO2CL primary G FEEDING LEVEL (1979BO08).
166HO CL E(P)       FROM LEAST-SQUARES FIT TO EG (cf. SN=6243.64 2 IN 2003AU03).
166HO CL J(Q)       S-WAVE capture on JPI=7/2- target.
166HO CL BAND(A)    KPI=0-, (|p 7/2[523])-(|n 7/2[633]) BAND.
166HO CL BAND(B)    KPI=7-, (|p 7/2[523])+(|n 7/2[633]) BAND.
166HO CL BAND(C)    KPI=3+, (|p 7/2[523])-(|n 1/2[521]) BAND.
166HO CL BAND(D)    KPI=5+ BAND.
166HO2CL CONFIGURATION: (|p 3/2[411]+|n 7/2[633])+(|p 7/2[523]+|n 3/2[521]).
166HO CL BAND(E)    KPI=6+, (|p 7/2[523])+(|n 5/2[512]) BAND.
166HO CL BAND(F)    KPI=4+, (|p 7/2[523])+(|n 1/2[521]) BAND.
166HO CL BAND(G)    KPI=1-, (|p 1/2[411])+(|n 1/2[521]) BAND.
166HO CL BAND(H)    KPI=1+, (|p 7/2[523])-(|n 5/2[523]) BAND.
166HO CL BAND(I)    KPI=2-, (|p 7/2[523])-(|n 7/2[633])+Q{-22} BAND.
166HO CL BAND(J)    KPI=2+ BAND.
166HO2CL CONFIGURATION: (|p 3/2[411]-|n 7/2[633])+(|p 7/2[523]-|n 3/2[521]).
-------------
166HO CL BAND(W)    KPI=2-, (|p 3/2[411])+(|n 1/2[521]) BAND.
166HO CL BAND(X)    KPI=5-, (|p 7/2[523])+(|n 7/2[633])-Q{-22} BAND.
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21

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166HO CL BAND(Y)    KPI=0-, (|p 1/2[411])-(|n 1/2[521]) BAND.
166HO CL BAND(Z)    KPI=3- BAND.
166HO2CL CONFIGURATION (|p 1/2[541])-(|n 7/2[633]) OR
166HO3CL (|p 1/2[411])+(|n 5/2[512]).
166HO CL BAND(1)    KPI=6+, (|p 7/2[523])+(|n 5/2[523]) BAND.
166HO CL BAND(2)    KPI=2+, (|p 7/2[523])-(|n 3/2[521]) BAND.
166HO CL BAND(3)    KPI=5+, (|p 7/2[523])+(|n 3/2[521]) BAND.
166HO CL J(5)       FROM Adopted Levels.
166HO CL T(6)       FROM Adopted Levels.
166HO CL J(7)       2 OR POSSIBLY 4 FROM 5812G(|q), NOT 4 FROM 5812G CIRCULAR
166HO2CL POLARIZATION (1979BO08).
166HO CL J(8)       J=3,4 FROM 5761G(|q) (1979BO08).
166HO CL J(9)       4 OR POSSIBLY 3 FROM 5523G(|q) (1979BO08).
166HO  N 1.0           1.0
166HO CN NR         FROM 1967MO05.  If, instead, one obtained NR by requiring
166HO2CN that SUMOF (TI to GS)=100, a value of 1.02 9 would be obtained, in
166HO3CN excellent agreement with the normalization recommended by 1967MO05.
166HO4CN THE RATIO ^R=IG(2007CHZX, 'Budapest DATA')/RI(1967MO05) VARIES WIDELY
166HO5CN BUT, IF CASES WHERE THE INTENSITIES DIFFER BY AT LEAST A FACTOR OF 3
166HO6CN ARE REMOVED FROM CONSIDERATION, THE AVERAGE VALUE OF ^R IS 0.93 FOR
166HO7CN SECONDARY LINES AND 1.10 FOR PRIMARY TRANSITIONS.  Some, but not all,
166HO8CN of the INCONSISTENCIES MAY STEM FROM THE POORER ENERGY RESOLUTION OF
166HO9CN THE 2007CHZX MEASUREMENT OR FROM THE PRESENCE OF UNIDENTIFIED
166HOACN IMPURITIES. For the strong 116.8G, 136.7G, 5181G, 5212G AND 5813G,
166HOBCN RI(2007CHZX)/RI(1967MO05) IS 0.83 9, 0.85 10, 0.95 9, 1.04 11 AND
166HOCCN 0.93 8, RESPECTIVELY.  WITH THE ADOPTED NORMALIZATION, THE TOTAL
166HODCN OBSERVED PRIMARY G INTENSITY IS 16%.
166HO PN                                                                C
166HO2PN IG PER 100 THERMAL NEUTRON CAPTURES IN 165HO.
166HO  G 37.42      4 0.014   3                                         D
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22

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166HO CG            PLACEMENT FROM 605 AND 672 LEVELS REJECTED IN 2000PR03.
166HO  G 57.469     100.07
166HO CG            PLACEMENT FROM 725 LEVEL REJECTED IN 2000PR03.
166HO  G 57.83      2 0.02                                              A
166HO  G 78.871     120.05
------------
166HO  G 715.3      6 0.60    18
166HO  G 734.4      100.3
166HO CG            PLACEMENT FROM 925 LEVEL REJECTED IN 2000PR03.
166HO CG            OTHER: EG=734.45 6, IG=0.41 3 ('Budapest data', 2007CHZX).
166HO  L 0.0          0-                26.824 H  12                    A
166HOF L FLAG=56
166HO  L 5.969      12 7-               1.20E3 Y  18                    BM
166HOF L FLAG=6
166HO  L 54.2391     7 2-                                               A
166HO  G 54.2392    7 2.50    25E2                      31.3             C
166HO CG M          from L12:L3:M:N=20:20:14:2 (1973PRZI);
166HO2CG EL12C=7.8 31, EL3C=7.8 31, EMC=5.9 29, ENC=0.8 5 (1973PRZI).
166HO3CG EL3C=14 5, L2:L3:M:N=125 38:138 41:54 16:16 5 (1967MO05).
166HO  L 82.4707    20 1-                                              A
166HO  G 28.242     9 0.040   3 M1                      16.99            D
166HO CG M          from Adopted Gammas.
166HO  G 82.470     2 0.97    10M1                      4.55             C
166HO CG M          from EL1C=1.0 5 (1973PRZI); EKC=2.8 14, EL1C=0.5 3
166HO2CG (1967MO05).
166HO CG            OTHER: EG=82.49 5, IG=0.68 5 ('Budapest data', 2007CHZX).
166HO  L 137.729    13 8-                                              B
166HO  G 131.759    5 0.140   21
166HO  L 171.0738   12 3-                                              A
166HO  G 88.60      3  0.03      [E2]                  4.466
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23

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166HO  G 116.835   1  15.8   16 M1                      1.673                  C
166HO CG           K:L1:M:N=100 15:15 2:4.7 14:1.6 5 (1967MO05);
166HO2CG K:L1:L2:L3=100 15:13 2:1.7 5:<0.9 (1967MO05, thin source);
166HO3CG K:L12:M:N=24:5:2:<1 (1973PRZI).
166HO4CG EKC=1.5 4, EL12C=0.29 15, EMC=0.13 6, ENC<0.06 (1973PRZI).
166HO DG E         116.833 10 (1963OR02)
166HO CG           OTHER: EG=116.84 4, IG=13.0 6 ('Budapest data', 2007CHZX).
166HO  L 180.467    3 4-                                                    A
166HO  G 9.393                                                 12.3      10   S
166HO CG E         FROM LEVEL ENERGY DIFFERENCE; transition expected but
166HO2CG not observed (see 1978BA78).
166HO CG TI        FROM TI IMBALANCE AT 180 LEVEL.
166HO  G 126.228   3 1.06    11E2                     1.200                  C
166HO CG           K:L2:L3=100 30:29 14:29 14; EKC=0.74 24 (1967MO05).
166HO CG           OTHER: EG=126.21 5, IG=0.89 6 ('Budapest data', 2007CHZX).
166HO  L 190.9021  20 3+                                                     C
166HOF L FLAG=u
166HO  G 10.43     2 0.052    9[E1]                    27.2                   D
166HO  G 19.840    6 1.09     9 E1                     4.79                   D
166HO CG M         from Adopted Gammas.
166HO  G 136.662   2 27.5    28E1                      0.1378                 C
166HO CG           K:L12:M:N=4:1:<1:<1 (1973PRZI); K:L12=9.8 12:1.1 2
166HO2CG (1967MO05); EKC=0.16 6, EL12C=0.039 23 (1973PRZI).
166HO DG E         136.653 14 (1963OR02); 136.665 8 (1965CS09 CRYST).
166HO CG           OTHER: EG=136.67 4, IG=23.3 11 ('Budapest data', 2007CHZX).
166HO  L 260.6625  23 4+                0.5 NS    LE                           C
166HOF L FLAG=hu
166HO  G 69.7604   14 2.8    3 M1                     7.37                   C
166HO CG           L12:M:N=5:<1:<1 (1973PRZI);
166HO2CG EL12C=1.9 10 (1973PRZI); EL1C=0.47 20 from 1967MO05 and
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24

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166HO3CG 0.80 15 quoted by 1967MO05 from other work.
166HO DG E         69.736 40 (1963OR02 CRYST); 69.769 7 (1965SC09 CRYST).
166HO CG           OTHER: EG=69.79 4, IG=1.76 10 ('Budapest data', 2007CHZX).
166HO  G 89.599    13 0.100  15[E1]                   0.424                  C
166HO  L 263.7876  24 5+              0.5 NS     LE                          D
166HOF L FLAG=h
166HO  G 3.1                                                  4.1       7    S
166HO CG E         FROM LEVEL ENERGY DIFFERENCE; transition expected but
166HO2CG not observed (see 1978BA78).
166HO CG TI        FROM TI IMBALANCE AT 264 LEVEL.
166HO  G 72.8859   150.20    4 E2                     9.62
166HO CG M         from
166HO2CG EL2C=2.8 15, EL3C=4.5 24 (1967MO05) one obtains mult=E2(+M1),
166HO3CG MR>1.6. The level scheme requires DJ=2. E1+M2 would require
166HO4CG MR>1.2 and thus is excluded by RUL.
166HO CG           OTHER: EG=72.89 7, IG=0.27 5 ('Budapest data', 2007CHZX).
166HO  G 257.81    2 0.26    4 M2                     0.844
166HO3 G EKC=0.5 3 (1967MO05)
166HO CG           OTHER: EG=257.54 12, IG=0.29 6 ('Budapest data', 2007CHZX).
-----------
166HO  L 377.806    4 6-                                                   A
166HO  G 48.0315   7 0.17    3
166HO  G 197.339   8 0.32    5 (E2)                   0.255                  C
166HO3 G EKC=0.26 17 (1967MO05)
166HO CG           OTHER: EG=197.58 5, IG=0.55 5 ('Budapest data', 2007CHZX);
166HO2CG PROBABLY A 197.7G+197.3G+197.1G UNRESOLVED MULTIPLET.
166HO  L 379.547    4 6+                                                   D
166HO  G 84.468    100.13    3                                             P
166HO CG           OTHER EG: 84.68 7, IG=0.229 26 ('Budapest data', 2007CHZX);
166HO2CG POSSIBLY FOR UNRESOLVED DOUBLET.
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25

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166HO CG            PLACEMENT FROM 348 LEVEL REJECTED IN 2000PR03.
166HO  G 115.759    3 0.34     5                                          P
166HO  G 373.47     7 0.45     7                                          P
166HO  L 416.086     6 2-                  0.2 NS     LE                   V
166HOF L FLAG=h
-----------------
166HO  L 2180.0     3
166HO  L 2182.92    22
166HO  L 2193.20    15
166HO  L 6243.714    8 3-,4-                                              S
166HOF L FLAG=PQ
166HO  G 4050.46    150.097    6
166HO CG            OTHER: EG=4049.4 5, IG=0.193 23 ('Budapest data', 2007CHZX).
166HO  G 4060.74    220.037    3
166HO  G 4063.66    250.029    3
---------
166HO  G 6052.66    3 0.374    20
166HO CG            OTHER: EG=6052.31 22 IG=0.30 3 ('Budapest data', 2007CHZX).
166HO  G 6063.21    160.014    1
166HO  G 6072.46    4 0.063    3
166HO CG            OTHER: EG=6072.7 4, IG=0.047 13 ('Budapest data', 2007CHZX).
166HO  G 6189.33    190.006    1
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^{169}Tm(n,γ) E = thermal: two-photon cascades

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170TM     169TM(N,G) E=THERMAL: G COIN  1996VA23,1996HO12
170TM  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 96,611 (2002)$CUT=15-Aug-2002$
170TM C  Others: 2001VA11 (level density and strength function deductions from
170TM2C  two-photon cascade data), 1999BO14.
170TM C  This dataset contains (N,G) E=thermal data obtained from measurements
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26

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170TM2C  of two-photon cascades only; for all other (N,G) E=thermal data,
170TM3C  please see the (N,G) E=0-136 EV dataset.
170TM C  1996VA23: EN=thermal; GELI and HPGe detectors, FWHM=3-4 KEV at E=1332,
170TM2C  time resolution 10-12 NS; measured EG, (high-energy G)-(low-energy G)
170TM3C  coin, I(GG coin) for two-photon cascades from capture state.
170TM C  1996VA23 and 1996HO12 have several authors in common and report on
170TM2C  the same two-photon cascade experiment. Apparently 1996HO12 present
170TM3C  only a subset of the data reported in 1996VA23; however, both EG and
170TM4C  IG data differ slightly from one paper to the other. The order in
170TM5C  which these papers were submitted for publication is unclear, so the
170TM6C  evaluator has chosen to present the data from the much more extensive
170TM7C  listing in 1996VA23. The differences between the two sets of data
170TM8C  are almost never of statistical significance.
170TM CG RI        1996VA23 report (high-energy G)-(low-energy G) coincidence
170TM2CG photon intensities, normalized so the area of the experimental
170TM3CG distribution in the interval 520<EG<(E(cascade)-520) is 100% for each
170TM4CG two-photon energy-sum gated spectrum. Data were reported for 14 strong
170TM5CG energy sums, corresponding to two-photon cascades terminating at
170TM6CG the GS and the 39, 115, 150, 183, 204, 220, 237, 271, 350, 447, 590,
170TM7CG 604 and 638?+649+650 levels. For completeness, these sum spectrum
170TM8CG intensities are shown here under the label I{-|g1|g2} opposite
170TM9CG the relevant G{-2} energy. Note that, due to experimental conditions,
170TMACG these intensities are only lower limits if EG<520 for one of the
170TMBCG coincident gammas (1996HO12); this affects a number of transitions
170TMCCG deexciting levels with E LE 760.
170TM CG RI$LABEL=I{-|g1|g2}
170TM CL E         From 1996VA23. In many cases, E(level) values based on a
170TM2CL least-squares adjustment of EG have significantly smaller
170TM3CL and apparently less realistic uncertainties; also, it should be noted
170TM4CL that an extraordinarily large number of EG data differ
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27

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170TM5CL by at least 4|s from the least-squares adjusted values.
170TM CG E         From 1996VA23. EG values for many secondary gammas differ
170TM2CG significantly (GE 4|s) from the least-squares adjusted values; such
170TM3CG cases are noted. The EG values given for the primary gammas are the
170TM4CG average of all values listed in 1996VA23. The authors do not give
170TM5CG uncertainties for these; it should be noted, however, that in the
170TM6CG worst cases, there can be a 6 KEV spread in the values averaged.
170TM7CG Data for unplaced gammas are not included here; please see 1996VA23
170TM8CG for those (AP 80 GAMMA pairs).
170TM CG E(A),RI(A)$From 1996HO12. Not reported in 1996VA23.
170TM CL E(B)      Rounded-off value from Adopted Levels.
170TM CG E(C)      1996VA23 place a 428.6G and a 532.6G from an otherwise
170TM2CG unknown E=647.9 6 level, but 1996HO12 place them from the adopted
170TM3CG 648.75 level which is known to be deexcited by a 429.0G.
170TM CG E(D)      Value differs by at least 4|s from that expected based on
170TM2CG least-squares adjusted level energies.
170TM3CG Possibly the precision of EG data has been overestimated
170TM4CG for some secondary transitions. Almost certainly, some closely-spaced
170TM5CG intermediate or final levels involved in the cascades have not been
170TM6CG resolved; for example, a large number of transitions to E(level) AP 640
170TM7CG KEV may be unresolved doublets comprised of G's feeding the adopted
170TM8CG 648.7 and 637.9 levels.
170TM CL E(E)      Added by evaluator. Although 1996VA23 do not include this
170TM2CL level and the spread of EG(primary) values suggests that only the
170TM3CL 648.6 level is significantly populated by the relevant primary G,
170TM4CL many G's which feed a level in the vicinity of 640 KEV have EG values
170TM5CL intermediate between those expected for transitions to the 648.6 and
170TM6CL 637.9 levels.
170TM CL E(Y)      From SN (1995AU04).
170TM CL J(Z)      L=0 neutron capture by JPI=1/2+ target.
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28

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170TM PN                                                              C6
170TM2PN I{-|g1|g2}
170TM  L 0.0
170TM  L 38.7                                                         B
170TM  L 114.5                                                        B
170TM  L 149.7                                                        B
170TM  L 183.20                                                       B
170TM  L 204.4                                                        B
170TM  L 219.7                                                        B
170TM  L 237.2                                                        B
170TM  L 270.5                                                        B
170TM  L 349.7                                                        B
170TM  L 447.1                                                        B
170TM  L 589.7      6
170TM  G  352.7     2 2.6     4
170TM  G  369.7     4 1.4     3
170TM  G  439.1     3 1.7     4
170TM  G  476.1     4 0.7     2
170TM CG E          presumably the 475G from GG coin in fig. 5 of 1996HO12.
170TM  G  551.4     1 8.0     5
170TM  G  589.7     1 6.8     4
---------
170TM  L 6593.3    11 0+,1+                                                 S
170TM3 L FLAG=YZ
170TM  G  6004.1
170TM DG            FL=589.7
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^{169}Tm(n,γ) E = 2, 24 keV

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170TM    169TM(N,G) E=2, 24 KEV        1996HO12
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29

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170TM  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 96,611 (2002)$CUT=15-Aug-2002$
170TM C  Target JPI=1/2+.
170TM C  1996HO12: three-crystal pair spectrometer, FWHM=5.5 KEV at 6.5 MEV;
170TM2C  oxide target; measured EG, IG for average resonance capture primary
170TM3C  transitions; deduced ^S(n)=6591.8 12 (cf. 6593.3 11 in 1995AU04).
170TM4C  Supersedes 1994HOZZ.
170TM CL E          Authors' best values based on both 2-KEV and 24-KEV data,
170TM2CL except as noted. EG data for primary transitions
170TM3CL are based on a chlorine calibration, and DE
170TM4CL ranges between 0.1 KEV and 1.6 KEV for these. E(level) values from
170TM5CL these data deviate by at most 1.2 KEV from adopted values for E<1160.
170TM6CL The evaluator, therefore, assigns DE=1.5 KEV to E(level) values which
170TM7CL have been adopted from this data set. Note that the level indicated
170TM8CL at 1.2 KEV is, in reality, the ground state.
170TM CL J          J LE 2 is expected for all levels fed by primary gammas
170TM2CL in this reaction. PI is based on reduced intensity of primary G
170TM3CL feeding level (PI=+ states are less strongly fed).
170TM CG RI$LABEL=IG/(EG{+5})
170TM CG RI         Reduced photon intensity (i.e., IG/(EG{+5})) for EN=2 KEV.
170TM CG TI$LABEL=IG(2)/IG(24)
170TM CG TI         G intensity for E(n)=2 KEV divided by G intensity for
170TM2CG E(n)=24 KEV.
170TM CG E(A)       Doublet.
170TM CL E(A)       Based on EG for 14 strong primary transitions in the 2-KEV
170TM2CL measurements and the knowledge that the effective neutron energy
170TM3CL would be AP 1.2 KEV (presumably as a result of moderation of the
170TM4CL neutrons in the target assembly), 1996HO12 deduce SN=6591.8 9 (cf.
170TM5CL 6593.1 11 in 1995AU04). The evaluator, therefore, estimates
170TM5CL E=(6591.8+1.2) for the capture state in the 2-KEV measurement and
170TM6CL assigns an uncertainty of 2 KEV. Since the effective neutron energy
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170TM7CL for the 24-KEV measurement is not known, the evaluator estimates
170TM8CL the capture state(s) energy from EG for the primary to the GS and
170TM9CL again assigns an uncertainty of 2 KEV.
170TM CL J(J)       Reduced IG(E(n)=2 KEV) for primary G to this level favors
170TM2CL PI=+, but DRI is unstated.
170TM  N
170TM PN                                                                C5
170TM2PN REDUCED INTENSITY, IG/EG{+5} FOR EN=2 KEV
170TM  L 1.2         4 (LE 2-)
170TM  L 39.6        1 (LE 2-)
170TM  L 150.0       2 (LE 2-)
170TM  L 203.8       2 (LE 2-)
170TM  L 219.9       2 (LE 2-)
170TM  L 237.3       1 (LE 2-)
170TM  L 589.7       1 (LE 2-)
170TM  L 6593        2                                                    S
170TMF L FLAG=A
170TM CL E          resonance capture state(s) for average n energy of 2 KEV.
170TM  G 6012.4      3                                          0.17      2
170TM  G 6026.8      1                                          0.46      7
170TM  G 6379.2      1                                          0.39      6
170TM  G 6397.1      1                                          0.25      4
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^{169}Tm(d,p)

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170TM    169TM(D,P)                    1996HO12,1966SH03,1966RY01
170TM  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 96,611 (2002)$CUT=15-Aug-2002$
170TM C  Target JPI=1/2+.
170TM C  1996HO12: E=12, 20, 26 MEV; |q(lab)=20|', 25|', 30|', 40|',
170TM2C  45|'; magnetic spectrograph; measured E(p), d|s/d|W(|q).
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170TM4C  Supersedes 1995HOZZ.
170TM C  1966SH03: E=12 MEV; measured |s(E(p),|q) in 5 DEG steps from
170TM2C  10|' to 45|' and 10|' steps from 45|' to 135|', magnetic
170TM3C  spectrograph with nuclear emulsions, FWHM|?12 KEV; DWBA analysis.
170TM C  1966RY01: E=11, 12 MEV; narrow range magnetic spectrograph,
170TM2C  FWHM AP 18 KEV; measured |s(E(p)), |q=90|' for
170TM3C  11 MEV, |q=90, 60 DEG for 12 MEV.
170TM CL E          From 1996HO12. Other data are given in comment on relevant
170TM2CL level. (For data from 1966SH03, DE for E LE 270 is statistical
170TM2CL uncertainty only, and reasonable DE for E>350 is 1 to 4 KEV. E from
170TM3CL 1966RY01 is quoted relative to E=0 for g.s.)
170TM CL L          From DWBA analysis of |s(|q) (1966SH03).
170TM CL S$LABEL=d|s/d|W(30 DEG)
170TM CL S          d|s/d|W(30|') in |mb/sr for E(d)=20 MeV (1996HO12). See
170TM2CL 1996HO12 for additional cross section data for E(d)=12 MeV (45|'),
170TM3CL E(d)=20 MeV (20|', 40|') and E(d)=26 MeV (25|').
170TM CL BAND(A)    KPI=0- BAND.
170TM2CL Configuration=(|p 1/2[411])-(|n 1/2[521])
170TM CL BAND(B)    KPI=1- GS BAND.
170TM2CL Configuration=(|p 1/2[411])+(|n 1/2[521])
170TM CL BAND(E)    KPI=2- BAND.
170TM2CL Configuration=(|p 1/2[411])-(|n 5/2[512])
170TM CL BAND(J)    KPI=3- BAND.
170TM2CL Configuration=(|p 1/2[411])+(|n 5/2[512])
170TM CL BAND(O)    KPI=1- BAND.
170TM2CL Configuration=(|p 3/2[411]-(|n 5/2[512]) plus (|p 1/2[411])+(|n
170TM3CL 1/2[510]) plus ((|p 1/2[411])-(|n 5/2[512])-|g vibration).
--------------------------
170TM CL BAND(b)    KPI=4+ BAND.
170TM2CL Configuration=(|p 1/2[411])+(|n 7/2[633])
```

Relabel 'S' field


```
170TM  L -0.03     18                                    1        112       3 B
170TM CL           Ground state. Other E: 2.5 15 (1966SH03).
170TM  L 38.8       3                                    1        17.1      15B
170TM CL           Other E: 39.5 6 (1966SH03); 38 3 (1966RY01).
170TM  L 114.30    19                                    3        29.9      17B
170TM CL           Other E: 115.0 6 (1966SH03); 115 3 (1966RY01).
170TM  L 149.80     9                                    1        71        3 A
170TM CL           Other E: 149.6 3 (1966SH03); 153 3 (1966RY01).
170TM  L 183.21    15                                    3        27.0      16B
170TM CL           Other E: 183.3 6 (1966SH03); 185 3 (1966RY01).
170TM  L 204.73    21                                    14.0      12E
170TM CL           Other E: 208.2 9 (1966SH03; 45|' spectrum only).
170TM  L 219.68    12                                    29.6      20A
170TM CL           Other E: 218.2 12 (1966SH03); 226 6 (1966RY01).
```

↑ No Jπ ↑ Record L ↑ No S, so give dσ/dω

^{170}Er(^{3}He,t)

```
170TM    170ER(3HE,T)                  1983JA03
170TM  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 96,611 (2002)$CUT=15-Aug-2002$
170TM C  E(3HE)=60.5 MEV; magnetic spectrograph, 96.1% 170ER target,
170TM2C  |q(lab)=0|'; measured reaction Q and |G for IAS.
170TM  L 15492      7 0+                104 KEV   8
170TM CL E          from reaction Q of -15825 KEV 6.
170TM CL J          isobaric analog of 170ER G.S.
```

^{92}Mo(d,d′), (pol d,d)

```
92MO    92MO(D,D'), (POL D,D)          1978WA11,1966KI04         NDS00    200101
92MO  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 91, 423 (2000)$CUT=7-Nov-2000$
```

```
92MO C  Others: 1987TA15, 1981BI09, 1975BA41.
92MO C  Enriched targets.
92MO C  1966KI04: E(d)=15 MEV; FWHM=40-50 KEV; |q(lab)=40|', 60|'.
92MO C  1975BA41: E(POL D)=15 MEV; measured |s(|q), vector and tensor
92MO2C  analyzing powers for 0,1540,2850 levels; DWBA analysis; deduced |b{-L}.
92MO C  1978WA11: E(d)=21.5 MEV; FWHM|?80 KEV; |q(lab)=20|'-150|'.
92MO C  1981BI09: E(POL D)=12.0 MEV; |q(c.m.)|?30|'-160|';
92MO2C  iT{-11}(|q).
92MO C  1987TA15: E(POL D)=22 MEV; |q(lab)=30|'-170|'; measured vector
92MO2C  and tensor analyzing powers. Elastic scattering only.
92MO CL E       From 1978WA11 if DE specified, from 1966KI04
92MO2CL otherwise.
92MO CL J       From adopted levels.
92MO CL S       |b{-L} from coupled-channels analysis of |s(|q) (1978WA11).
92MO CL S$LABEL=BL
92MO CL E(A)    This peak would mask that for the 0+ 2520 level, if present
92MO2CL (1978WA11).
92MO  L 0          0+
92MO  L 1510    10 2+                                          0.083
92MO  L 2300       4+
92MO  L 2527    10 5-                                                    A
92MO  L 2850    10 3-                                          0.124
```

^{171}Yb(t,α)

```
170TM    171YB(T,A)                    1981DE29
170TM  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 96,611 (2002)$CUT=15-Aug-2002$
170TM C  Target JPI=1/2-.
170TM C  E=17 MEV; 88.2% 171YB target, FWHM|?16 KEV, Q3D spectrometer;
```

34

```
170TM2C  measured EA and |s(|q) in 5|' steps from 15|' to 50|';
170TM3C  DWBA analysis of |s(|q); assigned Nilsson configurations.
170TM CL J       Authors' values, based on |s(|q), and on band
170TM2CL configuration analysis. Note that several of these differ from
170TM3CL values in Adopted Levels.
170TM CL L       Based on comparison of measured |s(|q) with DWBA
170TM2CL calculations (normalization factor=5.5).
170TM CL S$LABEL=d|s/d|W(30 DEG)
170TM CL S       d|s/d|W(30|') in |mb/sr; uncertainties not stated by
170TM2CL authors.
170TM CL BAND(A)   KPI=0- BAND.
170TM2CL Configuration=((|p 1/2[411])-(|n 1/2[521])).
170TM CL BAND(B)   KPI=1- GS BAND.
170TM2CL Configuration=((|p 1/2[411])+(|n 1/2[521])).
170TM CL BAND(C)   KPI=1- BAND.
170TM2CL Configuration=((|p 3/2[411])-(|n 1/2[521])).
170TM CL BAND(E)   KPI=2- BAND.
170TM2CL Configuration=((|p 1/2[411])-(|n 5/2[512])). The authors note that this
170TM3CL configuration can not be excited in (T,A) via a one-step mechanism;
170TM4CL the admixture of configuration=((|p 5/2[413])-(|n 1/2[521])) required
170TM5CL for consistency with experiment is much larger than predicted by
170TM6CL authors' residual interaction mixing calculations.
170TM CL BAND(F)   KPI=2- BAND.
170TM2CL Configuration=((|p 5/2[402])-(|n 1/2[521])).
170TM3CL Level's excitation is stronger than expected for this configuration.
---------------------
170TM CL BAND(J)   KPI=3- BAND.
170TM2CL Configuration=((|p 1/2[411])+(|n 5/2[512])). The authors note that this
170TM3CL configuration can not be excited in (T,A) via a one-step mechanism;
170TM4CL the admixture of configuration=((|p 5/2[413])+(|n 1/2[521])) required
```

35

```
170TM5CL for consistency with experiment is much larger than predicted by
170TM6CL authors' residual interaction mixing calculations.
----------------------
170TM CL BAND(Y)    KPI=1- BAND. GAMMA-VIBRATION BUILT ON KPI=1- GS BAND.
170TM  L 0.0           1-                                      6.9         B
170TM  L 40.0       18 2-                                      44.2        B
170TM  L 114.7      18 3-                                      4.6         B
170TM  L 148         4 0-                                      2.2         A
170TM  L 182         3 4-                                      5.1         B
```

^{170}Er(γ,γ′), (γ, pol γ′) (resonance fluorescence)

36

1996Ma18 – Maser *et al.*

TABLE III. Results for the reaction ^{170}Er(γ,γ'). The measured excitation energies E_x, the integrate scattering cross sections I_s, and decay branching ratios R_{expt} are summarized. Ground-state transition width Γ_0, spins J, and K quantum numbers were deduced. Quoted parities are taken from Refs. [10,11]. Th quoted reduced transition probabilities $B(M1)\uparrow$ and $B(E1)\uparrow$, given in the table, were calculated assumin negative parities for $K=0$ levels and positive parities for $K=1$ levels, respectively. For levels which do nc exhibit a decay branching to the first 2^+ state reduced transition probabilities are alternatively given for bot parities.

E_x [keV]	I_s [eV b]	Γ_0 [meV]	R_{expt}	K	Spin J^π	$B(M1)\uparrow$ [μ_N^2]	$B(E1)\uparrow$ [10^{-3} e^2 fm^2]
1825	41.7±6.5	31.8±5.5	1.87±0.09	0	1^-	-	14.99±2.59
2133	9.5±1.2	3.8±0.9	-	-	1	0.100±0.025	1.11±0.27
2701	13.4±1.7	12.5±2.5	0.52±0.08	1	1	0.164±0.033	-
2789	38.5±2.2	41.3±3.9	0.64±0.04	(1)	1^+	0.493±0.047	-
2897	6.4±1.3	4.7±1.4	-	-	1	0.050±0.015	0.55±0.16
2930	4.5±0.9	8.4±2.7	1.68±0.39	0	1	-	0.96±0.31
2938	7.6±1.1	9.1±2.6	0.65±0.15	1	1	0.093±0.027	-
3019	17.4±1.4	13.8±3.1	-	-	1	0.130±0.029	1.43±0.32

$\Gamma\gamma_0^2/\Gamma = 0.26\ E_\gamma^2\ I_s / (2J+1)$ meV $\Gamma\gamma_1/\Gamma\gamma_0 = R_{expt}\ (E\gamma_1/E\gamma_0)^3$

$\Gamma = \Gamma\gamma_0^2/\Gamma \times (1+ \Gamma\gamma_1/\Gamma\gamma_0)^2$ if $\Gamma = \Gamma\gamma_0+\Gamma\gamma_1$; $T_{1/2}$ (ps) = 0.4561 / Γ (meV)

37

```
170ER    170ER(G,G'), (G,POL G')       1996MA18,1976ME04
170ER  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 96,611 (2002)$CUT=15-Aug-2002$
170ER C  Others: 1973ME17, 1991ZI01.
170ER C  1996MA18: bremsstrahlung endpoint energy=3.80 MEV; 96.9% 170ER
170ER2C  oxide target; HPGe detector, 3 Ge detectors, true-coaxial HPGe
170ER3C  COMPTON polarimeter with 8-crystal ^BGO COMPTON shield; |q=95 DEG,
170ER4C  127 DEG; measured EG, integrated cross section, G anisotropy, G
170ER5C  polarization; deduced WIDTH0, |G{-|g0}{+2}/|G, |G{-|g1}/|G{-|g0},
170ER6C  JPI, K.
170ER C  1991ZI01: measured 1824G(|q), |G{-|g0}{+2}/|G; deduced |G{-|g0}.
170ER C  1976ME04: E(e)=1.6-4.2 MEV bremsstrahlung; 96.9% 170ER target;
170ER2C  measured |s(E; EG,|q), |q=98|' and 127|', and G linear polarization.
170ER C  1973ME17: E(e)=1.93 MEV bremsstrahlung; 96.9% 170ER target; measured
170ER2C  E|g', G(|q) (|q=98 DEG and 127 DEG), G linear polarization.
170ER CL          Values of K, deduced by 1996MA18 from measured
170ER2CL |G{-|g1}/|G{-|g0}, are given in comments on the relevant levels.
170ER CL E        From 1996MA18 if DE unstated, from 1976ME04 if DE=2.
170ER CL J        J from G(|q) and PI from G linear polarization, except
170ER2CL as noted; only states having J=1 or 2 can be excited (1976ME04).
170ER CL T        Deduced from |G{-|g0}{+2}/|G and adopted G-ray branching
170ER2CL assuming |G=|G{-|g0}+|G{-|g1}; consequently, these represent upper
170ER3CL limits for any level which has significant branching to states other
170ER4CL than the ground or first excited states.
170ER CL S$LABEL=|G{-|g0}{+2}/|G (meV)
170ER CL S        From 1996MA18, except as noted. Calculated by evaluator
170ER2CL from integrated cross section data of 1996MA18 assuming J indicated,
170ER3CL unless indicated otherwise.
170ER CG RI       Relative branching, based on measured |G{-|g1}/|G{-|g0}.
170ER2CG Calculated by evaluator from R=(|G{-|g1}/|G{-|g0})(E{-|g0}/E{-|g1}){+3}
170ER3CG in 1996MA18, except as noted.
```



```
170ER CG E        From E(level) difference, except for 1824G (from 1991ZI01).
170ER2CG Presumably DE{-|g} LE 2 KEV for transitions from levels given in
170ER3CG 1976ME04 since authors indicate |DE(level)=2 KEV. 1996MA18 do not
170ER4CG state uncertainty, but their level energies are within 1 KEV of
170ER5CG those from 1976ME04 for levels reported in both studies.
170ER CG M        DJ from G anisotropy (1996MA18), except as noted. DPI
170ER2CG from linear polarization (1976ME04).
170ER CG RI(A)    Weak
170ER CL E(A),J(A)$From Adopted Levels.
170ER CL E(B),J(B)$From 1973ME17.
170ER CG RI(B),M(B)$From 1973ME17.
170ER CL T(D)     From weighted average of |G=0.080 EV 7 (from adopted
170ER2CL |G{-|g0}/|G and (|G{-|g0}){+2}/|G=11.6 meV 10 (1973ME17,1996MA18))
170ER3CL and 0.094 EV 7 (from |G{-|g1}/|G{-|g0}=1.64 7 and |G{-|g0}=35.8 meV 24
170ER4CL (1991ZI01)).
170ER PN                                                              6
170ER  G  3059
170ER CG          (|G{-|g0}){+2}/|G=5 meV (1976ME04) if J=1 to GS transition.
170ER  G  3157
170ER CG          (|G{-|g0}){+2}/|G=14 meV if J=1 to GS transition; however,
170ER2CG this G probably includes a contribution from the 3238 to 79 transition.
170ER  G  3237
170ER CG          (|G{-|g0}){+2}/|G=18 meV if J=1 to GS transition; however,
170ER2CG probable doublet feeding GS and 79 level (1976ME04). Too strong for
170ER3CG known (1996MA18) transition to GS alone.
170ER  G  3317
170ER CG          (|G{-|g0}){+2}/|G=11 meV if J=1 to GS transition; nominated
170ER2CG as a GS transition because a 79 KEV lower EG(=3237) line is also
170ER3CG present (1976ME04).
170ER  G  3564
```

```
170ER CG           (|G{-|g0}){+2}/|G=24 meV (1976ME04) if J=1 to GS transition.
170ER  G  3619
170ER CG           (|G{-|g0}){+2}/|G=90 meV if J=1 to GS transition; however,
170ER2CG probable doublet feeding 0 and 79 levels (1976ME04). Presumably
170ER3CG includes 3623 to GS and 3695 to 79 transitions reported in 1996MA18.
-----------------
170ER  L 0.0          0+                                                    A
170ER  L 78.6         2+                                                    A
170ER  L 1824        1 1-              5.7 FS    5             11.6      10B
170ER3 L FLAG=D
170ER CL           (|G{-|g0}){+2}/|G: weighted average of 11.4 meV 11 (1976ME04)
170ER2CL and 12.0 meV 19 (1996MA18).
170ER CL           K=0 (1996MA18).
170ER  G 1745         163     5
170ER CG E         from 1973ME17.
170ER CG           Branching: from weighted average of |G{-|g1}/|G{-|g0}=1.64 8
170ER2CG (1996MA18), 1.63 7 (1976ME04).
170ER  G 1824        1 100       E1                                         B
170ER CG E         from 1991ZI01.
170ER  L 1973        2                                        0.6       5
170ER CL           (|G{-|g0}){+2}/|G: from 1976ME04, assuming J=1.
170ER  G 1973                                                             A
170ER  L 2039        2  1,2            0.10 PS   3             1.2       3
170ER CL           ^T{-1/2} and (|G{-|g0}){+2}/|G: if J=1 (1976ME04).
170ER  G 1960         93     10
170ER CG           Branching: from Adopted Gammas.
170ER  G 2039         100    10
170ER  L 2133        2 1              62 FS     9             3.8       4
170ER CL           (|G{-|g0}){+2}/|G: weighted average of 3.7 meV 5 (1976ME04)
170ER2CL and 3.8 meV 5 (1996MA18).
```

From Γ_1/Γ_0

From W(θ) and lin. pol.

40

```
170ER  G 2054          39     10
170ER CG           Branching: from |G{-|g1}/|G{-|g0} in 1976ME04.
170ER  G 2133          100       D
170ER  L 2685        2                                        0.1       9    ?
170ER CL           (|G{-|g0}){+2}/|G: assuming J=1 (1976ME04).
170ER  G 2685                                                           A  ?
170ER  L 2701        2 1              23 FS     3             9.1       12
170ER CL           (|G{-|g0}){+2}/|G: weighted average of 11.5 meV 22 (1976ME04)
170ER2CL and 8.5 meV 11 (1996MA18).
170ER CL           K=1 (1996MA18).
170ER  G 2622          48      6
170ER CG           Branching: from weighted average of |G{-|g1}/|G{-|g0}=0.48 7
170ER2CG (1996MA18), 0.49 13 (1976ME04).
```

^{58}Fe(p,p′)

```
59CO    58FE(P,P')                    1971LI14
59CO  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 95,215 (2002)$CUT=8-Feb-2002$
59CO C  Others: 1975BR29 (58FE(P,P'G)), 1972PE23.
59CO C  1971LI14: EP=2.0-3.1 MEV, but data not analyzed beyond 2.65 MEV;
59CO2C  measured SIGMA(EP,THETA), THETA=90 DEG, 120 DEG,
59CO3C  135 DEG, and 160 DEG, beam resolution 300-400 EV.
59CO C  See 1972PE23 for correlations between fine structure widths of 14
59CO2C  59FE(GS) analog fragments in (P,P), (P,P') and (P,G), EP AP 2210-2300.
59CO CL           Data are from 1971LI14. The fragmented analogs of
59CO2CL 59FE(GS) (JPI=3/2-, 14 fragments) and 59FE(287) (JPI=1/2-, 10
59CO3CL fragments) have their centroids at EP(lab)=2220 5 and 2512 5,
59CO4CL respectively. A third analog near EP=2.98 MEV was identified but not
59CO5CL analyzed. Since EP is well below the COULOMB barrier, only s-, p- and
59CO6CL d-wave resonances are expected.
```

41

```
59CO CL E          Calculated as EP(C.M.)+SP, assuming SP=7363.7 6 (1995AU04).
59CO CL J          From multilevel, multichannel R-matrix analysis of
59CO2CL SIGMA(EP,THETA).
59CO CL S          |G{-p0} in EV (1971LI14). |G{-p'}(811) was neglected in
59CO2CL analysis by 1971LI14 and, typically, WIDTHG<<|G{-p0} (see (P,G)), so
59CO3CL |G{-p0} AP WIDTH. See 1972PE23 for additional |G{-p0} and |G{-p1}
59CO4CL data.
59CO CL L          Laboratory proton energy of resonance (1971LI14); DE AP 3
59CO2CL KEV (absolute), 0.2 KEV (relative). EP from 1972PE23, 1975BR29 AP 5 KEV
59CO3CL higher.
59CO CL L$LABEL=EP(LAB)
59CO CL S$LABEL=|G{-p0} EV
59CO CL E(A)       Possible 59FE(GS) analog fragment (1971LI14). Analog energy
59CO2CL estimated to be 9545 5 (1971LI14).
59CO CL E(B)       Possible 59FE(287 level) analog fragment (1971LI14). Analog
59CO2CL energy estimated to be 9835 5 (1971LI14).
59CO  L 9465.3     30(3/2-)                              2137.8  10          5A
59CO  L 9491.3     30 1/2+                               2164.3  30          10
59CO  L 9513.7     30(3/2-)                              2187.1  30          10A
59CO  L 9523.1     30 1/2+                               2196.6  15           8
59CO  L 9525.4     30 1/2+                               2199.0  15           8
59CO  L 9534.9     30(3/2-)                              2208.6  30          10A
```

↑ $S_p + E_{res}$(c.m.) $E_p$res (lab) ↑ ↑ Γ_{p0}

^{92}Zr(p,p′), (pol p,p) IAR

```
93NB     92ZR(P,P'), (POL P,P) IAR     1970KE02                    97NDS    199703
93NB  H TYP=FUL$AUT=CORAL M. BAGLIN$CIT=NDS 80, 1 (1997)$CUT=1-Nov-1996$
```

42

```
93NB C  Includes 92ZR(P,P'G) and 92ZR(P,N) IAR studies.
93NB C  Others: 1965Ro23, 1968Th07, 1969El08, 1969Wi15, 1974Cu04.
93NB C  1974Cu04: (P,P'G); EP=4.85-5.25 MEV, |q(lab)=30 DEG, 45 DEG, 90 DEG;
93NB2C  measured angular correlation through 92ZR(2+, 934 level) and
93NB3C  93NB(4+, 1494 level) in vicinity of analog of 93ZR(GS).
93NB C  1970Ke02: (P,P'); EP AP 5.8 MEV to 10.0 MEV, 95% 92ZR target, cooled
93NB2C  SILI detectors, |q(lab)=60 DEG-170 DEG (10 DEG steps),
93NB3C  FWHM AP 40 KEV; deduced E, WIDTH, partial WIDTHP for each IAS
93NB5C  from ^S-matrix analysis of excitation functions across IAS,
93NB6C  and L for scattered protons from p'(|q)
93NB7C  measured on resonance.
93NB C  1969Wi15: (POL P,P); E(pol p) AP 5.0-8.3 MEV, surface
93NB2C  barrier detectors, measured energy and angle dependence
93NB3C  of analyzing power for elastic scattering;
93NB4C  deduced E, JPI, WIDTH, and WIDTHP0 for IAS.
93NB C  1969El08: (POL P,P); E(pol p)=4.65-8.65 MEV; deduced
93NB2C  E, WIDTH, WIDTHP0, determined JPI for IAS.
93NB C  1965Ro23: (P,P), (P,N); EP AP 5.75-6.25 MEV, 1-5 KEV thick targets;
93NB2C  measured excit across 93ZR(947 level) analog; deduced
93NB3C  |G{-p0} and WIDTH (see also 1968Th07).
93NB C  Partial WIDTHP (1970Ke02) for protons feeding GS, 934, 1382, 1847
93NB2C  and/or 2067 levels of 92ZR are given in comments. |G{-p0} deduced by
93NB3C  1969Wi15 and 1969El08 agree with data of 1970Ke02 within better than a
93NBxC  factor of 2.
93NB CL E          From SP=6043.2 16 (1995Au04) and EP for resonance (1970Ke02).
93NB2CL DE not stated; agreement with EP from 1969Wi15 is excellent.
93NB CL J          From L and analyzing power data of 1969Wi15
93NB CL J(B)       From L and analyzing power data of 1969El08.
93NB CL T          WIDTH from 1970Ke02; weighted average of all determinations.
93NB2CL Consistent with data of 1969El08 and 1969Wi15.
```

43

```
93NB CL L          From 1970Ke02.
93NB CL S          EP(lab) for resonance (1970Ke02); DE not stated by authors.
93NB2CL 60 KEV correction advised by authors has been applied, thereby
93NB3CL producing excellent agreement with EP from 1969Wi15.
93NB CL S$LABEL=EP(LAB)
93NB CL J(A)       L=0 from interference pattern in excitation functions
93NB2CL in (P,P) (1970Ke02).
93NB  L 11059        5/2+              13 KEV    5              5070
93NB CL            WIDTHP0=4 KEV.
93NB2CL All data from 1969Wi15.
93NB CL            Analog of 93ZR(GS).
93NB  L 11981      5 1/2+              90 KEV    9     0        6000        A
93NB CL E          from EP=6002.5 50 from 1968Th07.
93NB CL            Other WIDTH: 80 KEV 6 (1968Th07).
93NB CL            |G{-p0}=45 KEV 5 (1970Ke02), 37 KEV 3 (1968Th07).
93NB CL            Analog of 93ZR(947 level).
93NB  L 12503        3/2+              38 KEV    3     2        6530
93NB CL            |G{-p0}=8.0 KEV 8; |G{-p1}=5.2 KEV 15; |G{-p3}=0.72 KEV 2;
93NB2CL |G{-p4}=1.8 KEV 4.
93NB CL            Analog of 93ZR 1425 or 1450 level.
93NB  L 12993        1/2+              42 KEV    3     0        7025        A
93NB CL            WIDTHP0=10 KEV 1; |G{-p2}=3.5 KEV 11; |G{-p4}=0.45 KEV 22.
93NB CL            Possible analog of 93ZR 1909 or 1919 level.
```

ENSDF MODEL EXAMPLES: II

Adopted Levels, Gammas Datasets

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Workshop on Nuclear Structure and Decay Data: Theory and Evaluation, ICTP, Trieste, 28 Apr. - 9 May 2008

Adopted Dataset =

condensation of data from all Decay and Reaction datasets
(comprehensive and data readily traceable to source data sets)
+
New types of records, information:
Q
XREF
g.s. and isomer decay branching
Nuclear moments
Nuclear radius information
B(ML)W, B(EL)W
J^{π} arguments
+
New presentation of intensity data

Q-value data

```
169TM  Q -910       4 8033.6 15 5572.2 11 1199.7 13    2003AU03

 81ZR  Q -11.0E3    SY 11.0E3 15 4.56E3 24             2003AU03
 81ZR CQ            |DQ(|b)=1500 (2003Au03).
 81ZR CQ            Q(EC-P)=4.53E3 17 (2003AU03).

169IR  Q -9710      SY 11410  SY -621   24 6140   5    2003AU03,2005SC22
169IR CQ            |DQ(|b)=200, |DS(n)=150 (2003AU03).
169IR CQ            QA: from EA=5995 5, THE WEIGHTED AVERAGE OF EA=5993 4
169IR2CQ (2005SC22) AND EA=6005 8 (1999PO09), ASSUMING A GS to GS transition.
169IR3CQ QA=6151 8 IN 2003AU03 BASED ON THE DATUM FROM 1999PO09 ALONE.
```

Cross-Reference information

```
186W   XA186TA B- DECAY
186W   XB186RE EC DECAY (3.7183 D)
186W   XC186W(N,N'G)
186W   XDCOULOMB EXCITATION
186W   XE186W(G,G')
186W   XG186W(D,D'), (P,P'), (A,A')
186W   XH184W(T,P)
186W   XI186W(N,N')
186W   XJMUONIC ATOM
186W   XK186W(238U,238U'G): DELAYED G'S
186W  PN                                                          6
186W   L        0.0   0+              STABLE                     A
186W X L XREF=ABCDEGHIJK
```

```
186RE  L    417.792 8 (5)-                                                  D
186REX L XREF=BDE(*)
186RE CL J         M1+E2 149G to (4)-; no primary transitions to this level in
186RE2CL (N,G) E=2-110 EV; band assignment.
186RE  G    144.152 5     103LT [M1,E2]              1.4     4            @
?
186RE  G    148.994 5     10021 M1+E2     1.2    +8-4  1.21   16
186RE  G    271.47 10      40 6 [E2]                 0.1193
186RE  L    420.559 7 (4)+                                                  F
186REX L XREF=BE(*)
186RE CL J$M1+E2 107G to (3)+ 314; band assignment
186RE  G    106.550 4   100     M1+E2      1.7   +37-7 3.5     3

166HO  L 286.96    13 9-                                                   B
166HOX L XREF=ABD(287.5)F

 93ZR  L  2457.65  15 (1/2+,3/2)
 93ZRX L XREF=B(*)CE
 93ZR CL J         LOGF1UT<8.5 from 1/2-; G to 5/2+.
 93ZR2CL L(D,P)=2 for 2458 and/or 2474 level(s).
```

Nuclear Moments and Nuclear Radius Information:

```
 81BR  L      0.0    3/2-              STABLE                              Z
 81BRX L XREF=ABCDEFGHIKL
 81BR2 L MOMM1=+2.270562 4
 81BR CL MOMM1     From NMR (1989Ra17 FROM 1972BL07); relative to MOMM1(2H).
 81BR3 L MOME2=+0.2615 25
```

```
 81BR CL MOME2     FROM 2001BI17 (REASSESSMENT OF ATOMIC BEAM DATA FROM
 81BR2CL 1954KI11).  OTHERS: +0.266 4 (2004AL08) AND +0.254 6 (2000HA64),
 81BR3CL +0.276 4 (1989RA17 FROM 1978TA24; 1998SE09); ALL REASSESSMENTS OF
 81BR4CL ATOMIC BEAM DATA OF 1954KI11. Sternheimer CORRECTION INCLUDED.
 81BR4 L MOMM3=+0.129
 81BR CL MOMM3     Atomic beam magnetic resonance (1966Br03).
 81BR CL           <r{+2}>{+1/2}(CHARGE)=4.1599 21 (2004AN14).

169TM  L 8.41017   11 3/2+            4.09 NS   5                         A
169TMX L XREF=ABDEGHJ
169TM2 L MOMM1=+0.5148 48$ MOME2=-1.2 1
169TM CL MOMM1     MOSSBAUER (1989RA17); value relative to MOMM1=-0.2316 15
169TM2CL for 0.0 level.
169TM CL MOME2     MOSSBAUER (weighted average from 1989RA17); value
169TM2CL includes polarization correction.

169TM  L 316.14633 11 7/2+            659.9 NS  23                        B
169TMX L XREF=BDHJ
169TM2 L MOMM1=+0.156 8
169TM CL MOMM1     DPAC (1989RA17, FROM g=0.044 2 (1972NI03)).

 81KR  L      0.0    7/2+             2.29E+5 Y 11                        Z
 81KR2 L %EC=100$MOMM1=-0.908 2$MOME2=+0.644 4
 81KRX L XREF=ABCDEGHI
 81KR CL MOMM1     from collinear LASER fast-beam spectroscopy (1995Ke04);
 81KR3CL relative to 83KR standard, diamagnetic correction included.
 81KR3CL OTHER: -0.909 4 (1993Ca41; LASER RESONANCE FLUORESCENCE spectroscopy,
 81KR4CL 83KR standard).
 81KR CL MOME2     +0.629 13 (1993Ca41; LASER RESONANCE FLUORESCENCE
 81KR2CL spectroscopy, IF Q(83KR)=0.253 5 (1989RA17)), ADJUSTED BY 2001KE15
```

```
 81KR3CL TO +0.644 4 ASSUMING THEIR VALUE OF 0.259 1 FOR MOME2(83KR).
 81KR4CL Other: +0.64 7 (1995Ke04, COLLINEAR LASER FAST-BEAM SPECTROSCOPY);
 81KR5CL uncertainty includes uncertainty in electric-field gradient and
 81KR6CL the Sternheimer correction.
 81KR CL           DAVRSQ(86KR,81KR)=+0.099 (1995KE04); UNCERTAINTY 0.004
 81KR2CL (STATISTICAL ONLY), 0.018 (INCLUDING SYSTEMATIC UNCERTAINTIES), 0.034
 81KR3CL (TOTAL UNCERTAINTY).
 81KR CL           DAVRSQ(80KR,81KR)=-0.015 8 (1996LI25; STATISTICAL
 81KR2CL UNCERTAINTY ONLY).

169LU  L 0.0          7/2+            34.06 H   5                          a
169LUX L XREF=ABDE
169LU2 L %EC+%B+=100$MOMM1=2.295 4 (1998GE13)$MOME2=3.480 25 (1998GE13)
169LU CL          DAVRSQ(170,169)=-0.078 8 (1998GE13).
169LU CL MOMM1    From collinear laser spectroscopy. Other MOMM1: 2.297 13
169LU2CL from NMR on oriented nuclei (1996KO26).
169LU CL MOME2    From collinear laser spectroscopy. Other MOMM1: 3.42 12
169LU2CL from NMR on oriented nuclei (1996KO26).
169LU CL          <r{+2}>{+1/2}(CHARGE)=5.329 4 (2004AN14).
```

Decay branching

```
169IR  L 0.0          (1/2+)          0.353 S   4
169IR2 L %A=45 12$%EC+%B+=?$ %P=?
169IRX L XREF=AC
169IR CL          %A: WEIGHTED AVERAGE OF 42 15 (2005SC22) AND 50 18
(1999PO09)
169IR CL          %P: see 1983AL09 and 1984GR14 for discussions of
169IR2CL expected proton decay; SP (=-621 24 (2003AU03)) consistent with
169IR3CL predictions.

169W   L 0.0          (5/2-)          74 S      6                          A
169W X L XREF=A
169W 2 L %EC+%B+=100
169W  CL          %EC+%B+: only EC decay has been observed.
169W 2CL %A AP 0.01 can be estimated from extrapolation of
169W 3CL log T(ALPHA) versus log QA for 159W, 161W, 163W.

 81ZN  L 0            (5/2+)          0.29 S    5
 81ZN2 L %B-=100$%B-N=7.5 30
 81ZN CL           %B-N and T from 1991Kr15.  HOWEVER, FROM 80GA IN 81ZN
 81ZN2CL DECAY SPECTRUM, 2005KOZU ESTIMATE %B-N(81ZN)>10.

 81ZR  L 0.0          (3/2-)          5.5 S     4                          a
 81ZR2 L %EC+%B+=100$ %ECP=0.12 2 (1999HU05)
 81ZRX L XREF=A
 81ZRF L FLAG=YZ
 81ZR CL %ECP      FROM 1999HU05, BASED ON COMPARISON OF MEASURED
 81ZR2CL T WITH PARTIAL PROTON T CALCULATED USING STATISTICAL MODEL, ASSUMING
 81ZR3CL 24% 8 OF DELAYED PROTONS (1977FAZW, 1980HAZG; p-386G COIN) FEED
 81ZR4CL THE FIRST 2+ STATE OF 80SR.

169PT  L 0.0          (7/2-)          7.0 MS    2
169PT2 L %A AP 100
169PTX L XREF=ABC
169PT CL %A       1999SE14 REPORT THAT NUMBER OF 169PT DAUGHTER |a'S
CORRELATED
169PT2CL WITH 173HG DECAYS IS CONSISTENT WITH %A=100 FOR 169PT. THIS IS
169PT3CL CONSISTENT WITH gross |b decay theory PREDICTION OF A partial |b
```

```
169PT4CL half-life of AP 1 S (1973TA30) and MICROSCOPIC THEORY PREDICTION OF
169PT5CL 0.26 S (1997MO25), implying %EC+%B+ AP 0.7 AND 2.7, RESPECTIVELY.
169PT5CL Only |a DECAY has been observed for 169PT.
```

Reduced Transition Probabilities

Calculated by RULER in most cases

```
170TM  L  219.7060  6 (2)-              0.25 NS  3                          A
170TM2 L XREF=ABCDFHI
170TM CL J         220G to 1- g.s. and 105G to (3)- 115 are M1+E2.
170TM CL T         from BE2=0.085 10 in Coulomb excitation and adopted MR and
170TM2CL branching.
170TM  G 69.988    1  4.2     6 E2                     12.67
170TMB G BE2W=240 50
170TM  G 105.162   1  28.6    3M1+E2      0.4    3     2.66    5
170TMB G BM1W=0.0045 11$BE2W=30 +40-30
170TM  G 180.994   1  100     9 M1+E2     0.28   3     0.562   9
170TMB G BM1W=0.0033 6$BE2W=3.6 10
170TM  G 219.705    1 77.2    6 M1+E2     1.29   10    0.246   7
170TMB G BM1W=0.00058 10$BE2W=9.1 11
170TM CG           BE2W: from measured BE2.
```

RULER gives 9.1 *13*

```
192OS  L 1341.153  11 3-
192OSX L XREF=DEFGHILJKNR
192OSB L BE3UP=0.131 9 (1988BO08)
192OS CL           BE3UP: FROM (E,E').  OTHER VALUE: 0.37 4 FROM COULOMB
192OS2CL EXCITATION.
192OS CL J         E3 EXCITATION IN (E,E') AND COULOMB EXCITATION.
192OS2CL G-RAY BRANCHINGS TO 2+, 3+, AND 4+ LEVELS IN 192OS(P,P'G),
192OS2CL (D,D'G) FIT ALAGA RULE FOR E1.
```

```
192OS  G 271.594    8 98     10                                            M
192OS CG           OTHER RI: 58 4 AND 47 8 FROM (P,P'G), (D,D'G).
192OS  G 431.4      4 34      3
192OS  G 650.81    15 12.8   11
192OS CG           OTHER RI: 26 4 FROM (P,P'G), (D,D'G).
192OS  G 852.19     2 100     5
192OSL G FL=489.0602
192OS  G 1135.5     3 28.2   15
192OS  G 1341.15
S
```

```
168ER  L   1431.466 4        3-        41 PS                               E
168ERX L XREF=BD(*)EFGHLMO
168ER CL J         3-,4- from average resonance capture; E1 G to 2+.
168ER CL T         from 1987Me04 (see 168TM EC decay).
168ER  G    535.64221 0.35    6 [E1]                  0.00480
168ERB G BE1W=6.2E-8
168ER  G   1167.39615 98     10    E1                 1.04E-3
168ERB G BE1W=1.7E-6
168ER  G   1351.54  4 100     9    E1                 8.93E-4
168ERB G BE1W=1.1E-6
168ER  G   1431.7    4 0.50   18 [E3]                 0.00328             H
168ERB G BE3W=3.6
168ER CL           BE3W=3.7 5 FROM BE3=0.043 6 IN COULOMB EXCITATION
(1978MC02).
```

J^{π} arguments

```
166GD  L 0.0          0+              4.8 S     10
```

```
166GD2 L %B-=100
166GD CL J          GS OF EVEN-EVEN NUCLEUS.

166ER  L 859.389     5 3+               4.5 PS     8                          B
166ERX L XREF=ABDEFIJKL
166ER CL J          M1 73G to 2+ 786, E2+M1 594G TO 4+ 265.

169TM  L 345.028     3  5/2-                                                  C
169TMX L XREF=BDHJ
169TM CL J          E1 206G TO 7/2+ 139; E1(+M2) 337G TO 3/2+ 8-KEV LEVEL.

166HO  L 171.0738   12 3-                                                    a
166HOX L XREF=ABCDFGH
166HO CL J          M1 117G to 2- 54; (D,P) CROSS SECTION FINGERPRINT.

166LU  L 135.9      3 1+
166LUX L XREF=B
166LU CL J          EC decay from 0+ is unhindered allowed (LOGFT=4.5).
166LU CL CONF       (|p 7/2[523])-(|n 5/2[523]) (1974DE09).

 81BR  L SP+5003    105/2+             32 KEV    3
 81BRX L XREF=J
 81BR CL J          L(P,P)=2; IAS.
 81BR CL            Analog of 5/2+ 81SE(1304 level).

 81RB  L  153.481   20 5/2-            0.21 NS   10                          Y
 81RBX L XREF=ABCDHI
 81RB CL J          L(3HE,D)=3+1 for E=184 KEV doublet; this level must
 81RB2CL correspond to the L=3 component since J(188 level)<5/2;
 81RB3CL ^D(+Q) G to 3/2-.
```

```
 81AS  L        0    3/2-               33.3 S    8
 81AS2 L %B-=100
 81ASX L XREF=ABCD
 81AS CL J          L(D,3HE)=1; LOGF1UT<8.5 (LOGFT=6.0) to 5/2+.

166TM  L 82.298     8 1+               385 PS    40
166TMX L XREF=ABCD
166TM CL J          ALLOWED EC DECAY from 0+ 166YB (LOGFT=4.9).

166TB  L 40.00      16 (-)
166TBX L XREF=A
166TB CL J          40G NOT E1 TO (2-); 40G IN PROMPT COINCIDENCE WITH G FEEDING
166TB2CL THE 40 LEVEL.

166ER  L 1458.154    9(2)-                                                   C
166ERX L XREF=ADF(1452)I
166ER CL J          E1 G's to 2+ and 3+; fit to a band.


169YB  L              1/2,3/2,5/2+
169YB CL J(L)       Primary transition from 1/2+ in 168YB(N,G) E=thermal.

 81GE  L        0    (9/2+)             7.6 S     6                          A
 81GE2 L %B-=100
 81GEX L XREF=AB
 81GE CL J          shell model systematics for N=49 nuclei

 81SR  L    119.76  4(1/2+)            24 NS     4                          W
 81SRX L XREF=ABCEF
```

```
 81SR CL J         217G from (5/2+) has mult.=(E2) and linear polarization
 81SR2CL which excludes a J to J-1 transition; 5/2 unlikely from 119G excit.
 81SR3CL PI: BE1W more typical in this mass region than BM1W for
 81SR4CL 119G to 1/2-.  HOWEVER, LOGFT=6.5 FROM (5/2+) IS FAR TOO LOW FOR A
 81SR5CL DJ=2, DPI=NO DECAY.

166LU  L 57.2       3(1)-                                                  Z
166LUX L XREF=B
166LU CL J         E1 79G from 1+ 136; 23G to 3(-) 34; CONFIGURATION
ASSIGNMENT.
166LU CL CONF      (|p 7/2[404])-(|n 5/2[523]) (1974DE09).

166LU  L 144.79    14 (6,7,8)-
166LUX L XREF=CE
166LU CL J         E1 61G TO (5,6,7)+ 84 LEVEL; DJ LE 1 142G FROM J GE 7 287.

 81Y   L 268.74     7 (9/2+)                                              Z
 81Y X L XREF=AB
 81Y F L FLAG=G
 81Y  CL J          STRETCHED (E2) G to (5/2+); G to (7/2+).

166HF  L 1603.05   21 (2+,3,4+)
166HFX L XREF=A
166HF CL J         1144G TO 2+ 159, 1133G TO 4+ 470.

166HF  L   2680.1  16(10-)                                                L
166HFX L XREF=C
166HF CL J         STRETCHED Q 484G TO (8-) 2197; BAND ASSIGNMENT.

166DY CL J(A)      ESTABLISHED JPI FOR THE GS AND 76 LEVEL COMBINED WITH
```

```
166DY2CL KNOWN E2 MULTIPOLARITY FOR THE J=4 TO J=2 177-KEV TRANSITION AND
166DY3CL A REGULAR SEQUENCE OF LEVEL ENERGIES ENABLE THE ASSIGNMENT OF
166DY4CL DEFINITE JPI TO GS BAND MEMBERS WITH J LE 14.

169TM CL J(H)      DEFINITE JPI for GS band established THROUGH J=21/2 BASED ON
169TM2CL band structure and INDEPENDENTLY ESTABLISHED JPI(8 LEVEL)=3/2+, AND
169TM3CL INTRABAND M1+E2 110G AND E2 118G FROM 118 LEVEL.
166HF CL J(H)      The interband transition between side band 1 and the
166HF2CL ground-state band show angular distributions of pure
166HF3CL stretched dipole type, most likely E1.

166HF CL J(I)      Transitions connecting the two side bands have positive
166HF2CL anisotropies and are interpreted as mixed M1,E2 transitions (1987BL06)
166HF3CL IN (HI,XNG).

169TM CL E(Q),J(Q) From 169TM(G,G').  ^D EXCITATION FROM 1/2+ IS SUGGESTED BY
169TM2CL 1999HU01 IN (G,G') SO J=(1/2,3/2) IS ASSIGNED; FURTHER, PI=+ IS
169TM3CL ASSIGNED WHENEVER BE1W SIGNIFICANTLY EXCEEDS RUL.

166IR  L 172        6 (9+)             15.1 MS   9
166IR2 L %A=98.2 6 (1997DA07)$%P=1.8 6 (1997DA07)
166IRX L XREF=B
166IR CL J         h{-11/2} PROTON EMISSION OBSERVED FROM LEVEL (1997DA07).
166IR2CL PROBABLE CONFIGURATION={ (|p h{-11/2})~#(|n f{-7/2})}; THE
166IR3CL Nordheim WEAK RULE FAVORS JPI=9+ OR POSSIBLY 2+ (WHICH SHOULD NOT BE
166IR4CL ISOMERIC) FOR THE LOWEST ENERGY STATE FOR THIS CONFIGURATION
(1997DA07)
166IR5CL (POSSIBLY |p 11/2[505]+|n 7/2[514] AT SMALL PROLATE DEFORMATION).
```

Band and sequence descriptions

```
 93TC CL BAND(Y)    DOMINANT CONF=(|p p{-1/2}g{-9/2}{+4}).
 93TC2CL Seniority=1 states. (1994Ro08,1995Gh08).
 93TC CL BAND(Z)    DOMINANT CONF=(|p p{-1/2}{+2}g{-9/2}{+3}).
 93TC2CL Seniority=1 states. (1994Ro08,1995Gh08).

 93RH CL BAND(A)    POSSIBLE PI=+, YRAST SENIORITY=3 STATE.
 93RH2CL By analogy with shell-model calculations for 91TC.

169TM CL BAND(AH)   1/2[411] BAND.
169TM2CL BAND PARAMETERS: A=12.5, ^B=-4.8, a=-0.78 (1/2, 3/2, 5/2, 7/2, 9/2
169TM3CL levels).
169TM CL BAND(B)    7/2[404] BAND.
169TM2CL BAND PARAMETERS: A=13.3, B=-6.7 (7/2, 9/2, 11/2, 13/2 levels).
169TM CL BAND(C)    1/2[541], |a=+1/2 BAND.
169TM2CL BAND PARAMETERS: A=9.1, ^B=+0.8, a=+3.8 (J=1/2 THROUGH 21/2 levels);
169TM3CL HOWEVER, PARAMETERS VARY SIGNIFICANTLY DEPENDING ON WHICH LEVELS ARE
169TM4CL INCLUDED IN THE FIT.
169TM CL BAND(c)    1/2[541], |a=-1/2 BAND.
169TM2CL SEE COMMENT ON SIGNATURE PARTNER BAND.
169TM CL BAND(E)    3/2[411] band + 1/2[411] G vibration.
169TM2CL BAND PARAMETERS: A=12.6, B=-11.9 (3/2, 5/2, 7/2, 9/2 levels).
169TM3CL CONFIGURATION INCLUDES CONTRIBUTION FROM K-2 G VIBRATION BUILT ON
169TM4CL 1/2[411] ORBITAL.

169YB CL BAND(AJ)   7/2[633] BAND.
169YB2CL A=7.9, B=9.5 (7/2, 11/2, 15/2, 19/2 levels); A=8.1, B=4.5
169YB3CL (9/2, 13/2, 17/2, 21/2 LEVELS).
```

Parameters are particularly important for K = 1/2 bands

```
169YB CL BAND(BK)   1/2[521] BAND.
169YB2CL A=11.5, a=+0.80 (1/2, 3/2, 5/2, 7/2, 9/2 levels).
169YB CL BAND(F)    KPI=3/2[521] BAND.
169YB2CL INCLUDES LARGE ADMIXTURE OF K-2 G vibration BUILT ON 1/2[521]
169YB3CL (1968MI08).  A=12.2, B=6.4 (3/2, 5/2, 7/2, 9/2 levels).
169YB CL BAND(G)    KPI=3/2+ BAND.
169YB2CL 7/2[633] K-2 G vibration WITH SOME 3/2[651] ADMIXTURE (1968MI08).
169YB CL BAND(IP)   1/2[510] BAND.
169YB2CL ADMIXED WITH G vibration, POSSIBLY THE K-2 VIBRATION BUILT ON
5/2[512];
169YB3CL tentative assignment.
169YB CL BAND(R)    7/2[503]? BAND.
169YB2CL TENTATIVE BAND ASSIGNMENT FROM 1980BA07.
169YB CL BAND(S)    B VIBRATION BAND.
169YB2CL BUILT ON 7/2[633] GS; BAND ASSIGNMENT FROM 1988DZZW.

169LU CL BAND(D)    5/2[402] |a=+1/2 BAND (1993OG01).
169LU2CL BAND PARAMETERS: A=14.8, B=-13.9 (5/2, 7/2, 9/2, 11/2 levels).
169LU3CL Strongly mixed with 1/2[411] |a=+1/2 band.
169LU3CL FIRST BAND CROSSING AT ~h|w AP 0.26 MEV, ALIGNMENT GAIN AP 6.1~h.
169LU CL BAND(d)    5/2[402] |a=-1/2 BAND (1993OG01).

169HF CL BAND(G)    PI=+, |a=+1/2 3-quasineutron band (2001SC49).
169HF2CL Configuration=|n[(5/2[642])(1/2[521])(5/2[523]] (^AMF BAND).
169HF3CL IN-BAND ^B(E2) VALUES POSSIBLY ENHANCED BY PRESENCE OF COUPLING TO
169HF4CL 5/2[642] G-VIBRATION BAND.

169W  CL BAND(B)    PI=+, |n i{-13/2} BAND.
169W  CL BAND(C)    PI=(-) SIDE BAND.
```

```
169RE CL BAND(C)    |a=+1/2, 3-QUASIPARTICLE BAND (2002ZH42).
169RE2CL CONFIGURATION=(|p 9/2[514])~#(|n i{-13/2})(|n f{-7/2} OR h{-9/2}).

168ER CL BAND(M)    KPI=0+ BAND (4).
168ER2CL A=9.9 (J=0, 2, 4 LEVELS).
168ER CL BAND(P)    KPI=2+ BAND (3).
168ER2CL A=10.7 (J=2, 3, 4 LEVELS).

166HF CL            Quasiparticle orbitals used in band labels are as follows:
166HF CL $A=(|n 5/2[642]), |a=+1/2.
166HF CL $B=(|n 5/2[642]), |a=-1/2.
166HF CL $C=(|n 3/2[651]), |a=+1/2.
166HF CL $D=(|n 3/2[651]), |a=-1/2.
166HF CL $E=(|n 5/2[523]), |a=+1/2.
166HF CL $F=(|n 5/2[523]), |a=-1/2.
166HF CL $^G=(|n 3/2[521]), |a=+1/2.
166HF CL $H=(|n 3/2[521]), |a=-1/2.
166HF CL $a=(|p 7/2[404]), |a=+1/2.
166HF CL $b=(|p 7/2[404]), |a=-1/2.
166HF CL $k=(|p 1/2[660]), |a=+1/2.
166HF CL $e=(|p 9/2[514]), |a=+1/2.
166HF CL $f=(|p 9/2[514]), |a=-1/2.
166HF CL $g=(|p 1/2[541]), |a=+1/2.
166HF CL BAND(A)    ^BC BAND (2000RI11).
166HF CL BAND(B)    ^AB BAND (2000RI11).
166HF2CL YRAST ABOVE J=14.  ALIGNMENT GAIN ~ 10~h AT ~h|w AP 0.25 MEV.
166HF3CL BECOMES ABCDfg BAND AT HIGH SPIN WITH POSSIBLE ADMIXTURE OF ABEFfg.
166HF CL J(B)       JPI ESTABLISHED FOR J=12 THROUGH J=42 BAND MEMBERS BASED
166HF2CL ON SMOOTH PROGRESSION OF EG FOR INTRABAND CASCADE, JPI=14+ FOR
166HF2CL 3007 LEVEL AND E2 INTRABAND 275G TO 2566.
```

CSM notation can be used in band descriptions IF labels are identified by their respective orbitals

```
166HF CL BAND(C)    ^EFBC BAND (2000RI11).
166HF CL BAND(G)    KPI=10-, |a=0 gfAE BAND (2000RI11).
166HF2CL LIKELY CONFIGURATION: |n (5/2[642]+5/2[523])+ |p (1/2[541]+9/2[514]);
166HF3CL STRONGLY SUPPORTED BY MEASURED ^B(M1)/^B(E2) RATIOS.
166HF CL BAND(g)    KPI=10-, |a=1 geAE BAND (2000RI11).
166HF2CL SEE COMMENT ON KPI=10- SIGNATURE PARTNER BAND.
166HF CL BAND(H)    KPI=5- ^AE BAND (2000RI11).
166HF2CL ^A=13.7 IF ^B=0.
166HF CL BAND(J)    ^AGBC BAND (2000RI11).
166HF2CL LARGE ALIGNMENT, CONSISTENT WITH FOUR-QUASINEUTRON STRUCTURE.
166HF CL BAND(L)    ^BE BAND (2000RI11).
166HF2CL LOW ALIGNMENT AT LOW J
166HF CL BAND(O)    Band 2 (2000RI11).

170TM CL BAND(E)    KPI=(2)- BAND.
170TM2CL Configuration=(|p 1/2[411])-(|n 5/2[512]). ROTATIONAL PARAMETER:
170TM3CL A=11.0.  BAND IS ANOMALOUSLY POPULATED IN (T,A).
170TM CL BAND(H)    KPI=(0)+ BAND.
170TM2CL Configuration: (|p 7/2[404])-(|n 7/2[633]).  ROTATIONAL PARAMETER:
A=7.2
170TM3CL (J=even); +36 KEV Newby SHIFT.

166HF CL BAND(D)    Band 3 (2000RI11).
166HF CL BAND(Y)    KPI=2+ G-VIBRATIONAL BAND.

 93SR CL BAND(A)    5/2+ band.
 93SR2CL Possible (stretched) coupling of (|n d{-5/2}){+-1} to 94SR core.
 93SR CL BAND(B)    (11/2-) band.
 93SR2cL Possible coupling of (|n d{-5/2}){+-1} to octupole states in 94SR
core.
```

```
81SR CL BAND(B)    SD-2 band (2003Le08,1995Ch56).
81SR2CL Q(transition)=3.30 +27-21 (2003Le08), 3.8 +7-5 (1997De51,
81SR3CL reanalyzed data of 1995Ch56).
81SR4CL Configuration=|n5{+1}|p5{+0} (2003Le08).
81SR5CL Percent population=0.63 (2003Le08), |?1.0 (1995Ch56).
81SR6CL Probable (|p,|a)=(+,-1/2) corresponding to
81SR7CL configuration=((|n 1/2[431]){+-1}). Predicted |b{-2}=0.55 (1995Ch56)

AAZZ CL BAND(Z)    DJ=2 G CASCADE.

AAZZ CL BAND(Z)    G CASCADE FEEDING JPI=(37/2+) 5277.
```

Photon Intensities (strongest photon branch from level = 100)

```
93SR  L   986.12   5
93SRX L XREF=ABC
93SR  G 986.05    6 100

81RB  L  909.090  19 (3/2)-
81RBX L XREF=AF(*920)
81RB CL J         G to (5/2)+; LOGFT=5.8 from 1/2-. See also comment on
81RB2CL J(913 level).
81RB  G   197.32   8   2.5   7 [M1,E2]                0.05    3
81RB  G   206.98   7   8.4   8 [M1,E2]                0.044  22
81RB  G   422.47  15  10.4  15
81RB  G   465.80   5  34.2  20
81RB  G   607.88   3  38.6  14
81RB  G   663.6    3   2.4   5
```

```
81RB  G   720.81   3 100    3
81RB  G   909.03   3  76.7  25

169ER  L 654.06    25 (5/2-)
169ERX L XREF=CE
169ERF L FLAG=31
169ER  G 429.9     1  221    LT                                    &
169ER  G 579.3     4  7.1    17
169ER  G 589.6     3  100    21

169ER  L 769.56    10 (5/2-)
169ERX L XREF=ACE
169ERF L FLAG=41
169ER  G 545.0     6  15     LT                                    &
169ER  G 695.0     2  100    21
169ER  G 705.0     1  83     17
```

Example: ^{179}Hf

```
179HF    ADOPTED LEVELS, GAMMAS
179HF  H TYP=FUL$AUT=C. BAGLIN$CUT=30-Sep-2007$
179HF  Q -105.6     4 6098.99  87417.9  201803.8  15    2003AU03
179HF C  FOR hfs AND/OR ISOTOPE SHIFT MEASUREMENTS, SEE 1994AN14,
179HF2C  1994JI07, 1994ZI04, 1995JI15, 1996ZH35, 1997ZH36, 1999LE11.
179HF CG E,RI,M,MR From 178HF(N,G) E=thermal, unless otherwise specified.
179HF2CG M AND MR ARE FROM EKC AND/OR SUBSHELL RATIOS.
179HF CG E(U)       From 179LU B- decay.
179HF CG E(V)       From 179HF IT DECAY (25.05 D).
179HF CG E(X)       From 178HF(N,G) E=7.78 EV res.
```

```
179HF CG E(z,y),RI(z)$FROM (9BE,A2NG).
179HF CG E(Z),RI(Z)$EG from level energy difference in (N,G) E=thermal. RI is
179HF2CG relative to 100 for strongest transition observed; stronger
179HF3CG transition(s) from level may exist. Transition is deduced from
179HF4CG two-photon cascade data of 1988BO44, assuming that authors' cascade G
179HF5CG order is correct, that cascade G rays are consecutive and that only
179HF6CG two-photon cascades were identified.
179HF CL           Levels from (G,G'), (E,E') with E LE 2310 have been
179HF2CL omitted from ^XREF because their DE is large compared with the
179HF3CL energy spacing of many low-lying levels.
179HF CL E         From LEAST-SQUARES FIT TO EG, ASSIGNING DE=1 KEV TO DATA
179HF2CL FOR WHICH AUTHORS DID NOT STATE UNCERTAINTY, EXCEPT AS NOTED.
179HF CL J         Assignments given without comment are based on
179HF2CL G MULTIPOLARITIES, G DECAY PATTERNS, g-factor analysis,
179HF3CL CALCULATED BANDHEAD ENERGIES AND OBSERVED BAND STRUCTURE
179HF4CL in 176YB(9BE,A2NG)
179HF CL E(R)      DE GT 3 KEV.
179HF CL E(S)      DE GT 10 KEV.
179HF CL J(T)      Fed by primary G from 1/2+ in (N,G) E=thermal; G to 1/2-
179HF2CL and to 7/2-.
179HF CL J(W)      Fed by primary G from 1/2+ in (N,G) E=thermal; G to 1/2-.
179HF CL J(Y)      Fed by primary G from 1/2+ in (N,G) E=thermal.
179HF CL E(Z)      FROM 178HF(D,P), 180HF(D,T).  DE includes a systematic
179HF3CL uncertainty of 0.5 KEV (for E<1700) or 3 KEV (for 1700<E<2050)
179HF4CL combined in quadrature with the relevant statistical DE.
179HF5CL IF NO UNCERTAINTY IS STATED, DE>3 KEV.
179HF CL BAND(A)   9/2[624] GS BAND.
179HF2CL Level spacings perturbed by CORIOLIS mixing (1981TH05). A=11.6, B=3.1.
179HF3CL CONFIG supported by g{-K}(exp)=-0.22 4 cf. -0.245 FROM NILSSON MODEL.
179HF CL J(A)      DEFINITE JPI ASSIGNED TO J LE 23/2 MEMBERS OF 9/2[624] BAND
```

```
179HF2CL BASED ON INDEPENDENTLY ESTABLISHED JPI=9/2+ AND 11/2+ FOR THE GS AND
179HF3CL 123 LEVELS AND MULT=M1+E2 FOR THE INTRABAND 123G CONNECTING THEM.
179HF CL BAND(B)   7/2[514] BAND.
179HF2CL Rotational parameters: A=13.8, B=-3.6.
179HF3CL CONFIG supported by g{-K}(exp)=0.31 4 cf. 0.28 FROM NILSSON MODEL.
179HF CL BAND(D)   1/2[510] BAND.
179HF2CL rotational parameters: A=13.2, B=-5.9, a=+0.16, ^B{-2K}=-3.9.
179HF CL J(D)      DEFINITE JPI ASSIGNED TO J LE 25/2 MEMBERS OF 1/2[510] BAND
179HF2CL BASED ON INDEPENDENTLY ESTABLISHED JPI=1/2- FOR 375 LEVEL AND
179HF3CL MULT=M1+E2 FOR INTRABAND 46G.
179HF CL BAND(E)   5/2[512] BAND.
179HF2CL Rotational parameters: A=14.1, B=-4.2.
179HF3CL CONFIG supported by g{-K}(exp)=-0.27 12 cf. -0.38 FROM NILSSON MODEL.
179HF CL J(E)      DEFINITE JPI ASSIGNED TO J LE 15/2 MEMBERS OF 5/2[512] BAND
179HF2CL BASED ON INDEPENDENTLY ESTABLISHED JPI=5/2- FOR 518 LEVEL AND
179HF3CL MULT=M1+E2 FOR INTRABAND 98G.
179HF CL BAND(F)   1/2[521] BAND.
179HF2CL Rotational parameters: A=13.1, a=+0.67.
179HF CL J(F)      DEFINITE JPI ASSIGNED TO J LE 9/2 MEMBERS OF 1/2[521] BAND
179HF2CL BASED ON INDEPENDENTLY ESTABLISHED JPI=3/2- FOR 680 LEVEL AND
179HF3CL MULT=M1 FOR INTRABAND 148G.
179HF CL BAND(G)   3/2[512] BAND.
179HF CL J(G)      DEFINITE JPI ASSIGNED TO J LE 11/2 MEMBERS OF 3/2[512] BAND
179HF2CL BASED ON INDEPENDENTLY ESTABLISHED JPI=3/2- FOR 721 LEVEL AND
179HF3CL MULT=M1 FOR INTRABAND 147G.
179HF CL BAND(H)   7/2[503] BAND.
179HF2CL Rotational parameters: A=10.5, B=12.3.
179HF CL BAND(I)   KPI=5/2+ GS G-VIBRATIONAL BAND.
179HF CL BAND(J)   7/2[633] BAND.
179HF CL BAND(K)   KPI=9/2+ [9/2[624]+0+] GS B-VIBRATIONAL BAND.
```

```
179HF2CL B vibration (1199(0+) in 178HF) coupled to 9/2[624].
179HF CL BAND(L)    KPI=1/2+ (1/2[510]-1-) BAND.
179HF2CL Octupole vibration (1310(1-) in 178HF) coupled to 1/2[510].
179HF3CL See 1985RI09 for a discussion of unusual decay between octupole and
179HF4CL quadrupole vibrations built on different single-particle states.
179HF5CL Rotational parameters: A=10.9, a=+0.09.
179HF CL BAND(M)    KPI=3/2- [7/2[514]-2+] G-VIBRATIONAL BAND.
179HF2CL Quadrupole vibration (1175(2+) in 178HF) coupled to 7/2[514].
179HF3CL Rotational parameters: A=12.6, B=25.9.
179HF CL BAND(N)    3/2[521] BAND.
179HF CL BAND(O)    3/2[501] BAND.
179HF CL BAND(P)    1/2[501] BAND.
179HF CL BAND(Q)    KPI=3/2+ (1/2[521]+1-) BAND.
179HF2CL Octupole vibration (1310(1-) in 178HF) coupled to 1/2[521].
179HF CL BAND(C)    KPI=17/2+ BAND (2000MU06).
179HF2CL CONFIGURATION=((|n 7/2[514])+(|n 9/2[624])+(|n 1/2][510]))
179HF3CL (2000MU06).
179HF CL BAND(r)    KPI=(21/2+) BAND (2000MU06).
179HF2CL CONFIGURATION=((|n 9/2[624])+(|p 7/2[404])+(|p 5/2][402]))
179HF3CL (2000MU06); SUPPORTED BY g{-K}(exp)=0.54 5 cf. 0.48 FROM NILSSON
MODEL.
179HF CL BAND(s)    KPI=23/2+ BAND (2000MU06).
179HF2CL CONFIGURATION=((|n 7/2[514])+(|p 7/2[404])+(|p 9/2][514]))
179HF3CL (2000MU06); SUPPORTED BY g{-K}(exp)=0.86 20 cf. 0.78 FROM NILSSON
179HF4CL MODEL.
179HF CL BAND(t)    KPI=(19/2-) BAND (2000MU06).
179HF2CL CONFIGURATION=((|n 7/2[514])+(|p 7/2[404])+(|p 5/2][402]))
179HF3CL (2000MU06).
179HF CL BAND(u)    KPI=25/2- BAND (2000MU06).
179HF2CL CONFIGURATION=((|n 9/2[624])+(|p 7/2[404])+(|p 9/2][514]))
```

```
179HF3CL (2000MU06); supported by g{-K}(exp)=0.60 7 cf. 0.55 FROM NILSSON
MODEL.
179HF CL BAND(v)    KPI=(33/2-) BAND (2000MU06).
179HF2CL CONFIGURATION=((|n 7/2[514])+(|n 9/2[624])+(|n 1/2[510])+(|p
7/2[404])+
179HF3CL (|p 9/2][514])) (2000MU06); supported by g{-K}(exp)=0.46 4 cf. 0.45
179HF4CL FROM NILSSON MODEL.
179HF CL BAND(w)    POSSIBLE (|n 5/2[523]) BAND (2000MU06).
179HF2CL DEEXCITES TO 7/2[514] BAND.
179HF  XA178HF(N,G) E=THERMAL
179HF  XB179LU B- DECAY
179HF  XC179HF IT DECAY (18.67 S)
179HF  XD179HF IT DECAY (25.05 D)
179HF  XE178HF(N,G) E=7.78 EV RES
179HF  XFCOULOMB EXCITATION
179HF  XG178HF(D,P), 180HF(D,T)
179HF  XH180HF(3HE,A)
179HF  XI179TA EC DECAY
179HF  XJ179HF(G,G'), (E,E')
179HF  XK176YB(9BE,A2NG),
179HF  XL177HF(T,P)
179HF PN                                                                  6
179HF  L         0.0  9/2+              STABLE                           A
179HFX L XREF=ABCDEFGHIJK
179HF2 L MOMM1=-0.6409 13
179HF3 L MOME2=+3.79  3
179HF CL           DAVRSQ(179HF-178HF)=+0.027 2 (1994AN14), +0.028 3
(1997ZH36),
179HF2CL +0.036 1 (1999LE11, 10% SYSTEMATIC NORMALIZATION UNCERTAINTY NOT
179HF3CL INCLUDED; value is relative to DAVRSQ(178,180)=0.098 as measured
```

```
179HF3CL by 1994ZI04, much higher than DAVRSQ(178,180)=0.075 4 AND 0.076 5
179HF5CL from 1994AN14 and 1997ZH36, respectively). OTHER DAVRSQ: 1994ZI04.
179HF CL            <r{+2}>{+1/2}(CHARGE)=5.3358 24 (2004AN14).
179HF CL MOMM1      Atomic beam (direct) (1989RA17, from 1973BU25).
179HF CL MOME2      Muonic X-RAY hfs (1989RA17, from 1984TA04 and 1983TA14).
179HF2CL Other values: +3.7 7 (reanalysis of atomic beam data of
179HF2CL 1973BU25 quoted in 1985ST28, originally given as
179HF3CL +5.1 5 in 1973BU25); 3.93 5 (1983OL03), +5.3 5 (uncorrected,
1977BU23).
179HF CL J          L(3HE,A)=4 FOR GS AND M1+E2 123G FROM 123 LEVEL (FOR WHICH
179HF2CL L(3HE,A)=6) ESTABLISHES JPI=9/2+ FOR GS AND JPI=11/2+ FOR 123 LEVEL.
179HF3CL GS ASSIGNMENT SUPPORTED BY experimental MOMM1 which is consistent with
179HF4CL theoretical value of -0.6 calculated by evaluator for JPI=9/2+,
179HF5CL 9/2[624]. NILSSON orbital assignment based also on energy systematics
179HF6CL of this orbital in 177YB, 181W, and 183OS (N=107 isotones).
179HF  L  122.7904 24 11/2+            37 PS     3                            A
179HFX L XREF=ABDGHFK
179HF2 L MOME2=1.88 3
179HF CL MOME2      Muonic X-RAY hfs (1989RA17, from 1984TA10).
179HF CL J          SEE COMMENT ON JPI(GS).
179HF CL T          from CE delay (1960BL10) IN COULOMB excitation.
179HF  G    122.793 3     100  M1+E2      -0.27   3      2.18    4
179HF CG MR         from G(|q) in COULOMB EX. Others: 0.309 15 from BE2 and T;
179HF2CG 0.70 +12-11 from EKC in (N,G) E=thermal; 0.22 +20-22 from ELC in Hf
^IT
179HF3CG decay (25.05 D); 0.44 6 from EKC in COULOMB excitation; 0.44 9 from
179HF4CG CEK/CEL in COULOMB EXCITATION.
179HFB G BM1W=0.094 8$BE2W=245 14
179HF CG            BE2W: from measured BE2UP=1.76 10 for 122 LEVEL IN COULOMB
179HF2CG EXCITATION.
```

```
179HF  L  214.3395 22 7/2-             1.85 NS   4                          B
179HFX L XREF=ABCEGKL
179HF CL J          214.3G E1 to 9/2+, 1245G E2 from 3/2-. Spectroscopic factor
179HF2CL in (D,P) is consistent with 7/2-, 7/2[514]. NILSSON orbital assignment
179HF3CL based also on energy systematics of this orbital in 177YB and 181W
179HF4CL (N=107 isotones).
179HF CL T          weighted average of 1.86 NS 5 from 179HF IT DECAY (18.67 S)
179HF2CL and 1.82 NS 10 from (N,G) E=thermal.
179HF  G    214.335 3     100  E1                      0.063   4
179HF CG CC         experimental value from (N,G). Anomalous E1. CC(E1)=0.0494.
179HFB G BE1W=1.110E-5 25
179HF  L   268.92   6 13/2+            21 PS     3                            A
179HFX L XREF=DHFG(269.1)K
179HF CL T          from BE2 IN COULOMB excitation AND ADOPTED TRANSITION
179HF2CL PROPERTIES.
179HF CL J          L=6 in (3HE,A) and (D,P); INTRABAND E2 269G to 9/2+ GS AND
179HF2CL M1+E2 146G TO 11/2+ 123.
179HF  G 146.15    7 100     4 M1+E2     -0.39   4     1.290  22
179HFB G BM1W=0.106 17$BE2W=320 80
179HF CG E,M        from 179HF IT DECAY (25.05 D).
179HF CG RI         from (9BE,A2NG).
179HF CG MR         weighted average of -0.41 5 from G(|q) in COULOMB excitation
179HF2CG and -0.33 8 from G(|q) in Hf ^IT decay (25.05 D). Other: 0.26 +12-26
179HF3CG from EKC in COULOMB ex; inconsistent EKC in 179HF IT DECAY (25.05 D)
179HF4CG may result from contaminated CE line. MR<0.38 from RUL.
179HF  G   268.85  14 39.4    4 E2                    0.1107
179HF CG E,M        from 179HF IT DECAY (25.05 D).
179HF CG RI         from (9BE,A2NG).
179HFB G BE2W=49 6
179HF CG            From BE2UP=0.41 5 IN COULOMB EXCITATION.
```

```
179HF  L  337.7178 23 9/2-                                                  B
179HFX L XREF=ABEGHL
179HF CL J         L=5 in (3HE,A); E2 101.3G from 5/2- 476.
179HF2CL Spectroscopic factor in (D,P) is consistent with 9/2-, 7/2[514].
179HF  G  123.3790 20  100    4 E2                    1.582
179HF  G    214.930 3   78    4 [E1]                  0.0491
179HF  G    337.713 5   21.2  9 E1                    0.01607
179HF  L  375.0352 25 1/2-             18.67 S   4                          DM1
179HF2 L %IT=100
179HFX L XREF=ACEGKL
179HF CL J         L=0,1 in (D,P); 160.3G M3 to 7/2- 214. Spectroscopic
179HF2CL factor in (D,P), and band
179HF3CL structure with experimental decoupling constant a=+0.16,
179HF4CL are consistent with 1/2-, 1/2[510]. NILSSON orbital assignment based
179HF5CL also on energy systematics of this orbital in 177YB and 183OS
179HF6CL (N=107 isotones).
179HF CL T         FROM 179HF IT DECAY (18.67 S).
179HF  G    160.696 2     100  M3                  34.1
179HFB G BM3W=0.0364 9
179HF CG RI        FROM 179HF IT DECAY (18.67 S).
179HF  G 375       AP 0.2    AP[M4]                3.56
179HF CG E,RI      From 179HF IT DECAY (18.67 S).
179HFB G BM4W AP 0.14
179HF  L  420.8943 25 3/2-                                                  D
179HFX L XREF=AEGKL
179HF CL J         55.4G M1 from 5/2-; primary G from 1/2+ in (N,G) E=thermal.
179HF2CL Spectroscopic factor in (D,P) is consistent with that for 3/2-,
179HF3CL 1/2[510] level.
179HF  G    45.861010     100  M1+E2     0.11    +0-2  7.7     5
179HF  L     438.68 8 15/2+                                                 A
```

```
179HFX L XREF=DFGH
179HF CL E         from 179HF IT DECAY (25.05 D).
179HF CL J         INTRABAND M1+E2 170G TO 13/2+ 269 AND E2 316G
179HF2CL to 11/2+ 123.
179HF  G 169.77    9 96      4 M1+E2     -0.33   5     0.852  17            V
179HF CG RI,M,MR   from 179HF IT DECAY (25.05 D).
179HF  G 315.88    11100      E2                     0.0679                 V
179HF CG RI,M      from 179HF IT DECAY (25.05 D).
179HF  L  476.3341 25 5/2-                                                  D
179HFX L XREF=AEGHK
179HF CL J         M1 G to JPI LE 3/2-; L(D,P)=2,3,5. Spectroscopic factor in
179HF2CL (D,P) is consistent with 5/2- 1/2[510].
179HF  G   55.4420 10  100    1M1                    3.74
179HF  G  101.2980 10  90     5E2                    3.35
179HF  G    262.02  3    0.22 6
179HF  L    487.709 5(11/2-)                                                B
179HFX L XREF=AGKL
179HF CL J         spectroscopic factor in (D,P) is consistent with 11/2-,
179HF2CL 7/2[514]; G rays to 7/2-, 9/2+ and 9/2-; continuation of band BASED ON
179HF3CL JPI=7/2- 214 LEVEL.
179HF  G    150.01915 21.5   15
179HF CG RI        FROM (9BE,A2NG); 30 6 FROM (N,G) E=THERMAL.
179HF  G    273.368 4   100   5
179HF  G    487.70411    52  17
179HF CG           NOT REPORTED IN (9BE,A2NG).
179HF  L  518.3279 24 5/2-             0.2 NS    LT                         E
179HFX L XREF=ABGEK
179HF CL J         97.4G M1+E2 to 3/2- 421, 304.0G M1+E2 to 7/2- 214.
179HF2CL NILSSON orbital assignment based on rotational band structure.
179HF CL T         from 178HF(N,G) E=thermal.
```

```
179HF  G   41.9960 10   0.26  6M1(+E2)   0.13    +6-11 11      3
179HFB G BM1W>0.0023
179HF  G   97.4350 20  0.89   4M1+E2     0.28    +10-144.28    7
179HFB G BM1W>0.00074 $BE2W>0.93
179HF  G  143.301   9   0.11  3(E2)                    0.914
179HFB G BE2W>0.68
179HF CG M         EKC in (N,G) E=thermal consistent with E1 or E2; DPI=no
179HF2CG from level scheme.
179HF  G    180.613 2   0.79  4E2                      0.406
179HFB G BE2W>1.6
179HF  G    303.977 4 100.0  22M1+E2     0.62    +7-6  0.151   5
179HFB G BM1W>0.0021 $BE2W>3.4
179HF  L    582.230 3 7/2-                                                D
179HFX L XREF=AEGK
179HF CL J         105.9G M1 to 5/2- 476; spectroscopic factor in (D,P) is
179HF2CL consistent with 7/2-, 1/2[510]; continuation of band BASED ON JPI=1/2-
179HF3CL 375 LEVEL.
179HF  G  105.899   3 100      2 M1                     3.40
179HF  G  161.3390 20  19.0    8 (E2)                   0.600
179HF  G    367.89117    0.55 9
179HF  L    614.204 3 1/2-             0.50 NS   15                       F
179HFX L XREF=AEG(*)
179HF CL J         M1+E2 193G to 3/2- 421; E2 138G to 5/2- 476. NILSSON orbital
179HF2CL assignment based on rotational band structure with an
179HF3CL experimental decoupling constant of a=+0.67.
179HF CL T         from centroid shift in 178HF(N,G) E=thermal.
179HF  G    137.873 2   0.72  4E2                      1.051
179HFB G BE2W=1.5 5
179HF  G    193.310 2 100.0  21 M1+E2     0.59    4     0.542  11
179HFB G BM1W=0.0025 8$BE2W=10 4
```

```
179HF  G    239.165 3  16.4  12  M1                     0.344
179HFB G BM1W=0.00030 10
179HF  L  616.7562 25 7/2-                                                E
179HFX L XREF=ABHEG(*)K
179HF CL J         M1+E2 98.4G to 5/2- 518; M1+E2 279.0G to 9/2- 338.
179HF  G   98.433   2 100      1M1+E2     0.35    4     4.14
179HF  G  140.4260 20  10.8    7M1+E2     0.40    +15-191.45    6
179HF  G  195.861   6  2.05   24
179HF  G    279.029 4  75.9    8M1+E2     0.69    +12-110.185   10
179HF CG           I(279G):I(98G)=133 17:100 8 IN (9BE,A2NG).
179HF  G    402.409 6  37.2    7M1+E2     1.28    8     0.0534 18
179HF  G    616.768 9  22.9   19
```

Exercise: use the following data sets to create an Adopted Levels, Gammas dataset

```
168YB    168LU EC DECAY (6.7 M)          1999BA65
168LU  P 202.81    12 3+                 6.7 M     4              4515      50
168YB  N 0.164     22           0.992    GT 1.0
168YB PN                                                                    3
168YB  L 0.0          0+                STABLE
168YB  L 87.763    25 2+
168YB  G 87.77     3  0.82   12E2                        5.34
168YB CG M         FROM K:L2:L3:M:N= AP 140:210:230:110:30 (1966HA23).
168YB  L 286.60     3 4+
168YB  G 198.90    3  1.9     3E2                        0.274                C
168YB CG M         FROM K:L2:L3:M=62:21:12:11 (1966HA23).
168YB  L 585.35     5 6+
168YB  G 298.77    4  0.126  20E2                        0.0748
168YB  L 984.00     3 (2)+
168YB  E                                                                      ?
168YB  G  697.6     4 0.0093 25                                              C
168YB  G 896.261   24 1.00     E2                        0.00465
168YB CG M         EKC=0.0037 7 (1970CH28).
168YB  G 983.99    4  0.78   13(E2)                      0.00383
168YB CG M         EKC=0.0030 5 (1970CH28) FOR 984G+979G.

168YB    170YB(P,T)                      1973OO01
168YB CL BAND(A)   KPI=0+ GS band.
168YB  L 0.0                                          0                    A
168YB  L 87        5                                  2                    A
168YB  L 284       5                                  4                    A
168YB  L 586       5                                  (6)                  A
```

```
168YB    COULOMB EXCITATION              1977RO27
168YB  L 0.0          0+
168YB  L 87.9         2+                 1.49 NS   4
168YB2 L BE2=5.77 4 (1977RO27)
168YB CL T         FROM BE2 AND ADOPTED TRANSITION PROPERTIES.
168YB  G 87.9
168YB  L 286.9
168YB  G 199.0
168YB  L 586
168YB  G 299
168YB  L 971
168YB  G 385

168YB    (HI,XNG)                        1995FI01,1993OL02,1985BA47
168YB CL BAND(A)   KPI=0+ GS band.
168YB PN                                                                    5
168YB  L      0.0     0+                                                   A
168YB  L   87.73    1 2+                 20 NS     LT                        A
168YB  G      87.73 1           E2                          5.35
168YB CG M         A2=+0.12 5, A4=-0.10 4 (1972JO02).  NOT M2 FROM RUL.
168YB  L   286.550 23 4+                 20 NS     LT                        A
168YB  G     198.82 2 99.1   14 E2                         0.274
168YB CG M         A2=+0.41 3, A4=-0.04 4 (1985BA47).  NOT M2 FROM RUL.
168YB  L   585.30   8 6+                 20 NS     LT                        A
168YB  G     298.75 7 100.0  16 E2                         0.0749
168YB CG M         A2=+0.265 26, A4=-0.11 3 (1985BA47).  NOT M2 FROM RUL.
168YB  L   970.05  13 8+                 20 NS     LT                        A
168YB  G    384.75 10 114.0  11 E2                         0.0359
168YB CG RI        combined value for 384.3G and 384.8G.
168YB CG M         A2=+0.30 4, A4=-0.05 3 (1972JO02).  NOT M2 FROM RUL.
```

Resulting dataset

```
168YB    ADOPTED LEVELS, GAMMAS
168YB CG E          FROM (HI,XNG), EXCEPT AS NOTED.
168YB CG RI(Z),E(Z)$FROM EC DECAY.
168YB CG M          Q FROM G(|q) IN (HI,XNG), NOT M2 FROM RUL, EXCEPT AS NOTED.
168YB CL E          FROM LEAST-SQUARES FIT TO ADOPTED EG.
168YB CL T          LIMIT FROM BEAM-G(T) IN (HI,XNG), EXCEPT AS NOTED.
168YB CL BAND(A),J(A)$ KPI=0+ GS BAND.
168YB2CL DEFINITE JPI CAN BE ASSIGNED FOR J LE 8 BAND MEMBERS BASED ON REGULAR
168YB3CL PROGRESSION OF EG IN BAND AND ON INDEPENDENTLY-DETERMINED JPI FOR J=0
168YB4CL AND 2 MEMBERS AND MULTIPOLARITY=E2 FOR J=0 TO 2 TRANSITION.
168YB  Q -4510      50 9052    5 6315    5 1950    4    2003AU03
168YB  XA168LU EC DECAY (6.7 M)
168YB  XB170YB(P,T)
168YB  XCCOULOMB EXCITATION
168YB  XD(HI,XNG)
168YB PN                                                                    6
168YB  L 0.0          0+               STABLE
168YBX L XREF=ABCD
168YB CL            <r{+2}>{+1/2}(charge)=5.268 6 (2004AN14).
168YB CL J          GS OF EVEN-EVEN NUCLEUS.
168YB  L   87.730  10 2+               1.47 NS    3                         A
168YBX L XREF=ABCD
168YB CL J          E2 88G TO 0+ GS.
168YB CL T          FROM BE2 IN COULOMB EXCITATION AND ADOPTED TRANSITION
168YB2CL PROPERTIES.
168YB  G      87.73 1 100       E2                    5.35
168YB CG M          FROM SUBSHELL RATIOS IN EC DECAY.
168YBB G BE2W=210 3
```

```
168YB CG            BE2W: FROM MEASURED BE2.
168YB  L   286.550 23 4+               20 NS     LT                        A
168YBX L XREF=ABCD
168YB CL J          L(P,T)=4.
168YB  G     198.82 2 100       E2                    0.274
168YBB G BE2W>1.3
168YB CG M          FROM SUBSHELL RATIOS IN EC DECAY.
168YB  L   585.30   8 6+               20 NS     LT                        A
168YBX L XREF=ABCD
168YB  G     298.75 7 100       E2                    0.0749
168YBB G BE2W>0.20
168YB  L   970.05  13 8+               20 NS     LT                        A
168YBX L XREF=CD
168YB  G    384.75 10 100       E2                    0.0359
168YBB G BE2W>0.059
168YB  L 983.994   22 (2)+
168YBX L XREF=A
168YB CL J          (E2) 984G TO 0+ GS; E2 896G TO 2+ 88.
168YB  G  697.6     4 0.93   25                                           Z
168YB  G 896.261   24 100      E2                    0.00465              Z
168YB CG M          FROM EKC IN EC DECAY.
168YB  G 983.99    4  78     13(E2)                 0.00383              Z
168YB CG M          FROM EKC IN EC DECAY.
```

11.

Evaluated Nuclear Structure Data File

A Manual for the Preparation of Data Sets

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Formal Report

Evaluated Nuclear Structure Data File

A Manual for the Preparation of Data Sets

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Abstract

The structure and format for the Evaluated Nuclear Structure Data File (ENSDF) are described. ENSDF is used to store nuclear structure properties of nuclides and the results of various experiments to derive those properties.

Contents

Chapter I

I. INTRODUCTION

The organization and structure of the Evaluated Nuclear Structure Data File (ENSDF) are described in this manual. [1] This computer-based file is maintained by the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory for the international Nuclear Structure and Decay Data Network.[2]

For every mass number (presently $A \leq 293$), the Evaluated Nuclear Structure Data File (ENSDF) contains evaluated structure information. For masses $A \geq 44$, this information is published in the *Nuclear Data Sheets*; for A < 44, ENSDF is based on compilations published in the journal *Nuclear Physics*. The information in ENSDF is updated by mass chain or by nuclide with a varying cycle time dependent on the availability of new information.

The author gratefully acknowledges many suggestions and comments received during the revision of this manual. Special thanks are due to the following colleagues at NNDC: M. Blennau, T. Burrows, P. Dixon, C. Dunford, R. Kinsey, P. Oblozinsky, A. Sonzogni and D. Winchell. This research was supported by the Office of Basic Energy Sciences, U. S. Department of Energy.

[1] The format for ENSDF was first designed by W. B. Ewbank and M. R. Schmorak at the Nuclear Data Project, Oak Ridge National Laboratory, and was described in ORNL-5054/R1 (February 1978). The present report describes the current format and supersedes both the ORNL report and BNL-NCS 51655 (March 1983) and BNL-NCS-51655-Rev.87 (April 1987).

[2] Coordinated by the International Atomic Energy Agency, Vienna - see any issue of the *Nuclear Data Sheets* for list of evaluation data centers.

Chapter II

II. GENERAL ORGANIZATION AND STRUCTURE OF THE DATA FILE

A. General Organization

The Evaluated Nuclear Structure Data File (ENSDF) is made up of a collection of 'data sets' which present one of the following kinds of information:

1. The summary information for a mass chain giving information, *e.g.*, evaluators' names and affiliations, cutoff date, evaluators' remarks, and publication details, *etc*.
2. The references used in all the data sets for the given mass number. This data set is based upon reference codes (key numbers) used in various data sets for a given mass number and is added to the file by the NNDC.
3. The adopted level and gamma-ray properties for each nuclide.
4. The evaluated results of a single type of experiment, e.g., a radioactive decay or a nuclear reaction for a given nuclide.
5. The combined evaluated results of a number of experiments of the same kind, e.g., (heavy ion, xnγ), Coulomb excitation, etc. for a given nuclide.

The data sets in ENSDF are organized by their mass number. Within a mass number the data sets are of two kinds:

- Data sets which contain information pertaining to the complete mass chain. These data sets contain information of type (1) and (2) given above.
- Data sets belonging to a given nuclide (Z-value).

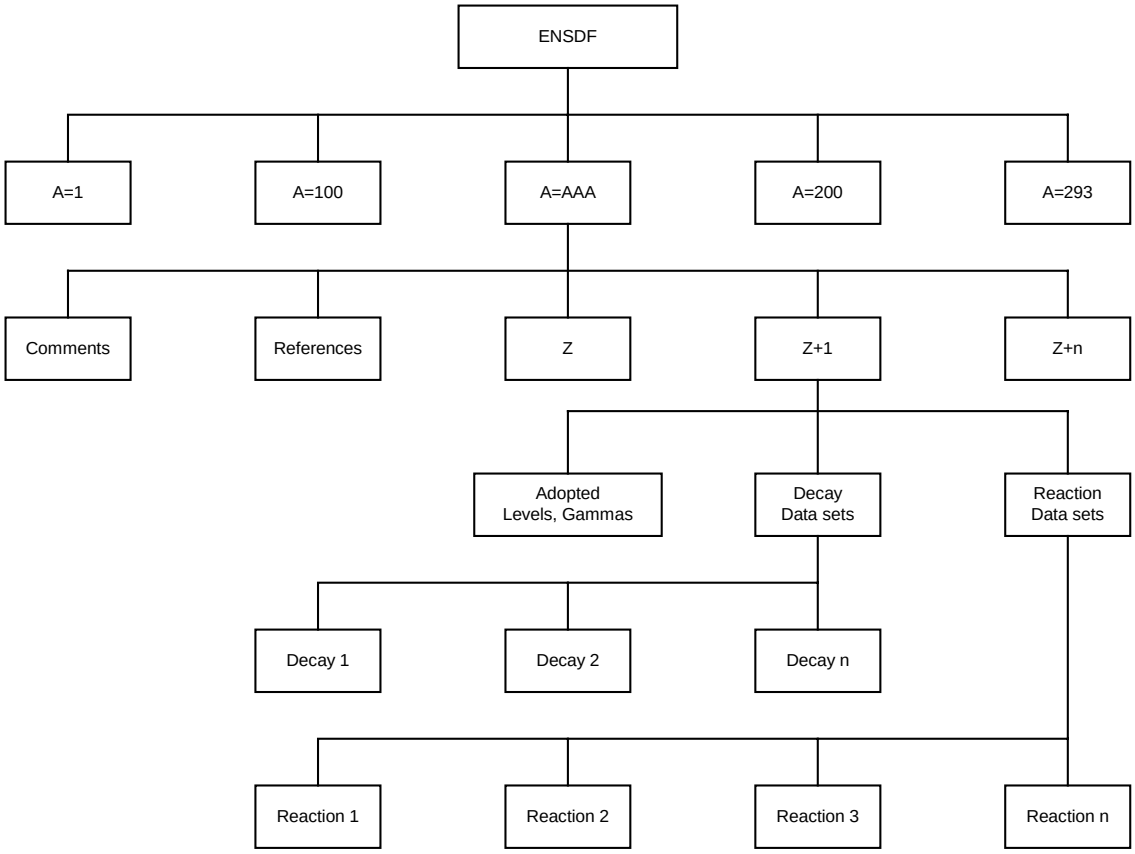
Latter data sets, i.e., for a given nuclide (Z-value), consist of the following:

- A Comments data set which gives abstract information for the nuclide. This data set contains summary information as described in (1) above. This data set exists only if the nuclide or the whole mass chain was evaluated.
- Adopted data set (only one per Z-value) giving adopted properties of the levels and gamma rays seen in that nuclide.
- Data sets giving information of type (4) or (5) above.

If there is more than one data set of type (4) or (5) for a given nuclide, then an adopted data set is *required* for that nuclide. If there is only one data set for a given nuclide and no gamma rays have been seen, then that data set is assumed also to present the adopted properties for that nuclide. However, if there is gamma information known for the nuclide, a separate Adopted Levels, Gammas data set must be given even though all the information may come from only one experiment (data set).

The general organization of ENSDF is shown in Fig. II.1.

Figure II.1: ENSDF Organization Chart



B. Data Set Structure

A data set is composed of 80-character records. A data set has at least two records, the beginning (DSID) and the end record. Data set structure is shown in Fig. II.2, and is described below:

A data set *must* begin with an IDENTIFICATION record and *must* end with an END record (a blank record). Between these two records, there can be as many additional records as are needed to describe fully the experimental or the evaluated information.

Immediately following the IDENTIFICATION record is a group of records which contain information about the entire data set (#1 and #2 in Fig. II.2). The History (H), general COMMENT (C), NORMALIZATION (N), Q-VALUE (Q), PARENT (P) and CROSS-REFERENCE (X) records are of this type. Not all of these records are included in every data set. For example, Q-VALUE (Q) and CROSS-REFERENCE (X) records normally appear only in adopted data sets while the PARENT (P) record is given only in radioactive decay data sets.

The body of a data set (#3 and #4 in Fig. II.2) is composed of numeric data records which describe the measured or deduced properties of levels, γ rays, α particles, etc. These records are associated with the level which decays (for GAMMA records) or the level which is populated (for BETA, EC, ALPHA, PARTICLE, or DELAYED-PARTICLE records). Thus, each LEVEL record is followed by a group of records describing β, ε, or (delayed-) particle decay into the level and γ-ray out of the level (#4 in Fig. II.2). The LEVEL records, and the corresponding radiation records, are placed in the data set in the order of increasing energy.

> If a GAMMA, ALPHA, EC, BETA, or (DELAYED-)PARTICLE record properly belongs in a data set but cannot be associated with any particular level, the record should be placed in the data set *before* any LEVEL records (#3 in Fig. II.2).
>
> The placement of COMMENT records is described in Section III.B.5.

C. File Storage and Transmittal

The data sets sent to NNDC for inclusion in ENSDF can be in any order, as the file is currently maintained using a data base management system which rearranges various data sets in their predetermined order. Copies of the file are transmitted in the form of a sequential file via various mass media. Unless requested otherwise the data sets in the sequential file are arranged by mass numbers in increasing numerical order. Data sets for a given mass number are organized as given in Fig. II.1, ordering them from left to right. Decay data sets are placed under the daughter nuclide and are ordered by A, Z and then the excitation energy of the parent nuclide. The reaction data sets are given under the residual nuclide and ordered by the A, Z of the target nuclide followed by the A, Z of the incident particle, and then by the energy of the incident particle. These are followed by other data sets, e.g., Coulomb Excitation, (HI, XNG), etc.

Data Set Structure

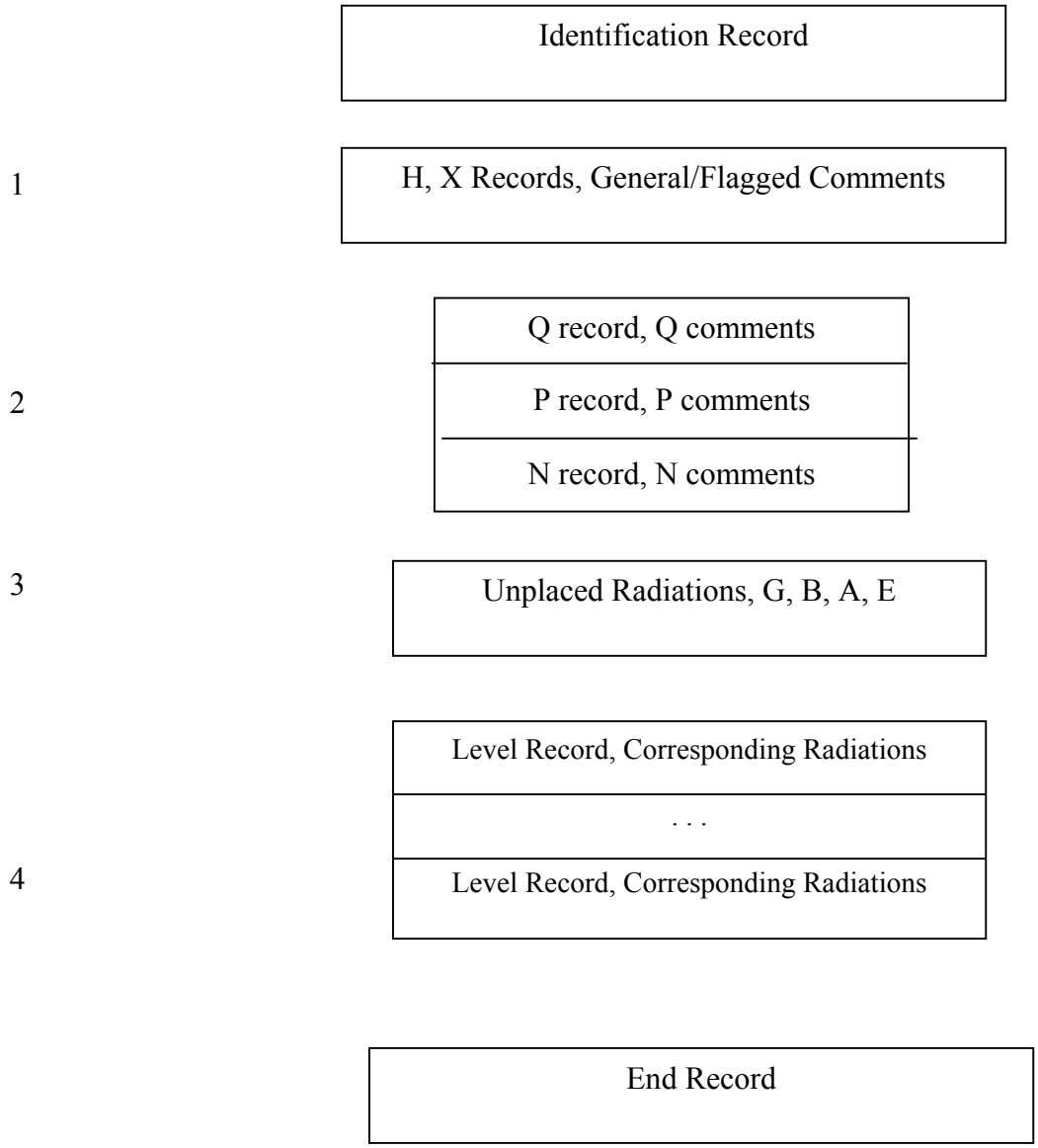


Fig. II.2

Chapter III

III. STANDARD RECORD FORMATS

A. Introduction

In most cases, all information for a record can be placed on a single 80-column (byte) card (record)[3]. A 'standard' format has been defined for each one-card record, such that the most commonly used quantities can be placed on a single card. The standard formats are described in this section for each record. If a needed quantity is not included in the standard format or if a value will not fit within the field defined for the value by the standard format, or if a record cannot be contained on a single card, then additional cards can be prepared as described in Chapter IV (for examples, see Appendices C and D). Note that many of the analysis programs may not process standard fields when placed on the continuation records.

B. Standard One-Card Record Formats

Record formats are given below in the same order in which they would normally be encountered in a data set. Conditions under which each record may appear or be required are given in parentheses. The format descriptions give the fields (in inclusive card-column numbers), the field names (the formal 'name' of the quantity that goes into the field), and a brief field description. Card columns not explicitly included in the fields are expected to be blank. A detailed description of each field can be found in the reference section noted. Any numerical field left blank usually implies that the numerical information is lacking. Numbers will usually be assumed to be positive unless stated otherwise. Numbers can be entered anywhere in the appropriate field (i.e., there is no need to left-adjust or right-adjust, unless stated otherwise.)

[3] Throughput this manual an 80-byte record is referred to as a card of 80 columns. Column number refers to the byte number on the record, starting from the left.

1. Identification Record

Required for all data sets.
Must precede all other records.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide Identification	V.1
6-9		Must be blank	
10-39	DSID	Data set identification	V.2
40-65	DSREF	References to main supporting publications and analyses	V.3
66-74	PUB	Publication Information	V.4
75-80	DATE	Date (year/month) when the data set was placed in ENSDF (entered automatically by computer)	V.5

Note: In the rare case when DSID field is insufficient for dataset identification it may be continued on a second identification record with columns 1-39 defined as above except that col. 6 will contain an alphanumeric character and columns 40-80 will be blank. If there is a continuation record, the DSID field on the first IDENTIFICATION record *must* end with a comma ‘,’.

2. History Record

The history records follow the Identification record and should appear in reverse-chronological order, with the most recent being the first.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than ‘1’ for continuation records	
7		Must be blank	
8	H	Letter ‘H’ is required	
9		Must be blank	
10-80	History	Dataset history consisting of various field descriptors and their values in cols 10-80 continued on any number of continuation records. Field descriptor is followed by an ‘=’ (without spaces before or after ‘=’) and the value and a terminator ‘$’ (‘$’ is not needed for the last field descriptor)	V.25

3. Q-value Record

Required for adopted data sets.
If there is only one data set for the nuclide, the Q-value record should be given in that data set.
Must precede ***L, G, B, E, A, DP*** *records.*
If signs are not given, they will be assumed to be +.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank	
7		Must be blank	
8	Q	Letter 'Q' is required	
9		Must be blank	
10-19	Q^-	Total energy (keV) available for β^- decay of the ground state ($Q^- > 0$ if β^- decay is energetically possible; $Q^- < 0$ represents the Q_ε energy of the Z+1 (Z = proton number) isobar).	V.10
20-21	DQ^-	Standard uncertainty in Q^-	V.11
22-29	SN	Neutron separation energy in keV	V.10
30-31	DSN	Standard uncertainty in SN	V.11
32-39	SP	Proton separation energy in keV	V.10
40-41	DSP	Standard uncertainty in SP	V.11
42-49	QA	Total energy (keV) available for α decay of the ground state	V.10
50-55	DQA	Standard uncertainty in QA	V.12
56-80	QREF	Reference citation(s) for the Q-values	V.3

4. Cross-Reference Record

Given only in adopted data sets.
*Must precede **L, G, B, E, A, DP** records.*

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank	
7		Must be blank	
8	X	Letter 'X' is required	
9	DSSYM	Any ASCII character that uniquely identifies the data set whose DSID is given in col. 10-39.	
10-39	DSID	*Must* exactly match one of the DSIDs used	V.2
40-80		Blank	

NOTES:

1. *Nuclear Data Sheets:* DSID on the first 'X' record in the data set will be identified with character 'A' and second DSID with 'B' and so on, irrespective of DSSYM on the X card. Only the first 14 DSIDs on 'X' records are given different symbols. All the rest are given the symbol 'O' (for others). By merely reshuffling the X-records, evaluators can ascertain the DSIDs that will be identified individually - this has no effect on the file and affects only the published output.
2. If the DSID for the data set is continued on to a second card, the DSID on XREF record must match the DSID on the first card, including the terminating ',' which will be translated into ellipses in the cross-reference table in the output.
3. There must be a data set corresponding to every given X-record.

5. Comment Record

General Comments
Must precede all **L, G, B, E, A, DP** *records*.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than '1' for continuation records	
7	C	Letter 'C', 'D', or 'T' is required *See notes 3 - 5 below*	
8	RTYPE	Blank or record type of records to which the comment pertains	V.6
9	PSYM	Blank, or symbol for a (delayed-)particle, e.g., N, P, etc.	
10-80	CTEXT	Text of the comment. [See ENSDF Translation Dictionary (Appendix F)]	V.7

NOTES:

1. The comment refers only to records of specified RTYPE given in that data set. The comment will normally appear only in the table for that RTYPE in the output. For example, if the comment is on levels ('L' in col. 8), that comment will appear only in the level properties table.

2. If col. 8 and 9 are blank, the comment refers to the whole data set. These general comments precede the formatted level or the radiation records. See Appendix B for use of comment records in COMMENTS data set.

3. Letter 'T' in place of 'C' in col. 7 of a comment record indicates to the output programs that this record should be reproduced 'as is' and the blanks in the record should not be squeezed out.

4. Letter 'D' in place of 'C' in col. 7 of a comment record indicates to the output programs that this is a documentation record and can be ignored. This record will also be ignored by the various analysis programs.

5. Lower case letters 'c' and 't' in col. 7 of a comment record indicate to the output programs that CTEXT in these records should not be translated. These will appear as written in *Nuclear Data Sheets*. One must write special characters directly in this mode, for example, '|g' for γ, '{+238}Pu' for ^{238}Pu. See Appendix A for list of special characters.

Record Comments

Must follow the record to which the comment pertains.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than '1' for continuation records	
7	C	Letter 'C' or 'D' is required *See notes 4 and 5 on General Comments*	
8	RTYPE	Record type being commented upon - can be blank for Particle records	V.6
9	PSYM	Blank, or symbol for a particle, e.g., N, P, etc.	
10-80	SYM$ or SYM, SYM…$	SYM = type of data being commented upon Specified SYMs must be followed by a '$' except as in note 1 below.	V.8
10-80	CTEXT	Text of comment follows the '$' On continuation comment records, CTEXT may start in col. 10, and SYM or SYMs are *not* repeated. [See ENSDF Translation Dictionary, Appendix F]	V.7

NOTES:

1. The old format, where SYM was specified in col. 10-19, will be accepted without the '$' delimiter as long as col. 19 is a blank, and comment text begins in col. 20.

2. Record comments placed following a record of the same **RTYPE** refer only to that one record (for example, a comment record with 'CL' in cols. 7-8 and 'T$' in col. 10-11 following the level record for the second-excited state refers to the half-life of *only* the second-excited state).

Footnote Comments

Must precede **L, G, B, E, A, DP** *records*

Field (Col.)	Name	Description	Reference
1-9		Same as in ii (Record Comments)	
10-80	SYM$ or SYM, SYM…$or SYM(FLAG)$ or SYM(FLAG), SYM(FLAG)…$	SYM = see note 1 below FLAG = any ASCII alphanumeric character or string of alphanumeric characters *Field must end with a '$'* *See note 1 on Record comments for exception*	V.8
10-80	CTEXT	Text of comment follows '$' On continuation comment records SYM or SYM (FLAG) are *not* repeated. [See ENSDF Translation Dictionary (Appendix F)]	V.7

NOTES:

1. SYM can only be one of the following:
   - The fields defined in formatted L, G, B, E, A, DP records.
   - BAND. This SYM *must* be accompanied with a FLAG. Also note that text following '$' delimiter, or in col. 20-80 in old format, will appear as the band label in some of the drawings. Therefore, any other information on that band should be given on continuation records.

2. Footnote without FLAG
   - This refers to all records of specified RTYPE in the data set.
   - The footnote will normally appear only in the table for that RTYPE in the output. For example, if the footnote is on levels ('L' in col. 8), this footnote will appear only in the level properties table.
   - Footnote with FLAG

     Only those records are footnoted for which footnote flags are given, see note 4 below.

     Only those data values of data types specified by SYM which is associated with a given FLAG are footnoted.

3. Footnote FLAG must be either a single character placed in col. 77 of the formatted record, or a string of characters assigned to a special data type called FLAG on the following continuation record.

   Examples of flags on a continuation record:

   ```
   152EU2 G FLAG=ABCD$
   156GD2 L FLAG=KMP$
   ```

4. No footnotes are allowed for records of RTYPE: N, P, or Q.

5. Change of the standard label heading of a formatted field, e.g., S to C^2S for L records - CTEXT should have the form LABEL=name, where ‘name’ is the new label desired. The new label should be kept as short as possible. Note that FLAG can not be specified with relabelling; also any other comment on the relabelled field must appear on a different record.

   Examples of field relabel:

   156GD CL S$LABEL=C2S
   156GD CL S$LABEL=DSIGMA/DOMEGA (45 DEG)

6. Parent Record

Required for all decay data sets.
Must precede ***L, G, B, E, A, DP*** *records.*

Field (Col.)	Name	Description	Reference
1-5	NUCID	Parent Nuclide identification	V.1
6		Must be blank	
7		Must be blank	
8	P	Letter 'P' is required	
9		Blank or an integer in case of multiple P records in the data set	
10-19	E	Energy of the decaying level in keV (0.0 for g.s.)	V.18
20-21	DE	Standard uncertainty in E	V.11
22-39	J	Spin and parity	V.20
40-49	T	Half-life; units *must* be given	V.14
50-55	DT	Standard uncertainty in T	V.12
56-64		Must be blank	
65-74	QP	Ground-state Q-value in keV (total energy available for g.s. $\rightarrow$ g.s. transition); it will always be a positive number Not needed for IT and SF decay	V.9
75-76	DQP	Standard uncertainty in QP	V.11
77-80	ION	Ionization State (for Ionized Atom decay), otherwise blank	

NOTES:

1. More than one parent card is allowed in a data set. If the decay scheme is due to more than one parent, separate P records should be given for each parent level.

2. Currently, publication program allows maximum of two parent cards.

3. Parent information, *namely*, E, J, T, QP must be identical to their values given in the Adopted Levels data set.

7. Normalization Record

*Must precede **L, G, B, E, A, DP** records.*
Required if an absolute normalization is possible;
used mainly with decay and (n, γ) reaction data sets.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide (Daughter/Product) identification	V.1
6		Must be blank	
7		Must be blank	
8	N	Letter 'N' is required	
9		Blank or an integer in case of multiple P records in the data set Should correspond to the designator on the P record	
10-19	NR	Multiplier for converting relative *photon* intensity (RI in the GAMMA record) to *photons* per 100 decays of the parent through the decay branch or to *photons* per 100 neutron captures in an (n, γ) reaction. *Required* if the absolute photon intensity can be calculated	V.9
20-21	DNR	Standard uncertainty in NR	V.11
22-29	NT	Multiplier for converting relative *transition* intensity (including conversion electrons) [TI in the GAMMA record] to *transitions* per 100 decays of the parent through this decay branch or per 100 neutron captures in an (n, γ) reaction. *Required* if TI are given in the GAMMA record and the normalization is known	V.9
30-31	DNT	Standard uncertainty in NT	V.11
32-39	BR	Branching ratio multiplier for converting intensity per 100 decays through this decay branch to intensity per 100 decays of the parent nuclide *Required if known*	V.9
40-41	DBR	Standard uncertainty in BR	V.11
42-49	NB	Multiplier for converting relative β^- and ε intensities (IB in the β^- record; IB, IE, TI in the EC record) to intensities per 100 decays through this decay branch *Required if known*	V.9

Field (Col.)	Name	Description	Reference
50-55	DNB	Standard uncertainty in NB	V.11
56-62	NP	Multiplier for converting per hundred delayed-transition intensities to per hundred decays of precursor	V.9
63-64	DNP	Standard uncertainty in NP	V.11
65-80		Must be blank	

Normally β^- and ε intensities are given as per 100 parent decays. One should remember that the multiplier for conversion to per 100 decays is NB x BR, and therefore NB = 1/BR. Also, the uncertainties in $I(\beta^-)$ will be calculated from the addition of three quantities $\Delta(I(\beta^-))$, DBR and DNB in quadrature. Unless the uncertainties are precisely known, NB should be given without uncertainty. See PN record.

If more than one P records exist in the data set, there should be corresponding N records giving the respective branching ratios.

8. Production Normalization Record

*Must follow **N** record, if **N** record present.*
*Should be given when **G** records with intensities are present.*

Field	Name	Description
1-5	NUCID	Nuclide (Daughter/Product) identification
6		Blank
7	P	Letter 'P' (for production) is required
8	N	Letter 'N' is required
9		Must be blank
10-19	NRxBR	Multiplier for converting relative *photon* intensity (RI in the GAMMA record) to *photons* per 100 decays of the parent (normally NRxBR) If left blank, (NR DNR)x(BR DBR) from N record will be used for normalization
20-21	UNC[4]	Standard uncertainty in NRxBR
22-29	NTxBR	Multiplier for converting relative *transition* intensity (including conversion electrons) [TI in the GAMMA record] to *transitions* per 100 decays of the parent (normally NTxBR) If left blank, (NT DNT)x(BR DBR) from N record will be used for normalization
30-31	UNC[1]	Standard uncertainty in NTxBR
42-49	NBxBR	Multiplier for converting relative β^- and ε intensities (IB in the B- record; IB, IE, TI in the EC record) to intensities per 100 decays If left blank, (NB DNB)x(BR DBR) from N record will be used for normalization.
50-55	UNC[1]	Standard uncertainty in (NB DNT)x(BR DBR)
56-62	NP	Same as in 'N' record
63-64	UNC[1]	Standard uncertainty in NP
77	COM	Blank or 'C' (for comment) If blank, comment associated with the intensity option will appear in the drawing of *Nuclear Data Sheets* If letter 'C' is given, the desired comment to appear in the drawing should be given on the continuation ('nPN') record(s), col. 10-80
78	OPT	Intensity Option - option as to what intensity to display in the drawings of *Nuclear Data Sheets*; available options are given below (default option 3)

[4] If left blank no uncertainty will appear in the publication.

Option	Intensity displayed	Comment in drawing
1	TI or RI(1+α)	Relative I(γ+ce)
2	TIxNT or RIxNRx(1+α)	I(γ+ce) per 100 (mode) decays
3	TIxNTxBR or RIxBRxNRx(1+α)	I(γ+ce) per 100 parent decays
4	RIxNTxBR	I(γ) per 100 parent decays
5	RI	Relative I(γ)
6	RI	Relative photon branching from each level
7	RI	photon branching from each level

9. Level Record

Optional, although a data set usually has at least one.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than `1' for continuation records	
7		Must be blank	
8	L	Letter 'L' is required	
9		Must be blank	
10-19	E	Level energy in keV - m*ust not be blank*	V.18
20-21	DE	Standard uncertainty in E	V.11
22-39	J	Spin and parity	V.20
40-49	T	Half-life of the level; units *must* be given Mean-life expressed as the width of a level, in units of energy, may also be used	V.14
50-55	DT	Standard uncertainty in T	V.12
56-64	L	Angular momentum transfer in the reaction determining the data set (whether L_n, L_p, ΔL, etc., is determined from the DSID field of the IDENTIFICATION record)	V.22
65-74	S	Spectroscopic strength for this level as determined from the reaction in the IDENTIFICATION record (spectroscopic factor for particle-exchange reactions; β for inelastic scattering) If a quantity other than spectroscopic factor is given in this field, a footnote relabelling the field is required	V.21
75-76	DS	Standard uncertainty in S	V.11
77	C	Comment FLAG used to refer to a particular comment record	V.8
78-79	MS	Metastable state is denoted by 'M' or 'M1' for the first (lowest energy) isomer; 'M2', for the second isomer, etc. Ionized Atom Decay: field gives the atomic electron shell or subshell in which β^- particle is captured	V.17
80	Q	Character '?' denotes an uncertain or questionable level Letter 'S' denotes neutron, proton, alpha separation energy or a level expected, but not observed	

10. Beta (β^-) Record

Must follow the LEVEL record for the level which is fed by the β^-.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than '1' for continuation records	
7		Must be blank	
8	B	Letter 'B' is required	
9		Must be blank	
10-19	E	Endpoint energy of the β^- in keV *Given only if measured*	V.18
20-21	DE	Standard uncertainty in E	V.11
22-29	IB	Intensity of the β^--decay branch[5]	V.13
30-31	DIB	Standard uncertainty in IB	V.11
42-49	LOGFT	Log *ft* for the β^- transition for uniqueness given in col. 78-79	V.9
50-55	DFT	Standard uncertainty in LOGFT	V.12
56-76		Must be blank	
77	C	Comment FLAG (Letter 'C' denotes coincidence with a following radiation	V.8
	A	'?' denotes probable coincidence with a following radiation)	
78-79	UN	Forbiddenness classification for the β^- decay, e.g., '1U', '2U' for first-, second-unique forbidden (blank field signifies an allowed transition; non-unique forbiddenness can be indicated in col 78, with col 79 blank)	V.16
80	Q	Character '?' denotes an uncertain or questionable β^- decay Letter 'S' denotes an expected or predicted transition	

[5] Intensity units are defined by the NORMALIZATION record.

11. EC (or EC + β^+) Record

Must follow the LEVEL record for the level being populated in the decay.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than '1' for continuation records	
7		Must be blank	
8	E	Letter 'E' is required	
9		Must be blank	
10-19	E	Energy for *electron capture* to the level end-point energy Given only if measured or deduced from measured β^+	V.18
20-21	DE	Standard uncertainty in E	V.11
22-29	IB	Intensity of β^+-decay branch[6]	V.13
30-31	DIB	Standard uncertainty in IB	V.11
32-39	IE	Intensity of electron capture branch[6]	V.13
40-41	DIE	Standard uncertainty in IE	V.11
42-49	LOGFT	Log ft for ($\varepsilon + \beta^+$) transition for uniqueness given in col. 78-79	V.9
50-55	DFT	Standard uncertainty in LOGFT	V.12
65-74	TI	Total ($\varepsilon + \beta^+$) decay intensity[6]	V.13
75-76	DTI	Standard uncertainty in TI	V.11
77	C	Comment FLAG (letter 'C' denotes coincidence with a following radiation	V.8
	A	'?' denotes probable coincidence with a following radiation)	
78-79	UN	Forbiddenness classification for ε, β^+ decay e.g., '1U', '2U' for first, second unique forbidden (blank signifies an allowed or a non-unique forbidden Transition: non-unique forbiddenness can be indicated in col 78, with col 79 blank)	V.16
80	Q	Character '?' denotes an uncertain or questionable ε, + β^+ branch Letter 'S' denotes an expected or predicted transition	

[6] IE, IB and TI must be in the same units (see also NB in NORMALIZATION record).

12. Alpha Record

Must follow the LEVEL record for the level being populated in the decay.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank	
7		Must be blank	
8	A	Letter `A' is required	
9		Must be blank	
10-19	E	Alpha energy in keV	V.18
20-21	DE	Standard uncertainty in E	V.11
22-29	IA	Intensity of α-decay branch in *percent* of the total α-decay	V.13
30-31	DIA	Standard uncertainty in IA	V.11
32-39	HF	Hindrance factor for α decay	V.9
40-41	DHF	Standard uncertainty in HF	V.11
42-76		Must be blank	
77	C	Comment FLAG (letter ‘C’ denotes coincidence with a following radiation ‘?’ denotes probable coincidence with a following radiation)	V.8
78-79		Must be blank	
80	Q	Character ‘?’ denotes uncertain or questionable α branch Letter ‘S’ denotes an expected or predicted α branch	

13. (Delayed-) Particle Record

Must follow the LEVEL record for the level which is fed by the particle. Records for particles which are unassigned in a level scheme should precede the first level of the data set.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than '1' for continuation records	
7		Must be blank	
8	D	Blank for prompt-, letter 'D' for delayed-particle emission	
9	Particle	The symbol for the (delayed) particle (N = neutron, P = proton, A = alpha particle) is required)	
10-19	E	Energy of the particle in keV	V.18
20-21	DE	Standard uncertainty in E	V.11
22-29	IP	Intensity of (delayed) particles in *percent* of the total (delayed-)particle emissions	V.13
30-31	DIP	Standard uncertainty in IP	V.11
32-39	EI	Energy of the level in the 'intermediate' (mass = A+1 for n, p; A+4 for α) nuclide in case of delayed particle	V.13
40-49	T	Width of the transition in keV	V.14
50-55	DT	Uncertainty in T	V.12
56-64	L	Angular-momentum transfer of the emitted particle	V.22
65-76		Blank	
77	C	Comment FLAG used to refer to a particular comment record	V.8
78	COIN	Letter 'C' denotes placement confirmed by Coincidence; symbol '?' denotes probable coincidence	V.15
79	Blank		
80	Q	Character '?' denotes an uncertain placement of the transition in the level scheme Letter 'S' denotes an expected, but as yet unobserved, transition	

NOTES:

1. The delayed-particle record will appear in a delayed-particle data set (e.g., B-N DECAY, ECP DECAY, etc.) which should be given under the A-chain for the final nuclide. For example, '95RB B-N DECAY' should be given as data set for ^{94}Sr.

2. Intensity units are defined by the NORMALIZATION record.

14. Gamma Record

Must follow the LEVEL record for the level from which the γ ray decays. Records for γ rays which are unassigned in a level scheme should precede the first level of the data set.

Field (Col.)	Name	Description	Reference
1-5	NUCID	Nuclide identification	V.1
6		Blank Any alphanumeric character other than '1' for continuation records	
7		Must be blank	
8	G	Letter 'G' is required	
9		Must be blank	
10-19	E	Energy of the γ ray in keV *Must not be blank*	V.18
20-21	DE	Standard uncertainty in E	V.11
22-29	RI	Relative *photon* intensity[1]	V.13
30-31	DRI	Standard uncertainty in RI	V.11
32-41	M	Multipolarity of transition	V.19
42-49	MR	Mixing ratio δ (sign must be shown explicitly if known; if no sign is given, assumed to be unknown)	V.10
50-55	DMR	Standard uncertainty in MR	V.12
56-62	CC	Total conversion coefficient	V.9
63-64	DCC	Standard uncertainty in CC	V.11
65-74	TI	Relative total transition intensity[6]	V.13
75-76	DTI	Standard uncertainty in TI	V.11
77	C	Comment FLAG used to refer to a particular comment record; symbol '*' denotes a multiply-placed γ ray; symbol '&' denotes a multiply-placed transition with intensity <u>not</u> divided; symbol '@' denotes a multiply-placed transition with intensity suitably divided; symbol '%' denotes that the intensity given as RI is the branching in the Super Deformed Band	V.8
78	COIN	Letter 'C' denotes placement confirmed by Coincidence; symbol '?' denotes questionable coincidence	V.15
79		Blank	
80	Q	Character '?' denotes an uncertain placement of the transition in the level scheme, 'S' denotes an expected, but as yet unobserved, transition	

[7] Intensity units are defined by the NORMALIZATION record.

15. Reference Record

Record can occur only in Reference data set.
NNDC provides the Reference data set.

Field (Col.)	Name	Description	Reference
1-3	MASS	Mass Number	
4-7		Must be blank	
8	R	Letter 'R' is required	
9		Must be blank	
10-17	KEYNUM	Reference key number	V.3
18-80	REFERENCE	Abbreviated reference (from NSR file)	

16. End Record

Required for <u>all</u> data sets.
Must be the last record in a data set.

Field (Col.)	Description
1-80	All columns are blank

C. Summary

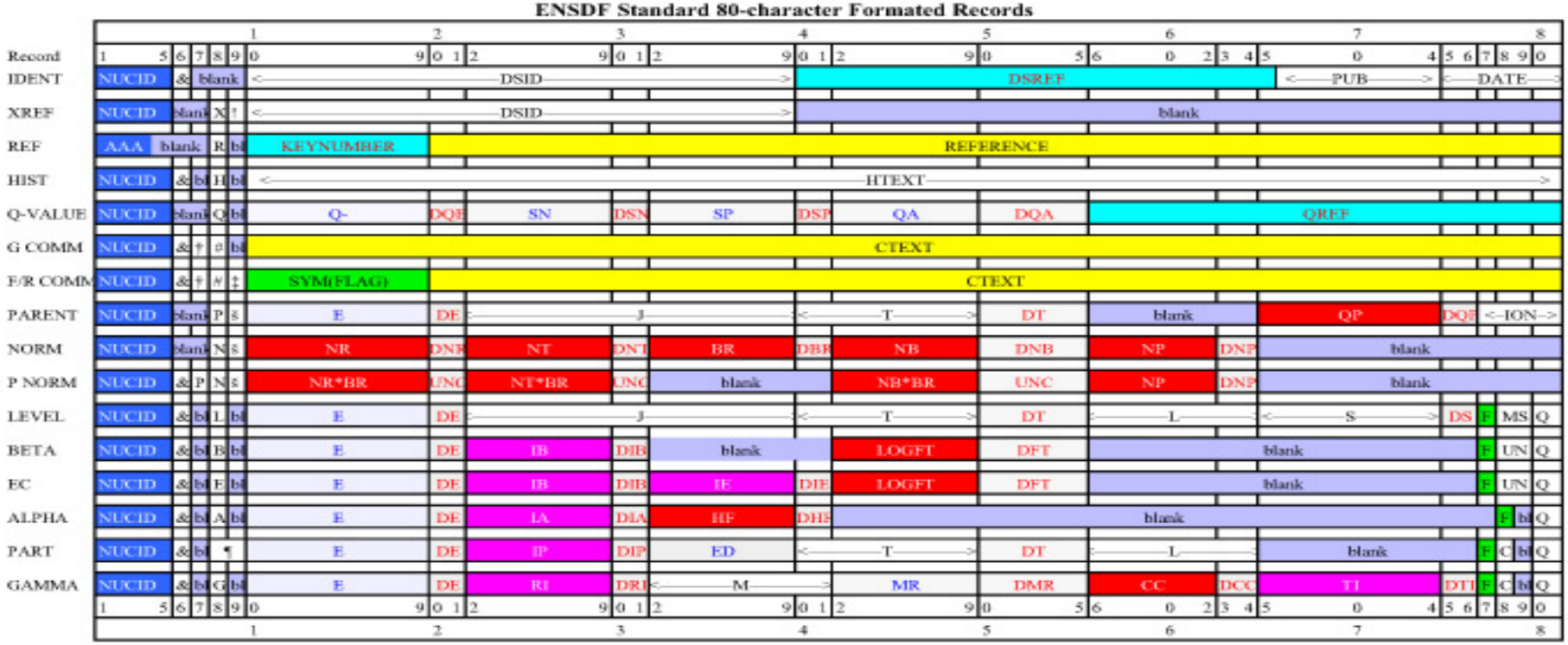
The following two pages summarize the standard one-card formats for all allowed record types.

SUMMARY OF STANDARD ONE-CARD RECORD FORMAT

Col				Record TYPE								
No.	R	I	X	C/D	Q	N	P	L	G	B	E	A	Particle
--	---	---	---	---	---	---	---	---	---	---	---	---	---
1-3	←----------Mass----------→												
4-5	←----------Element symbol----------→												
6		#		#	#	#	#	#	#	#	#	#	
7				C/D									
8	R			@	Q	N	P	L	G	B	E	A	D(delayed)
9		#											P/N/A
10-39		ID	ID										
10-19	key#		SYM		Q-	NR	←----------E----------→						
20-21					DQ-	DNR	←----------DE----------→						
20-80	Ref		Com										
22-39						J	J						
22-29				SN	NT			RI	IB	IB	IA	IP	
30-31				DSN	DNT			DRI	DIB	DIB	DIB	DIP	
32-41									M				
32-39				SP	BR					IE	HF	ED	
40-41				DSP	DBR					DIE	DHF		
40-49							T	T					T
40-65	Ref												
42-49				QA	NB			MR	←LOGFT→				
50-55				DQA	DNB	DT	DT	DMR	←DFT→				
56-62								CC					
56-64								L					L
56-80				Qref									
63-64								DCC					
65-74						QP	S	TI		TI			
66-74	PUB												
75-76						DQP	DS	DTI		DTI			
75-80	Date												
77								C	a	C	C	C	C
78-79							MS	C/?	UN	UN			
80								Q	Q	Q	Q	Q	Q

Any ASCII Character
@ L,G,B,A,E,N,Q,P for record comments following the respective record
* denotes multiply placed
@ denotes multiply placed, intensity sitably divided
& denotes multiply placed, undivided intensity given
% denotes that the intensity given is % branching in SD band

ENSDF Standard 80-character Formated Records



Notes:

blank	These fields must be blank.
&	Primary record must have a blank or "1" in this field. Continuation records should have any printable ASCII character except for blank or "1" (one).
!	Unique alphanumeric character identifying the source data set.
†	Allowed characters for this field are C, c, D, d, T, and t.
#	Character identifying the record being commented on. Allowed characters for this field are N, P, Q, L, G, B, E, A, D, and blank.
‡	Must be blank except for: 1) Particle code for a (delayed-)particle record. 2) Sequence number for normalization and parent records.
§	Must be blank except when there are multiple parent records then this field should contain an integer relating the parent record to the related normalization record.
¶	Byte 8 must either be blank for a prompt particle radiation or D for a delayed particle radiation. Byte 9 identifies the particle (N, P, D, or T).

Chapter IV

IV. RECORDS CONTAINING MORE THAN ONE CARD

A. Card Enumeration

Certain record types, namely the Identification, History, Parent, and Normalization records, can have multiple occurrence of records with qualifications as indicated in the descriptions of these record types. For other record types if all the information cannot be contained on a single card, additional cards can be used to describe the record fully. The first card of a record will have a blank in col. 6 and subsequent cards will have an ASCII character different from blank or 1 (usually running numbers: 2 to 9 or letters A to Z).

B. Format for Continuation Cards

CONTINUATION RECORD
Must follow the record of the same RTYPE.

Field	Name	Description
1-5	NUCID	Nuclide identification
6		Any alphanumeric character other than 1 'S' is reserved for computer-produced records which will usually be suppressed in *Nuclear Data Sheets*
7		Must be blank
8	RTYPE	Letter corresponding to the record type L, B, E, G or H
9		Must be blank
10-80	Data	< quant >< op >< value >[< op >< value >][< ref >]$ …

The following abbreviations have been used in the description of the data above:

< quant >: Standard symbol for a quantity as defined in IV.C below
1. Ratios of more than two quantities should be indicated by colons and not by slashes (e.g., K:L1:L2:L3 and not K/L1/L2/L3)
2. See Section V.24 for description of < value > when < quant >=XREF
3. See Section V.25 for description of items for H record

< op >: =, <, >, <=, >=, EQ, AP, LT, LE, GT, GE
blanks before and after the last 6 operators are required.

< value>: Numeric value with units as needed and optional uncertainty.
Uncertainty is as defined in Sections V.11 and V.12.
Uncertainties should not be included for ranges.
A bounded range of values is specified by a second operator (=, EQ, AP are not valid) and value,
See examples below.

[…]:	Optional
< ref >:	8 character key numbers, KEYNUM (see Section V.3), separated by commas and enclosed within parentheses, e.g., (1976TU01,1981BO01)
$:	Delimiter (end of record is also a delimiter; thus '$' is not needed for the last item on a record)

Examples:

```
126TE 2   G       BE2W=25.3 7(1970LAZM)
126I  2 L %EC+%B+=56.3 20 (1977JA04)$%B- EQ 43.7 20 (1977JA04)
126SN S   B       EAV=2030 60
126TE 2   L       G LE 0.19 GT 0.1 (1981SH15)$MOME2 AP -0.20$BE2=0.478 12
```

C. Allowed Data Types on Continuation Records

Each record type is permitted to contain only a limited (but extendable) set of data types. For example, a GAMMA record is not allowed to contain information of data type DTYPE = J (nuclear spin); similarly, a LEVEL record is not allowed to contain LOGFT information.

A and DP records: only FLAG in addition to the quantities on the formatted records can be given on a continuation record. The allowed data types for LEVEL, GAMMA, B-, and EC records are described below.

1. Level Record

Allowed data types E, DE, J, T, DT, L, S, DS, C, MS, Q are described with the standard formats in Section III.B.9. Additional allowed data types are:

TYPE	**Description**
%EC,%B+,%EC+%B+,	Percent decay of the level by ε, β^+, ε + β^+,
%B-,%IT,%SF	β^-, isomeric transition, spontaneous fission,
%A,%P,%N …	α, proton, or neutron decay, …
%B-N; %B-XN …	Percent delayed decay through n, xn emission,…. Similarly, for other particle emissions, e.g., p, xp, α, xα, etc., following β^-, β^+, or ε decays. *Decay modes must be given on '2 L' card in adopted set, and on an 'S L' card in decay and (n, γ) data sets*
ION	Ionization State (used in Ionized Atom Decay)
CONF	Nuclear configuration of the level
BE1, BE2 …	Reduced electric transition probability (upward) given in units e^2 x $(barns)^L$, where L = 1, 2, … for the transition from the ground state to this level
B2, B3 …	2^L - pole (L=2,3,…) nuclear deformation parameter
FLAG	Additional footnote symbols
G	g-factor of the level
ISPIN	Isobaric spin
ISPINZ	Z-component of Isobaric Spin
MOME1, MOME2 …	Electric moments: dipole, quadrupole, …
MOMM1, MOMM2 …	Magnetic moments: dipole, quadrupole, …
WIDTH,WIDTHG, WIDTHG0,WIDTHN, WIDTHP, WIDTHA	Level width, Γ, Partial-γ , -γ0, -n, -p, -α widths, Γ (γ), Γ(γ0), Γ(n), Γ (p), Γ(α), respectively
XREF	Cross-reference to other data sets for that nuclide; this is generally given only in the adopted set

2. Gamma Record

Allowed data types, E, DE, RI, DRI, M, MR, DMR, CC, DCC, TI, DTI, C, COIN, Q, are described with the standard formats in Section III.B.14. Additional allowed data types are:

DTYPE	**Description**
BE1, BE2 …	Reduced electric transition probability (downward) given in units of e^2 x $(barns)^L$, where L = 1, 2, …
BE1W, BE2W …	Reduced electric transition probability (downward) given in single-particle (Weisskopf) units
BM1,BM2 …	Reduced magnetic transition probability (downward) given in units of μ^2_N x $(barns)^{L-1}$, where L = 1, 2 …
BM1W,BM2W …	Reduced magnetic transition probability (downward) given in single-particle (Weisskopf) units
CE	Total conversion electron intensity
CEK,CEL …	Conversion-electron (ce) intensity for K, L, …
CEL1 …	L_1 … conversion
ECC	Measured total conversion coefficient
EKC, ELC, EL1C …	Measured K-, L-, L1-… conversion coefficient
FL	Final level energy; must be either identical to a level energy in the data set optionally followed by a '?' (latter expresses uncertain placement) or a '?' (if the final level is not known)
FLAG	Additional footnote symbols
KC,LC,L1C …	Theoretical K-, L-, L_1-… conversion coefficient
K:L,M:L,L1:L2 …	Conversion-electron intensity ratios
K:T,L:T …	Ratio of K, L …ce-intensity to total (γ+ ce) intensity

3. Beta (β^-) Record

Allowed data types E, DE, IB, DIB, LOGFT, DFT, C, UN, Q, are described with the standard formats in Section III.B.10. Additional allowed data types are:

DTYPE	Description
EAV	Average energy of the β^- spectrum
FLAG	Additional footnote symbols 'C' and '?' may not be used - see Section III.B.10 for their special meaning

4. EC Record

Allowed data types, E, DE, IB, DIB, IE, DIE, LOGFT, DFT, TI, DTI, C, UN, Q, are described with the standard formats in Section III.B.11. Additional allowed data types are:

DTYPE	Description
EAV	Average energy of the β^+ spectrum
CK,CL,CM … CL+	Calculated fraction of decay by electron capture from the K, L, M …, L+M+…shells
ECK,ECL,ECM … ECL+	Measured fraction of decay by electron capture from the K, L, M …, L+M+… shells
CK/T,CL/T ...	Ratio of K, L ... ε-intensity to total ε intensity
FLAG	Additional footnote symbols 'C' and '?' may not be used - see Section III.B.11 for their special meaning

Chapter V

V. DETAILED FIELD DESCRIPTIONS

1. NUCID

The standard nuclide identification consists of two parts - mass number in cols. (1-3), right justified, and element name (or Z – 100 for Z 109) in (col. 4-5), left justified. The nuclide identification must be contained within the defined field (cols. 1-5). The nuclide identification must be included on every card of a data set except the END record. Comments and reference data sets pertaining to the whole A-(mass) chain evaluation contain only the A-value in the NUCID field.

2. DSID

Data Set ID for an ENSDF data set serves as a unique, computer recognizable identification for the data set. There can not be two data sets with identical DSID and NUCID. However rare circumstances do occur when two data sets with the same DSID for a given NUCID are accommodated by ending DSID with a colon (:), followed by a unique identifier which will then be different for the various data sets with that DSID.

The following rules for DSID should be strictly observed for ENSDF entries. Single blanks have meaning and should be used according to the formats below. Optional fields are given in italics in the description below. General categories are given in upper and lower cases and are further defined. DSID \underline must be confined to the 30 spaces allowed. However the field may be continued into the DSID field on the second ID record as explained in Chapter III, in which case the DSID on the first record \underline must end with a comma ‘,’.

GENERAL IDs
REFERENCES
COMMENTS (see Appendix B for format for this data set)
ADOPTED LEVELS
ADOPTED LEVELS, GAMMAS
DECAY DATA SET IDs
Parent Mode Decay (Half-life)
Parent should be the parent nuclide symbol, e.g., 52CR
For SF decay more than one parent can be given separated by commas
For Ionized Atom Decay parent nuclide symbol is followed by ionization state in square brackets, e.g., 187RE[+75]
Mode may be one of B+, B-, EC, IT, A, P, B-N, ECP, SF ...
List of decay modes may be expanded.
Half-life can be of the form T defined in Section V.14.1

MUONIC ATOM
REACTION DATA SET IDs
Target(Reaction), (Reaction), Target(Reaction) E=Energy Qualifier
COULOMB EXCITATION
(HI,XNG)
Target should be the target (nuclide or element) symbol
Reaction should be given as (in,out), e.g., (N,P)
'in' is the incident particle, 'out' are the outgoing particles
Energy may be one of the following
NUM, NUM Units (for definition of NUM see Section V.9.)
NUM-NUM Units
TH (for thermal)
RES (for resonance)
Qualifier may be one of the following
RES
IAR
IAS
EXAMPLES:

187RE B- DECAY	187OS IT DECAY (231 US)
187RE[+75] B- DECAY	187AU P DECAY:?
190PT A DECAY (6E11 Y)	95RB B-N DECAY
186OS(N,G) E=THERMAL	186W(N,G) E=TH: SECONDARY
RE(N,N'):TOF	238U(N,FG) E=TH
186W(N,G) E=RES: AVG	189OS(P,T) E=19 MEV
187OS(D,D') E=12, 17 MEV	185RE(A,2NG) E=23-42.8 MEV
187RE(D,2NG), 187RE(P,NG)	44CA(P,G) E=856, 906 KEV IAR
PB(238U,FXG)	PB(238U,XG)

3. DSREF, KEYNUM, QREF

The DSREF and QREF fields may include up to three key numbers (KEYNUM), each of which refers to a particular publication. Additional key numbers may be placed in COMMENT records. Key numbers must be left-justified and separated by commas with no blanks between the comma and the reference. A reference key number must be of the form YYYYAABB where YYYY is a four digit integer, AA are two alphabetic characters and BB is either a two digit integer or consists of two alphabetic characters. Examples: 1981TU01, 1981TUXY, etc.

4. PUB

Publication information generally consists of the year of the A-chain publication denoted by two digit year indicator, followed by the three-character code NDS for Nuclear Data Sheets and two-letter code NP for Nuclear Physics-A. This may be optionally followed by a comma and other updating information, e.g., the initials of the person modifying the data set after publication. Example: 78NDS,TWB or 81NDS.

5. DATE

This field is of the form YYYYMM where YYYY and MM are four and two digit integers, respectively, within the following ranges: YY $\geq$ 1900 and 01 $\leq$ MM $\leq$ 12.

6. RTYPE

RTYPE is a two-letter code in col. 8-9 that gives a name to the RECORD type. Note that col. 9 is blank for most of the RTYPE tabbing.

RTYPE	Description
blank	May be IDENTIFICATION, general COMMENT, or END record
H	HISTORY record
N	NORMALIZATION record Production Normalization record has 'P' in col 7.
P	PARENT record
Q	Q-VALUE record
L	LEVEL record
G	GAMMA record
B	BETA (β^-) record
E	EC (for ε, β^+ or ϵ + β^+) record
A	ALPHA record
R	REFERENCE record
X	CROSS-REFERENCE record
DP	DELAYED PARTICLE record, or PARTICLE (col.8=blank) record Particle symbol (e.g., 'P' for proton) is given in col. 9

7. CTEXT

This field consists of free text. The various expressions used in CTEXT can be translated via dictionary lookup. The translation dictionary is given in Appendix F. The unit expression used in translation is the string of characters between adjacent 'delimiters'. Characters presently used as 'delimiters' are:
b(blank) ,(comma) .b(period followed by a blank) ; : ( ) - = + < > / and $

The dictionary lookup programs in some cases look beyond the next delimiter for proper translation.

8. SYM(FLAG)

The SYM(FLAG) field (with FLAG given) is valid only for records with RTYPE: L, G, B, E, A, DP. However, SYM (without FLAG) may additionally be used for record types N, P, and Q.

FLAG can be a string of characters optionally separated by commas. Any character other than a comma and parentheses can be used as a FLAG symbol. 'C' for B and E records can not be used as a FLAG because 'C' in column 77 of B, E, and A records denotes coincidence. Similarly '*', '@', '%', and '&' for G records are reserved with special meaning (Section III.B.14). See notes on SYM and FLAG under description of COMMENT record. FLAG can be used only with SYMs which are valid data types on a formatted card or with BAND (FLAG must be given for BAND)

Allowed symbols to be used as SYM for various RTYPE are currently limited to the fields allowed on the formatted records.

9. BR, CC, HF, LOGFT, NB, NP, NR, NT, QP

These fields consist of either a blank or a single unsigned number (NUM) in one of the following forms:

1. An integer (e.g., 345)
2. A real number (e.g., 345.23)
3. An integer followed by an integer exponent (e.g., 345E-4, 4E+5)
4. A real number followed by an integer exponent (e.g., 345.E-4)

Note: desirable to write a number as '0.345' rather than '.345'.

10. MR, Q-, QA, SN, SP

These fields have the same form as the quantities in Section V.9. above, with the difference that they are allowed to have signature (positive or negative).

11. DBR, DCC, DE, DHF, DIA, DIB, DIE, DIP, DNB

Includes DNR, DNP, DNT, DQP, DQ-, DS, DSP, DTI

These two character fields represent uncertainty in the 'standard' form in the given quantity. The 'standard' numeric uncertainty denotes an uncertainty in the last significant figure(s), for example, NR=0.873, DNR=11 represent a normalization factor of 0.873 ± 0.011, similarly QP=2.3E6, DQP=10 stand for a Q-value of $(2.3 \pm 1.0) \times 10^6$ (see also General Policies given in Appendix H). The non-numeric uncertainty, e.g., <, >, or ≥, etc. is denoted by expressions LT, GT and GE, etc. The allowed forms for these fields are summarized below:

1. Blank
2. An integer <99, preferably <25, (left or right justified)
3. One of the following expressions:
   LT, GT, LE, GE, AP, CA, SY
   for <, >, ≤, ≥, ≈ , calculated, and from systematics, respectively.

12. DFT, DMR, DT, DNB, DQA

These fields allow for the specification of 'standard' asymmetric uncertainty. For example, T=4.2 S, DT=+8-10 represent a half-life=$4.2^{+0.8}_{-1}$ s, similarly MR=-3, DMR=+1-4 represent mixing ratio=-3^{+1}_{-4} (meaning a range from -7 to -2 (asymmetric uncertainties add algebraically)). When the +/- construction is missing from this field, the digits or the expressions given in this field represent either the numeric 'standard' symmetric or the non-numeric uncertainty, as described in Section V.11 above.

Summarizing this field, there are two cases:

1. Symmetric uncertainty - the field consists of an integer number or an expression of the type described in Section V.11 above.

2. Asymmetric uncertainty - the field is of the form +x-y, where x and y are integers.

13. IA, IB, IE, IP, RI, TI

The following numbers/expressions are valid for these fields:

1. NUM (number as defined in Section V.9 above)

2. (NUM)

Parentheses denote that the number given has been deduced (not directly measured) or taken from other experiment(s).

14. T

The field for half-life T must have one of the following forms:

1. NUM-Blank-Units (i.e., number as defined in Section V.9 above, followed by a blank and units). Valid symbols for units are: Y, D, H, M, S, MS, US, NS, PS, FS, AS, EV, KEV, and MEV, for year, day, hour, minute, second(s), 10^{-3} s, 10^{-6} s, 10^{-9} s, 10^{-12} s, 10^{-15} s, 10^{-18} s, eV, 10^{3} eV, and 10^{6} eV, respectively.

2. Word 'STABLE'

A question mark following the half-life denotes that the assignment to that level is not certain. A comment should be given to explain the exact meaning intended.

15. COIN

This one character field can either be blank or have character ‘C’ or ‘?’. The character ‘C’ denotes coincidence, while ‘?’ denotes questionable coincidence.

16. UN

This two character field can either be blank for allowed transitions, or have an integer between 1 and 9 indicating order of forbiddeness, followed by a blank for ‘non-unique’ or a ‘U’ for unique transition.

17. MS

This two character field can either be blank or have character ‘M’ followed by a blank or a digit between 1 and 9.

18. E

An energy field (E) can only have one of the following forms:

1. NUM (as defined in Section V.9 above)

2. NUM+A or A+NUM, where A=X, Y, Z, U, V, W, A, B,... in this order: i.e., for the first occurrence ‘X’ is used, for second occurrence ‘Y’ is used, and so on.

3. SN+NUM, SP+NUM - resonance energies should be given in center-of-mass system, as far as possible.

4. A (as defined in 2. above)

Parentheses are allowed for this field. They denote that the number given has been deduced (not directly measured) or taken from other experiment(s). Explanation as to what is intended should be given.

19. M

The multipolarity field can be one of the following:

1. Mult
2. Mult + Mult
3. Mult, Mult
4. NOT Mult

MULT

where Mult = E_L or M_L'
(where L, L' are single digits – $L \geq 0$, $L' \geq 1$)

$M_L' + E_L$ or
$E_L + M_L'$ or
D or Q

Parentheses in the multipolarity field denote that the assignment is probable and not definite. Square brackets indicate assumed or derived assignment.

20. J

The spin-parity field can have only one of the following forms:

1. JPI (can be J, π, or Jπ)

2. PI OR JPI (',' (comma) can be used in place of 'OR')

3. JPI AND JPI ('&' (ampersand) can be used in place of 'AND')

4. OP JPI (where OP is AP, LE, or GE)
This will be interpreted as π = PI and J is OP J
Example: $\leq$ 5+ means π = + and J $\leq$ 5

5. NOT JPI

6. JPI TO JPI (':' (colon) can be used in place of 'TO')
If parity is given in the range this parameter will be interpreted as follows:

   a) J to J'PI means J $\leq$ J $\leq$ J' and π = PI

   b) JPI to J'PI' means JPI, J = J+1 PI = $\pm$,...,J = J'-1 PI = $\pm$,J'PI'

   c) JPI to J' means JPI, J = J+1 PI = $\pm$,...,J = J'-1 PI = $\pm$, J'PI = $\pm$

Examples:

a) 3 to 6- means Jπ = 3-, 4-, 5-, 6-

b) 3+ to 6- means Jπ = 3+, 4±, 5±, 6-

c) 3+ to 6 means Jπ = 3+, 4±, 5±, 6±

7. NATURAL/UNNATURAL

8. A or A+JPI (where A is one of the characters, J, K, L, M, N, O, P...)

As given above J = N or N/2 (N is a positive integer or zero)
PI(π) = + or -
JPI = J or PI or J followed by PI

Note:

1. Parentheses in the J^{π} field indicate that the parenthesized value(s) is/are based upon weak arguments. See 'Bases for Spin and Parity Assignments' in Appendix H. Note that JPI = (3,4)- is interpreted as J = (3) or (4) and π =-.

2. As far as possible, do not give more than three JPI values.

3. Ranges such as 3- to 5+ are better written as 3-, 4, 5+.

4. Square brackets around J^{π} value indicate assumed value.

21. S

This field may contain no more than three S-values in the form of NUM defined in Section V.9, separated by a '+' or a comma, for corresponding L-values given in the L-field (col. 65-74). Parentheses are allowed and will be interpreted to mean probable values.

22. L

This field may contain no more than three integer numbers optionally preceded by LE or GE and separated by a '+' or a comma. Parentheses are allowed and will be interpreted to mean probable values. Square brackets indicate assumed or derived values.

For certain reactions the L value may be accompanied by the electric or magnetic character in the form similar to multipolarity (see Section V.19).

23. ION

This field is either blank or a signed integer, left justified, denoting order of ionization of the atom, e.g., +75. Used in Ionized Atom Decay data sets.

24. Cross Reference

Cross referencing of a record (currently allowed only for the 'L' record in an ADOPTED data set) is made through specification on the continuation record and takes the following forms:

1. NUCID 2 L XREF=ABC$
   Above record indicates that the adopted level (specified by preceding 'L' record) has been seen in data sets 'A', 'B' and 'C', and that the corresponding levels are unambiguous.

2. NUCID 2 L XREF=A(E1)B(E2)C(E3)$
   This record indicates that the adopted level is the same as the E1 level in data set 'A', the E2 level in data set 'B', etc.

3. NUCID 2 L XREF=A(E1,E2)B(E3)$
   This record indicates that the adopted level is either the E1 or the E2 level in data set 'A', the E3 level in data set 'B'.

4. NUCID 2 L XREF=A(*E1)B(E2)$
   This record indicates that a level with energy E1 in data set 'A' is associated with more than one adopted level. An '*' must appear on all occurrences of a multiply assigned level. Alternatively, the notation A(*) may be used if the energy is apparent.

5. NUCID 2 L XREF=+$
   This record indicates that the adopted level has been seen in all data sets.

6. NUCID 2 L XREF=-(AB)$
   This record indicates that the adopted level has been seen in all data sets except the data sets 'A' and 'B'.

The symbols A, B, C relating to specific data sets must be defined through Cross-Reference records (see Section III.B.4).

25. History record

1. All individual ENSDF data sets (except the REFERENCE and COMMENTS data sets), contain the following information (the information is required, unless indicated optional) on an H record every time changes are made to the data set (see Section III.B.2 for description of H record):

TYP Type of change/evaluation (required)
AUT Author's name (person who makes or is responsible for the change, and not necessarily the evaluator of the data set) (required)
DAT Date of change (optional, if cut-off date given)
CUT Literature cutoff date (optional when changes do not involve fresh evaluation)
CIT Citation (optional, if not published)
COM Comments (optional)

2. Current list of evaluation types (can be expanded) are

FUL Complete revision of the nuclide based on all information to the cut-off date indicated. Cut-off date required
FMT Some format changes done
ERR Errata (fix error(s) in the dataset, should be accompanied with COM)
MOD Modified dataset for partial update of nuclide. Type of modification should be indicated as comment. Cut-off date is optional.
UPD Update due to scan of new literature. Cut-off date is required.
EXP Experimental (not evaluated) data set.

There can be only one type specification per history record given.

3. Date and Cut-off date must be given as DD-MMM-YYYY (e.g., 31-MAY- 1996)

4. Citation (optional) gives the reference where the evaluation is published. CIT=ENSDF means included in ENSDF, but not published.

5. Comments (optional) may give general remarks about evaluation/update.

6. The fields can be in any order on an 'H' record.

History records indicate various revisions - these are wiped out at the next FULL evaluation.

NNDC will introduce 'H' records based on the COMMENTS data set for FULL evaluation

Examples:

```
156DY H  TYP=MOD$AUT=B. Singh$DAT=31-DEC-1995$
156DY2H COM=Updated SDB data only$
156DY H  TYP=UPD$AUT=R. Helmer$CUT=15-DEC-1994$
156DY2H COM=Updated data set since last full evaluation$
156DY H  TYP=FMT$AUT=J. Tuli$DAT=1-DEC-1994$COM=FIXED T1/2$
156DY H  TYP=FUL$AUT=R. Helmer$CUT=01-May-1991$
156DY2H CIT=NDS 65, 65 (1992)$
```

Appendix A

Character Set

The base character set is the standard 7-bit ASCII character set up to octal 173. Characters with octal values of 173 and greater are used as control characters. An alternate character set consists primarily of the Greek alphabet and some special symbols. The backslash character (octal 134) is interpreted as a backspace command. An alternate character in the input file consists of two characters, a control character and the standard character equivalent of the alternate character. All available alternate characters and their standard equivalents are given in the table on the following page.

There are four control characters, | (octal 176), ~ (octal 176), { (octal 173), and } (octal 175). The vertical bar and the tilda are used to shift the next character into the first and second alternate character sets, respectively. The entire string of characters may also be modified from their standard form - in this case, the string to be modified is enclosed by the open and close brace control characters. The character immediately following the open brace is interpreted as a control character. Available control character values and their meanings are given below. The modified character strings may be nested, and the control characters may be in either upper or lower case.

Examples:

|g will be displayed as γ
{B{+238}Pu will be displayed as ^{238}Pu

String Control Characters:

| first alternate character
~ second alternate character
+ superscript
- subscript (+ and – are mutually exclusive)
I italic
B bold
U underline

Symbol ^ (caret) may be used before a word to preserve case, e.g., ^A for A (and not a).

Alternate Character Sets

Standard	1st alt.	2nd alt.	Standard	1st alt.	2nd alt.
!	©	!	N	N	N
"	-	"	O	O	Ö
#	§	θ	P	Π	P
$	e	$	Q	⊇	Õ
%	√	%	R	P	R
&	≡	&	S	Σ	S
'	°	Å	T	T	T
(	←	(	U	ϒ	Ü
)	→	)	V	∇	V
*	x	.	W	Ω	W
+	±	+	X	Ξ	X
’	½	’	Y	∇	Y
-	₮	-	Z	Z	Z
.	‰	.	[	{	[
/	÷	/	]	}	]
0	(	0	^	↑	^
1	)	1	-	↓	-
2	[	2	‘	´	‘
3	]	3	a	α	ä
4	<	4	b	β	b
5	>	5	c	η	c
6	√	6	d	δ	d
7	∫	7	e	ε	é
8	∏	8	f	φ	f
9	∑	9	g	γ	g
:	†	:	h	©	h
;	‡	;	i		i
<	≤	<	j	є	j
=	≠	=	k	κ	k
>	≥	>	l	λ	λ
?	≈	?	m	μ	m
@	∞	•	n	ν	n
A	A	Ä	o	o	ö
B	B	B	p	π	p
C	H	C	q	Θ	õ
D	Δ	D	r	ρ	r
E	E	É	s	σ	s
F	Φ	F	t	⎮	t
G	Γ	G	u	⎫	ü
H	X	H	v	?	v
I	I	I	w	ω	w
J	~	J	x	ξ	x
K	K	K	y	ψ	y
L	Λ	L	z	ζ	z
M	M	M			

Appendix B

Format for Comments Data Set

This data set consists only of general comment records (defined in III.B(4)). The format of the comment records is similar to general comments in other data sets except that the NUCID field will contain only the mass number AAA, and that a SYM field is required as in a flagged comment. In the flagged comments, the SYM field will either occupy columns 10 to 19 with column 19 being blank, or SYM will be followed by a '$'. Continuation records for a given comment are allowed, with the additional feature that a new line will be started if the continuation character in column 6 is a '#' and that a new paragraph will be started if the character is a '@'. This feature is intended to facilitate the entry of information into the COMM comments.

SYM	Meaning
TITLE	Title of evaluation. Required if the evaluation spans several masses.
AUTH	Authors - list of authors from the institution given in the following INST comment. A letter or number in parenthesis following an author's last name will signal a permanent address which is different from the institution (see PERM).
INST	Institution - name and address of the authors' institution.
INST	Comment must follow the appropriate AUTH comment. The # continuation character is used so the address does not run together into one line. More than one set of AUTH and INST comments can be given if more than one institution is involved.
ABST	Abstract - should be terse and to the point. Additional details should be given under COMM comments.
CUT	Cut-off data and associated comments.
COMM	General comments on techniques used in the evaluation or on other information common to many of the isotopes.
ACKN	Acknowledgments.
PERM(a)	Permanent address of an author. The letter or number 'a' within the parenthesis corresponds to the letter or number within the parenthesis which follows the author's last name in the AUTH comment.
FUND	Funding, an acknowledgment of funding which will result in a footnote being added to the title.
CIT	Citation - added by the NDS production staff so that the publication can be correctly cited by persons using a retrieval of the A chain. The authors may leave out this information.

EXAMPLE of a COMMENTS data set

```
156       COMMENTS
156  C    TITL$  Nuclear Data Sheets for A=156
156  C    AUTH$R. G. Helmer
156  C    INST$Idaho National Engineering Laboratory
156  #C   EG&G Idaho, Inc.
156  #C   Idaho Falls, Idaho 83415 USA
156  C    ABST$The experimental results from the various reaction and decay
156  2C   studies leading to nuclides in the A=156 mass chain, and ALPHA decays
156  3C   from it, have been reviewed. These data are summarized and presented,
156  4C   together with adopted levels schemes and properties.
156  C    CUT$Data available prior to May 1991 have been evaluated.
156  C    ACKN$The evaluator wishes to thank C. W. Reich, the reviewer, and the
156  2C   editors for many helpful discussions.
156  C    FUND$Research sponsored by the U. S. Department of Energy.
156  C    CIT$R. G. Helmer, NDS 65, 65 (1992)
156  C    COMM$General Comments: In this evaluation, the following expression
156  2C   was used to define the rotational-band parameters a and B:
156  C    E(J)=E{-0} + a[J(J+1)-K{+2}] + B[J(J+1)-K{+2}]{+2}.
156  C    with the following terms sometimes added for K=1 and 2 bands
156  C    + (-1){+J+1}a{-2}J(J+1) for K=1
156  C    and
156  C    + (-1){+J}a{-4}(J-1)J(J+1)(J+2) for K=2.
156  C    In the determination of the values of these parameters, the energy
156  2C   spacings of only the lowest levels, and minimum number of levels, were
156  3C   used.
156  C    The ENSDF file (the computer data base from which these Data Sheets
156  3C   are produced), contains some information that is not printed in these
156  4C   Data Sheets. This includes the theoretical internal-conversion
156  6C   coefficients for each shell, where the values are significant, for
156  8C   each |g for which a multipolarity is given in the Data Sheets. Also, a
156  9C   short comment is made about the experimental methods for each
156  BC   reference.  This information would be available if a copy of the ENSDF
156  DC   file were obtained.
```

Output for above COMMENTS data set is shown on the following page.

Nuclear Data Sheets for A = 156*

Nuclear Data Sheets 65, 65 (1992)

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1.Idaho Falls, Idaho 83415 USA

(Received June 24, 1991; Revised August 20, 1991)

Abstract: The experimental results from the various reaction and decay studies leading to nuclides in the A=156 mass chain, and α decays from it, have been reviewed. These data are summarized and presented, together with adopted levels schemes and properties.

Cutoff Date: Data available prior to May 1991 have been evaluated.

General Policies and Organization of Material: See the January issue of Nuclear Data Sheets.

Acknowledgments: The evaluator wishes to thank C. W. Reich, the reviewer, and the editors for many helpful discussions.

General Comments: In this evaluation ,the following expression was used to Define the rotational–band parameters A and B:

$E(J)=E_0 + A[J(J+1)–K^2] + B[J(J+1)–K^2]^2$.

with the following terms sometimes added for K=1 and 2 bands

$+ (–1)^{J+1}A_2J(J+1)$ for K=1

and

$+ (–1)^{J}A_4(J–1)J(J+1)(J+2)$ for K=2.

In the determination of the values of these parameters ,the energy spacings of only the lowest levels ,and minimum number of levels, were used.

The ENSDF file (the computer data base from which these Data Sheets are produced), contains some information that is not printed in these Data Sheets. This includes the theoretical internal–conversion coefficients for each shell, where the values are significant ,for each γ for which a multipolarity is given in the Data Sheets. Also, a short comment is made about the experimental methods for each reference. This information would be available if a copy of the ENSDF file were obtained.

* Research sponsored by the U. S. Department of Energy.

Appendix C

Example of an Adopted Data Set

```
162TB    ADOPTED LEVELS, GAMMAS                                99NDS    199909
162TB  H TYP=FUL$AUT=R. G. Helmer and C. W. Reich$CIT=NDS 87, 317 (1999)$
162TB2 H CUT=1-Jan-1999$
162TB  Q  2506     36 6284   36 7457   36 -895   85    1995AU04
162TB C  Data are from 162GD B- decay (1982Ge07,1970Ch02) and 163DY(T,A)
162TB2C  reaction (1989BuZW,1988BuZP).
162TB CL E         Other levels up to 1600 keV are indicated by the 163DY(T,A)
162TB2CL spectrum in 1988BuZP.
162TB CL J         For the levels reported from the 163DY(T,A) reaction, the
162TB2CL JPI values are based on L=2 transfers and intensity patterns
162TB3CL within bands that indicate pickup of a 3/2[411] proton.
162TB CL BAND(A)   KPI = 1- band.
162TB2CL CONF=((P,3/2(411))(N,5/2(523))).
162TB@CL ^A=9.78
162TB DL           Levels: 1- (0), 2- (39), 3- (97), 4- (176), 5- (267).
162TB CL BAND(B)   KPI = 4- band.
162TB2CL CONF=((P,3/2(411))(N,5/2(523))).
162TB@CL ^A AP 10
162TB CL BAND(C)   Bandhead of KPI = 1+ band.
162TB2CL CONF=((P,7/2(523))(N,5/2(523)))
162TB  XY162GD B- DECAY
162TB  XZ163DY(T,A)
162TB PN                                                 6
162TB  L   0         1-              7.60 M   15                    A
162TB2 L %B-=100 $ XREF=+
162TB CL T         Unweighted average of 7.43 MIN 4 (1965Sc24) and 7.76 MIN 10
162TB2CL (1977Ka08). Others: 7.48 M 3 (1965Sc24), 8.0 M 5 (1966Fu08),
162TB3CL 7.75 M 31 (1966Sc24), 7.5 M 10 (1967Gu03), and 7.6 M 2 (1968Ka10).
162TB4CL See 1951Bu25, 1960Wi10, and 1962Ta12 for half-life measurements
162TB5CL related to nuclide identification.
162TB CL J         Configuration is assigned as
162TB2CL CONF=((P,3/2(411))(N,5/2(523))) based on the ground-state
162TB3CL assignments of CONF=(P,3/2(411)) for 161TB and
162TB4CL CONF=(N,5/2(523)) for 161GD and 163DY.
162TB CL J         LOGFT=4.95 of the B- transition to the 2- level at 1148 keV
162TB2CL in 162DY indicates an allowed-unhindered B transition, which
162TB3CL must be CONF=(N,5/2(523)) to CONF=(P,7/2(523)). This confirms
162TB4CL the configuration assignment to this ground state as well as
162TB5CL helping establish the configuration assignment to the 1148-keV
162TB6CL level in 162DY as CONF=((P,3/2(411))(P,7/2(523))). See 162DY
162TB6CL Adopted Levels and 1995Be02 for further discussion.
162TB  L  39.10    9  2-                                    A
```

```
162TB2 L XREF=+
162TB CL J        From M1 component in G to 1- ground state, expected energy
162TB2CL spacing in rotational band, and (T,A) reaction results.
162TB  G  39.0     2  100       M1+(E2)
162TB CG M         From intensity balance at 39 level in 162GD B- decay,
162TB2CG transition is primarily M1 (1970Ch02); x/G intensity ratio and
162TB3CG ^L x-ray energy are consistent with this.
162TB  L   97      1  3-                                    A
162TB2 L XREF=Z
162TB  L  176      1  4-                                    A
162TB2 L XREF=Z
162TB  L  216      1  4-                                    B
162TB2 L XREF=Z
162TB CL J        Configuration is assigned as that of the ground state,
162TB2CL namely, (PI 3/2[411])(NU 5/2[523]) recoupled. The systematics
162TB3CL of 1998Ja07 suggest a "theoretical" Gallagher-Moszkowski splitting
162TB4CL of 82 keV compared to the observed 216 keV, if this assignment
162TB5CL is correct.
162TB  L  267      2  5-                                    A
162TB2 L XREF=Z
162TB  L  310      1  5-                                    B
162TB2 L XREF=Z
162TB  L 341.41    9 (0-,1)
162TB2 L XREF=Y
162TB CL J        From LOGFT=5.9 in B- decay from 0+ 162GD.
162TB  G 302.30    15  58    9
162TB  G 341.42    10 100    9
162TB  L 442.11    8  1+                                     C
162TB2 L XREF=Y
162TB CL J        From allowed-unhindered (LOGFT=4.4) B- transition from the
162TB2CL 162GD ground state (0+). This also uniquely establishes the
162TB3CL configuration of this level as CONF=((N,5/2(523))(P,7/2(523))).
162TB  G 403.00    8   85    4
162TB  G 442.12    8  100
```

Output for above data set is shown in the following pages.

$^{162}_{65}Tb_{97}$-1

Adopted Levels, Gammas

Q(β⁻)=2506 *36*; S(n)=6284 *36*; S(p)=7457 *36*; Q(α)=−895 *85* 1995Au04.
Data are from ^{162}Gd β⁻ decay (1982Ge07,1970Ch02) and ^{163}Dy(t,α) reaction (1989BuZW,1988BuZP).

^{162}Tb Levels

Cross Reference (XREF) Flags

A ^{162}Gd β⁻ Decay
B ^{163}Dy(t,α)

E(level)†	Jπ‡	XREF	$T_{1/2}$	Comments
0.0§	1−	AB	7.60 min *15*	%β⁻=100. $T_{1/2}$: Unweighted average of 7.43 min *4* (1965Sc24) and 7.76 min *10* (1977Ka08). Others: 7.48 min *3* (1965Sc24), 8.0 min *5* (1966Fu08), 7.75 min *31* (1966Sc24), 7.5 min *10* (1967Gu03), and 7.6 min *2* (1968Ka10). See 1951Bu25, 1960Wi10, and 1962Tal2 for half-life measurements related to nuclide identification. Jπ: Configuration is assigned as configuration=((π 3/2[411])(ν 5/2[523])) based on the ground-state assignments of configuration=(π 3/2[411]) for ^{161}Tb and configuration=(ν 5/2[523]) for ^{161}Gd and ^{163}Dy. Jπ: log *ft*=4.95 of the β⁻ transition to the 2− level at 1148 keV in ^{162}Dy indicates an allowed-unhindered β transition, which must be configuration=(ν 5/2[523]) to configuration=(π 7/2[523]). This confirms the configuration assignment to this ground state as well as helping establish the configuration assignment to the 1148-keV level in ^{162}Dy as configuration=((π 3/2[411])(π 7/2[523])). See ^{162}Dy Adopted Levels and 1995Be02 for further discussion.
39.10§ *9*	2−	AB		Jπ: From M1 component in γ to 1− ground state, expected energy spacing in rotational band, and (t,α) reaction results.
97§ *1*	3−	B		
176§ *1*	4−	B		
216# *1*	4−	B		Jπ: Configuration is assigned as that of the ground state, namely, (π 3/2[411])(ν 5/2[523]) recoupled. The systematics of 1998Ja07 suggest a "theoretical" Gallagher-Moszkowski splitting of 82 keV compared to the observed 216 keV, if this assignment is correct.
267§ *2*	5−	B		
310# *1*	5−	B		
341.41 *9*	(0−,1)	A		Jπ: From log *ft*=5.9 in β⁻ decay from 0+ ^{162}Gd.
442.11@ *8*	1+	A		Jπ: From allowed-unhindered (log *ft*=4.4) β⁻ transition from the ^{162}Gd ground state (0+). This also uniquely establishes the configuration of this level as configuration=((ν 5/2[523])(π 7/2[523])).

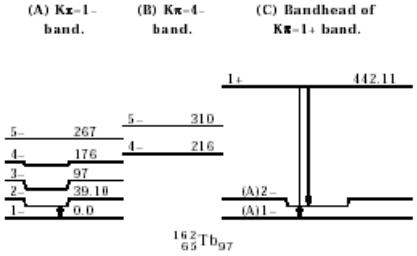
† Other levels up to 1600 keV are indicated by the ^{163}Dy(t,α) spectrum in 1988BuZP.
‡ For the levels reported from the ^{163}Dy(t,α) reaction, the Jπ values are based on L=2 transfers and intensity patterns within bands that indicate pickup of a 3/2[411] proton.
§ (A): Kπ=1− band. Configuration=((π 3/2[411])(ν 5/2[523])). A=9.78.
# (B): Kπ=4− band. Configuration=((π 3/2[411])(ν 5/2[523])). A=10.
@ (C): Bandhead of Kπ=1+ band. Configuration=((π 7/2[523])(ν 5/2[523])).

γ(^{162}Tb)

E(level)	Eγ	Iγ	Mult.	Comments
39.10	39.0 *2*	100	M1+(E2)	Mult.: From intensity balance at 39 level in ^{162}Gd β⁻ decay, transition is primarily M1 (1970Ch02); x/γ intensity ratio and L x-ray energy are consistent with this.
341.41	302.30 *15*	58 *9*		
	341.42 *10*	100 *9*		
442.11	403.00 *8*	85 *4*		
	442.12 *8*	100		

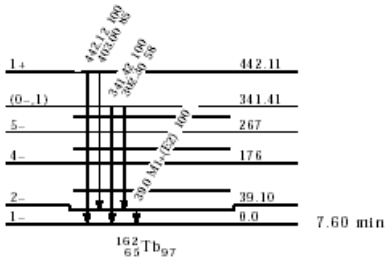
$^{162}_{65}Tb_{97}$-2

Adopted Levels, Gammas (continued)



Level Scheme

Intensities: relative photon branching from each level



Appendix D

Example of a Decay Data Set

```
162TB    162GD B- DECAY                1982GE07,1970CH02        99NDS    199909
162TB  H TYP=FUL$AUT=R. G. Helmer and C. W. Reich$CIT=NDS 87, 317 (1999)$
162TB2 H CUT=1-Jan-1999$
162TB C  162GD has been produced by double-neutron capture in enriched 160GD
162TB2C  with radiochemistry (1967Wa05,1970Ch02) and from spontaneous fission
162TB3C  of 252CF with radiochemistry (1982Ge07). Measurements include
162TB4C  G singles and GG, GX, and GB coincidences.
162TB CL          Decay scheme is from 1982Ge07, and is similar to those of
162TB2CL 1970Ch02 and 1967Wa05.
162TB CL          The consistency of the scheme is supported
162TB2CL by the fact that the sum of the energies of the radiations is
162TB3CL 1395 keV 56 which agrees with the Q value of 1400 100.
162TB CL E        From least-squares fit to G energies.
162TB CL J        From 162TB Adopted Levels. Rotational band and Nilsson
162TB CG          Data are from 1982Ge07, unless otherwise noted. Others:
162TB2CG 1970Ch02, 1967Wa05.
162TB CB E        From 1970Ch02.
162TB CB IB       From evaluators' assumption that 100% of the decays
162TB2CB depopulate the levels at 341 and 442 keV (that is, no B-
162TB3CB feeding of the ground state and 39 level) and no G feeding of
162TB4CB the 341-keV level. From LOGFT GE 5.9 for 0+ to 1- ground state
162TB5CB (1973Ra10), IB-(0) LE 13% and from LOGF1T GE 8.5 for 0+ to 2- at
162TB6CB 39 keV (1973Ra10), IB-(39) LE 0.15%.
162TB2CL configuration assignments are given there.
162TB D  Experimental methods:
162TB D  1967Wa05: 162GD from double-neutron capture in enriched (94%) 160GD
162TB2D      with radiochemistry.  G's measured with NAI(TL) detectors.
162TB D  1970Ch02: 162GD from double-neutron capture in enriched (94.8%) 160GD
162TB2D      with radiochemistry.  G's measured with Ge and Si(Li) detectors
162TB3D      and B's with Si(Li) detector.  GX and GB coincidences measured.
162TB D  1982Ge07: 162GD from 252CF spontaneous fission with radiochemistry.
162TB2D      G's measured with Ge detector.
162GD  P   0         0+              8.4 M    2             14E2     1
162TB  N   0.51    2          1.0       1.0
162TB CN NR       Based on evaluators' assumption that 100% of the decays
162TB2CN depopulate the levels at 341 and 442 keV.
162TB PN                                                    3
162TB  L   0         1-              7.60 M   15
162TB CL T        From 162TB Adopted Levels and based on 7.43 M 4 (1965Sc24)
162TB2CL and 7.76 M 10 (1977Ka08).
162TB  L  39.10    9  2-
162TB  G  39.0     2   10    2  M1+(E2)              8     2            C
162TBS G LC=6 2$ MC=1.4 3
162TB CG E        Average of 39.1 2 (1982Ge07) and 38.8 2 (1970Ch02).
```

```
162TB CG RI       Average of 9 2 (1982Ge07) and 14 3 (1970Ch02).
162TB CG M,CC     CC value deduced by evaluators from intensity balance at 39
162TB2CG level for current decay scheme; added G's feeding 39 level will
162TB3CG increase CC value. From CC(M1)=5.58 and CC(E2)=135, G is
162TB4CG primarily M1 with some E2 probable. Measured x/G intensity
162TB5CG ratio and L x-ray energy are consistent with this (1970Ch02).
162TB  L 341.41    9 (0-,1)
162TB  B             4.5  5          5.9    2
162TBS B EAV=362 14
162TB  G 302.30    15   3.1  5
162TB  G 341.42    10   5.3  5
162TB  L 442.11    8  1+
162TB  B  10E2     1   95.5  5          4.4    2                    C
162TBS B EAV=322 40
162TB  G 403.00    8   85    4  [E1]              0.008              C
162TBS G KC=0.0069$ LC=0.0010$ MC=0.0002
162TB  G 442.12    8  100      [E1]              0.007              C
162TBS G KC=0.0056$ LC=0.00076$ MC=0.0002
```

Output for above data set is shown in the following pages.

^{162}Gd β⁻ Decay 1982Ge07,1970Ch02

Parent ^{162}Gd: E=0; Jπ=0+; $T_{1/2}$=8.4 min *2*; Q(g.s.)=1400×10² *1*; %β⁻ decay=100.
^{162}Gd has been produced by double-neutron capture in enriched ^{160}Gd with radiochemistry (1967Wa05,1970Ch02) and from spontaneous fission of ^{252}Cf with radiochemistry (1982Ge07). Measurements include γ singles and γγ, γX, and γβ coincidences.

^{162}Tb Levels

Decay scheme is from 1982Ge07, and is similar to those of 1970Ch02 and 1967Wa05.
The consistency of the scheme is supported by the fact that the sum of the energies of the radiations is 1395 keV 56 which agrees with the Q value of 1400 *100*.

E(level)†	Jπ‡	$T_{1/2}$	Comments
0.0	1−	7.60 min *15*	$T_{1/2}$: From ^{162}Tb Adopted Levels and based on 7.43 min *8* (1965Sc24) and 7.76 min *10* (1977Ka08).
39.10 *9*	2−		
341.41 *9*	(0−, 1)		
442.11 *8*	1+		

† From least-squares fit to γ energies.
‡ From ^{162}Tb Adopted Levels. Rotational band and Nilsson.

β⁻ radiations

Eβ⁻†	E(level)	Iβ⁻†§	Log *ft*	Comments
1000 *100*	442.11	95.5 *5*	4.4 *2*	av Eβ=322 *40*.
(1060 *100*)	341.41	4.5 *5*	5.9 *2*	av Eβ=362 *14*.

† From 1970Ch02.
‡ From evaluators' assumption that 100% of the decays depopulate the levels at 341 and 442 keV (that is, no β⁻ feeding of the ground state and 39 level) and no γ feeding of the 341-keV level. From log *ft*≥5.9 for 0+ to 1− ground state (1973Ra10), Iβ⁻(0)≤13% and from log f^1t≥8.5 for 0+ to 2− at 39 keV (1973Ra10), Iβ⁻(39)≤0.15%. configuration assignments are given there.
§ For β⁻ intensity per 100 decays, multiply by 1.0.

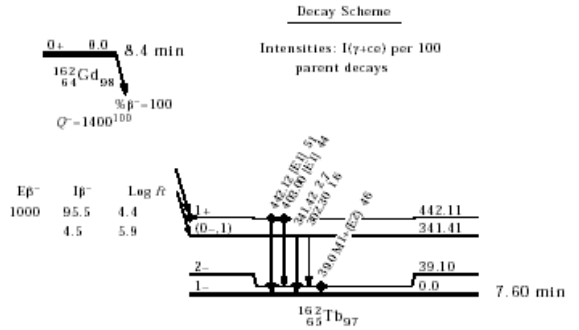
γ(^{162}Tb)

Data are from 1982Ge07, unless otherwise noted. Others: 1970Ch02, 1967Wa05.
Iγ normalization: Based on evaluators' assumption that 100% of the decays depopulate the levels at 341 and 442 keV.

Eγ	E(level)	Iγ†	Mult.	α	Comments
39.0 *2*	39.10	10 *2*	M1+(E2)	8 *2*	α(L)=6 *2*; α(M)=1.4 *3*. Eγ: Average of 39.1 *2* (1982Ge07) and 38.8 *2* (1970Ch02). Iγ: Average of 9 *2* (1982Ge07) and 14 *3* (1970Ch02). Mult.,α: α value deduced by evaluators from intensity balance at 39 level for current decay scheme; added γ's feeding 39 level will increase α value. From α(M1)=5.58 and α(E2)=135, γ is primarily M1 with some E2 probable. Measured x/γ intensity ratio and L x-ray energy are consistent with this (1970Ch02).
302.30 *15*	341.41	3.1 *5*			
341.42 *10*	341.41	5.3 *5*			
403.00 *8*	442.11	85 *4*	[E1]	0.008	α(K)=0.0069; α(L)=0.0010; α(M)=0.0002.
442.12 *8*	442.11	100	[E1]	0.007	α(K)=0.0056; α(L)=0.00076; α(M)=0.0002.

† For absolute intensity per 100 decays, multiply by 0.51 *2*.

^{162}Gd β⁻ Decay 1982Ge07,1970Ch02 (continued)



Appendix E

ENSDF Coding for Ionized Atom decay

Decay Data Set

1. ID record

The ionization state of the atom should be in square brackets following the nuclide symbol in the DSID field.

2. Parent record
   - Energy field: level energy of the parent nucleus
   - Half-life field: half-life for the decay of the ionized itom
   - Q-value field: nuclear ground-state to ground-state value
   - New field (77-80): ionization state

3. Level records
   - Energy field: level energy of the daughter nucleus
   - MS field: atomic electron shell or subshell in which the emitted beta particle is captured.
   - A new quantity ("ION") giving the ionization state required on an "S L" record following the level record.

4. Daughter Adopted Levels, Gammas

The adopted levels cross-referenced to the observed states in the ionized atom decay dataset.

5. Parent Adopted Levels, Gammas

The half-life and decay branching of the ionized atom decay should be given as comments (analagous to the current practice for half-lives which differ due to chemical effects). This should be regarded as an interim solution; after more experience is gained, methods of giving these data on level continuation records will be derived.

Examples:

187Re

```
187OS    187RE[+75] B- DECAY          96BO37
187OS C  BOUND STATE B- DECAY OF BARE 187RE (75+ CHARGE STATE)
187OS C  96BO37 (ALSO 97NO07,97KL06,97WE08): DECAY OF FULLY IONIZED
187RE
187OS2C  NUCLEI CIRCULATING IN A STORAGE RING.  .....
187OS C  T1/2 OF 187RE ION (75+ CHARGE STATE)=32.9 Y 20
187RE  P  0          5/2+            32.9 Y 20           2.663     19+75
187OS  N                    1.0
187OS  L  0          1/2-                                  K
187OSS L ION=+75
187OS  B             WEAK              11  AP                    1U?
187OS  L  9.75        3/2-                                   K
187OSS L ION=+75
187OS  B             100             7.87  3
187OS  G  9.75                                              S
187OS  L  0          1/2-                                  L1
187OSS L ION=+75
187OS  B                                                   ?

187RE    ADOPTED LEVELS, GAMMAS
187RE CL BAND(A)$5/2[402]?
187RE  L       0.0   5/2+           4.35E10 Y 13                  A
187RE2 L %B-=100$%A LT 0.0001
187RE CL $%B-({+187}Re{++75})=100; T1/2({+187}Re{++75})=32.9 20 Y

187OS    ADOPTED LEVELS, GAMMAS
187OS CL BAND(A)$1/2[501] BAND
187OS CL BAND(B)$3/2[512] BAND
187OS  XA187RE B- DECAY
187OS  XB187IR EC DECAY
187OS  XC186OS(N,G) E=THERMAL
187OS  XD187RE(D,2NG), 187RE(P,NG)
187OS  XECOULOMB EXCITATION
187OS  XF189OS(P,T)
187OS  XG186OS(D,P)
187OS  XH187OS(D,D')
187OS  XI188OS(D,T),(T,A)
187OS  XJ187RE[+75] B- DECAY
187OS  L       0.0   1/2-           STABLE                      A
187OSX L XREF=ABCDEFGHIJ
187OS  L     9.746 24 3/2-            2.38 NS 18                  B
187OSX L XREF=BCDFJ
```

163Dy

163HO C BOUND STATE B- DECAY OF {+163}Dy{+66+} ION
163HO C 92JU01: T1/2 MEASURED BY STORING BARE 163DY 66+ IONS IN A HEAVY-ION
163HO2C STORAGE RING. .....
163HO C T1/2({+163}Dy{+66+})=47 +5-4 D
163DY P 0+Y 5/2- 47 D +5-4 -2.565 14+66
163HO N 1.0
163HO L 0 7/2- K
163HOS L ION=+66
163HO B 100

163DY ADOPTED LEVELS, GAMMAS
163DY L 0.0 5/2- STABLE
163DY CL $%B-({+163}Dy{+66+})=100; T1/2({+163}Dy{+66+})=47 +5-4 D
163HO XA163HO IT DECAY (1.09 S)
163HO XB163ER EC DECAY
163HO XC162DY(P,P) IAR
163HO XD162DY(3HE,D),(A,T)
163HO XE163DY(D,2NG),(P,NG)
163HO XG164ER(POL T,A)
163HO XI165HO(P,T)
163HO XJ163DY[+66] B- DECAY
163HO CL BAND(A) 7/2(523). A=11.12, B=-0.313 EV
163HO L 0.0 7/2- 4570 Y 25
163HO2 L %EC=100
163HO3 L FLAG=A$XREF=-(C)

Appendix F.

ENSDF Dictionary – Translation into True-type Character Set

ENSDF	Translation
"A"	"A"
%12C	%{+12}C
%14C	%{+14}C
%2B-	%2|b{+-}
%A	%|a
%B+A	%|b{++}|a
%B+N	%|b{++}n
%B+P	%|b{++}p
%B+_	%|b{++}
%B-2N	%|b{+-}2n
%B-N	%|b{+-}n
%B-P	%|b{+-}p
%B-_	%|b{+-}
%BEC	%|b{++}|e
%E0	%E0
%E2	%E2
%EC	%|e
%ECA	%|e|a
%ECF	%|eF
%ECK	%|ek
%ECP	%|ep
%EWSR	%EWSR
%G	%|g
%I	%I
%IB	%I|b
%IG	%I|g
%IT	%IT
%M1	%M1
%N	%n
%P	%p
%RI	%I|g
%SF	%SF
(A)	(|a)
(B)	(|b)
(COUL.)	(Coul.)
(CV)	(CV)
(DOWN)	(|_)
(H,T)	(H,T)

ENSDF	Translation
(IT)	(IT)
(T)	(t)
(THETA,H)	(|q,H)
(THETA,H,T,T)	(|q,H,t,T)
(THETA,T,H)	(|q,T,H)
(UP)	(|^)
*	|*\
**(J+1/2)	{+(J+|,)}
**-1	{+-1}
**-3	{+-3}
**-4	{+-4}
**1/2	{+1/2}
**1/3	{+1/3}
**2	{+2}
**3	{+3}
**L	{+L}
*A**(1/3)	|*|A{+1/3}
*DS/DW	d|s/d|W
*E	|*E
*EG	E|g
*EKC	|a(K)exp
*G*WIDTHG0**2	g|G{+2}\{-|g0}
*G2	g{-2}
*IB-	|*I|b{+-}
*IE	|*I|e
*Q	|*Q
*R	R
*RI	I|g
*SIGMA	|*|s
*SUMOF	|S
*T1/2	|*T{-1/2}
*TAU	|t
*WIDTH	|G
*WIDTHP	|G{-p}
2B-	2|b{+-}
2J	2J
2N*SIGMA	2N|s
4PI	4|p

ENSDF	Translation
4PIB	4|p|b
4PIBG	4|p|b|g
4PIG	4|p|g
A DECAY	|a decay
A DECAYS	|a decays
A SYST	|a syst
A'	|a'
A(THETA)	A(|q)
A**1/3	A{+1/3}
A**2/3	A{+2/3}
A-DECAY	|a-decay
A-N	A-N
A-SYST	|a-syst
A0	A{-0}
A1	A{-1}
A11	A{-11}
A2	A{-2}
A2/A0	A{-2}/A{-0}
A22	A{-22}
A2P2	A{-2}P{-2}
A3	A{-3}
A4	A{-4}
A44	A{-44}
A5	A{-5}
A6	A{-6}
A7	A{-7}
A=	A=
AA	|a|a
AA0	Aa{-0}
AAS	AAS
AB	AB
ACE	(|a)(ce)
AG	|a|g
AJ	AJ
ALAGA	Alaga
ALPHA	|a
ALPHA0	|a{-0}
ALPHA1	|a{-1}
ALPHA2	|a{-2}
ALPHA3	|a{-3}
ALPHAS	|a's
AP	|?
APRIL	April
AUGER	Auger
AUGUST	August

ENSDF	Translation
AVRSQ	{ <r{+2}>}
AXK	(|a)(K x ray)
AY	Ay
B	|b
B(E0	B(E0
B(E1	B(E1
B(E2	B(E2
B(E3	B(E3
B(E4	B(E4
B(IS	|b(IS
B(J	B(J
B*R	|bR
B*RHO	B|*|r
B+	|b{++}
B-2N	|b{+-}2n
B-N	|b{+-}n
B-VIBRATIONAL	|b-vibrational
B-_	|b{+-}
B/A	B/A
B0	|b{-0}
B00	|b{-00}
B02	|b{-02}
B03	|b{-03}
B04	|b{-04}
B1	|b{-1}
B12	|b{-12}
B2	|b{-2}
B2*R	|b{-2}R
B20	|b{-20}
B22	|b{-22}
B24	|b{-24}
B3	|b{-3}
B3*R	|b{-3}R
B30	|b{-30}
B4	|b{-4}
B4*R	|b{-4}R
B42	|b{-42}
B4C	B{-4}C
B5	|b{-5}
B5*R	|b{-5}R
B6	|b{-6}
B6*R	|b{-6}R
B7	|b{-7}
B=	B=
BA	|b|a

ENSDF	Translation
BAVRSQ	{ <|b{+2}>{+1/2}}
BB	|b|b
BC	|bc
BCE	|bce
BCS	BCS
BE(L)	BE(L)
BE-	|be{+-}
BE0	B(E0)
BE0W	B(E0)(W.u.)
BE1	B(E1)
BE1UP	B(E1)|^
BE1W	B(E1)(W.u.)
BE2	B(E2)
BE2DWN	B(E2)|_
BE2UP	B(E2)|^
BE2W	B(E2)(W.u.)
BE3	B(E3)
BE3UP	B(E3)|^
BE3W	B(E3)(W.u.)
BE3WUP	B(E3)(W.u.)|^
BE4	B(E4)
BE4UP	B(E4)|^
BE4W	B(E4)(W.u.)
BE5	B(E5)
BE5W	B(E5)(W.u.)
BE6	B(E6)
BE6UP	B(E6)|^
BE6W	B(E6)(W.u.)
BE7	B(E7)
BE7W	B(E7)(W.u.)
BE8	B(E8)
BEC DECAY	|b{++}|e Decay
BEL	B(EL)
BELW	B(EL)(W.u.)
BERKELEY	Berkeley
BESSEL	Bessel
BETA	|b
BETA*R	|bR
BETAS	|b's
BETHE	Bethe
BF3	BF{-3}
BG	|b|g
BGG	|b|g|g
BGN	|b|gn
BGO	BGO

ENSDF	Translation
BGT	|b(GT)
BIEDENHARN	Biedenharn
BJ**2	BJ{+2}
BL	|b{-L}
BL**2	|b{-L}{+2}
BL*R	|b{-L}R
BL*R*A**(1/3)	|b{-L}RA{+1/3}
BLAIR	Blair
BM(L)	BM(L)
BM1	B(M1)
BM1UP	B(M1)|^
BM1W	B(M1)(W.u.)
BM2	B(M2)
BM2UP	B(M2)|^
BM2W	B(M2)(W.u.)
BM3	B(M3)
BM3W	B(M3)(W.u.)
BM4	B(M4)
BM4W	B(M4)(W.u.)
BM5W	B(M5)(W.u.)
BM8UP	B(M8)|^
BML	B(ML)
BMLW	B(ML)(W.u.)
BN	|bn
BOHR	Bohr
BORN	Born
BP	|bp
BR	Branching
BREIT	Breit
BRINK	Brink
Be	Be
C	C
C.M.	c.m.
C12G	{+12}C|g
C2S	C{+2}S
CA(OH)	Ca(OH)
CC	|a
CCBA	CCBA
CCC	CCC
CE	ce
CEB	ce|b
CEG	ce|g
CEK	ce(K)
CEL	ce(L)
CEL1	ce(L1)

ENSDF	Translation
CEL12	ce(L12)
CEL2	ce(L2)
CEL23	ce(L23)
CEL3	ce(L3)
CEM	ce(M)
CEM1	ce(M1)
CEM2	ce(M2)
CEM23	ce(M23)
CEM3	ce(M3)
CEM4	ce(M4)
CEM45	ce(M45)
CEM5	ce(M5)
CEN	ce(N)
CEN1	ce(N1)
CEN2	ce(N2)
CEN3	ce(N3)
CEN4	ce(N4)
CEN45	ce(N45)
CEN5	ce(N5)
CEO	ce(O)
CEO+CEP	ce(O)+ce(P)
CEO1	ce(O1)
CERENKOV	Cerenkov
CERN	CERN
CHI	|h
CHI**2	|h{+2}
CK	|eK
CL	|eL
CLEBSCH	Clebsch
CM	|eM
CM2	cm{+2}
CM3	cm{+3}
CN	|eN
CO	Co
COMPTON	Compton
CONF	configuration
CONF=	configuration=
CORIOLIS	Coriolis
COS2TH	cos{+2}|q
COSTER	Coster
COUL	Coul
COULOMB	Coulomb
CP	CP
CRC	CRC
CSI	CsI
CURIE	Curie
Cm	Cm
D)	D)
D+(Q)	D+(Q)
D+Q	D+Q
D3HE	d{+3}He
DA	|DA
DA2	|DA{-2}
DA4	|DA{-4}
DAVRSQ	{ |D<r{+2}>}
DAVRSQ4	{ |D<r{+4}>}
DAVRSQ6	{ |D<r{+6}>}
DAVYDOV	Davydov
DBR	branching uncertainty
DCC	|D|a
DCO	DCO
DCOQ	DCOQ
DE	|DE
DE/DX	dE/dx
DECEMBER	December
DEG	|'
DELTA	|D\
DFT	|D(log ft)
DG	d|g
DHF	|D(HF)
DIA	|DI|a
DIB	|DI|b
DIE	|DI|e
DISPIN	|DT
DJ	|DJ
DJPI	|DJ|p
DK	|DK
DL	|DL
DMR	|D|d
DN	|DN
DNB	|D(|b-normalization)
DNR	|D(|g-normalization)
DNT	|D(|g+ce-normalization)
DOMEGA	d|W
DOPPLER	Doppler
DPAC	DPAC
DPAD	DPAD
DPI	|D|p
DQ+	|DQ(|e)
DQ-	|DQ(|b{+-})

ENSDF	Translation
DQA	|DQ(|a)
DRI	|DI|g
DS	|DS
DS/DW	d|s/d|W
DSA	DSA
DSAM	DSAM
DSIGMA	d|s
DSN	|DS(n)
DSP	|DS(p)
DT	|DT{-1/2}
DT1/2	|DT{-1/2}
DTI	|DI(|g+ce)
DUBNA	Dubna
DWBA	DWBA
DWIA	DWIA
DWUCK	DWUCK
E	E
E'(THETA)	e'(|q)
E(A)	E(|a)
E(D)	E(d)
E(E)	E(e)
E(N)	E(n)
E(P)	E(p)
E(P1)	E(p{-1})
E(P2)	E(p{-2})
E(T)	E(t)
E**1/2	E{+1/2}
E**2	E{+2}
E+	e{++}
E+-	e{+|+}
E-E	E-E
E.G.	{Ie.g.}
E/DE	E/|DE
E0	E0
E1	E1
E10	E10
E2	E2
E3	E3
E4	E4
E5	E5
E6	E6
E7	E7
E8	E8
E9	E9
EA	E|a

ENSDF	Translation
EAV	av E|b
EB	E|b
EB-	E|b{+-}
EBE2UP	|eB(E2)|^
EBE3UP	|eB(E3)|^
EB_	E|b
EC	|e
EC2P	|e2p
ECA	|e|a
ECC	|a(exp)
ECE	E(ce)
ECK	|eK(exp)
ECL	|eL(exp)
ECL1	|eL1(exp)
ECL2	|eL2(exp)
ECL3	|eL3(exp)
ECM	|jM(exp)
ECN	|jN(exp)
ECP	|ep
ED	E(d)
EDE	E|DE
EE	Ee
EEC	E|e
EG	E|g
EG**3	E|g{+3}
EG**5	E|g{+5}
EKC	|a(K)exp
EL	EL
EL12C	|a(L12)exp
EL1C	|a(L1)exp
EL23C	|a(L23)exp
EL2C	|a(L2)exp
EL3C	|a(L3)exp
ELC	|a(L)exp
EM1C	|a(M1)exp
EM2C	|a(M2)exp
EM3C	|a(M3)exp
EM4C	|a(M4)exp
EM5C	|a(M5)exp
EMC	|a(M)exp
EN	E(n)
EN1C	|a(N1)exp
EN23C	|a(N23)exp
EN2C	|a(N2)exp
EN3C	|a(N3)exp

ENSDF	Translation
EN4C	|a(N4)exp
ENC	|a(N)exp
ENDF/B-V	ENDF/B-V
ENDF/B_	ENDF/B
ENDOR	ENDOR
ENGE	Enge
EP	E(p)
EPR	EPR
EPSILON	|e
EPSILONB	|eB
ESR	ESR
ET	E(t)
EV	eV
EVEN-A	even-A
EWSR	EWSR
EX.	ex.
E{	E{
F+B	F+B
F-K	F-K
F/B	F/B
FEBRUARY	February
FERMI	Fermi
FESHBACH	Feshbach
FG	(fragment)|g
FM	fm
FM**-1	fm{+-1}
FM**2	fm{+2}
FM**4	fm{+4}
FM-1	fm{+-1}
FOCK	Fock
FOURIER	Fourier
FWHM	FWHM
G FACTOR	g factor
G FACTORS	g factors
G(2+	g(2+
G*T	gT
G*W*WIDTHG0	gw|G{-|g0}
G*W*WIDTHG0**	2gW|G{-0}\{+2}
G*WIDTH	g|G
G*WIDTHG0	g|G{-|g0}
G*WIDTHG0**2	g|G{+2}\{-|g0}
G*WIDTHN	g|G{-n}
G+-	|g{+|+}
G-FACTOR	g-factor
G-FACTORS	g-factors

ENSDF	Translation
G-M	G-M
G/A	|g/|a
G0	|g{-0}
G1	g{-1}
G1*WIDTH	g{-1}|G
G2	g{-2}
G2*WIDTH	g{-2}|G
G=	g=
GA	|?>
GA2	g{-A}\{+2}
GALLAGHER	Gallagher
GAMMA	|g
GAMOW	Gamow
GARVEY	Garvey
GAUSSIAN	Gaussian
GB	|g|b
GB-	|g|b{+-}
GCE	|gce
GDR	GDR
GE	|>
GE(LI)	Ge(Li)
GE-	|ge{+-}
GEIGER	Geiger
GEIGER-MULLER	Geiger-Muller
GELI	Ge(Li)
GEV	GeV
GG	|g|g
GGG	|g|g|g
GGN	|g|gn
GGT	|g|g|t
GM	GM
GMR	GMR
GN	|gn
GP	|gp
GP'	|gp'
GP(T)	|gp(t)
GQR	GQR
GS	g.s.
GSI	GSI
GT	>
GT1/2	gT{-1/2}
GTOL	GTOL
GWIDTH0WIDTHG	g|G{-0}|G|g
GX	|gX
G_	|g

ENSDF	Translation
H(	H(
H**2	h{+2}
H,	H,
H=	H=
HAGER	Hager
HARTREE	Hartree
HAUSER	Hauser
HERA	HERA
HF	HF
HI	HI
HOMEGA	h|`|w
HP	HP
HPGE	HPGE
I	I
I.E.	{Ii.e.}
IA	I|a
IAR	IAR
IAS	IAS
IB	I|b
IB+	I|b{++}
IB-	I|b{+-}
IBA	IBA
IBM	IBM
IBS	IBS
ICC	|a
ICE	Ice
ICE(K)	Ice(K)
ICE(N)	Ice(N)
IE	I|e
IEC	I|e
IG	I|g
IG*EG	I|gE|g
IGISOL	IGISOL
IMPAC	IMPAC
IN(	In(
INFNT	|@
IPAC	IPAC
IS D	is D
ISOLDE	ISOLDE
ISPIN	T
ISPINZ	T{-z}
IT BRANCHING	IT branching
IT DECAY	IT decay
IT DECAYS	IT decays
IT TRANSITION	IT transition

ENSDF	Translation
IT-	IT-
IT=	IT=
IX	I(x ray)
J	J
J**2	J{+2}
J0	J{-0}
J1	J{-1}
J2	J{-2}
JANUARY	January
JF	J{-f}
JI	J{-i}
JKP	JK|p
JMAX	Jmax
JMIN	Jmin
JOSEF	JOSEF
JPI	J|p
JULIE	JULIE
JULY	July
JUNE	June
K	K
K/L+M	K/L+M
K/LM	K/LM
K/T	ce(K)/(|g+ce)
KAPPA	|k
KC	|a(K)
KELSON	Kelson
KEV	keV
KEVIN	Kelvin
KG	kG
KL1L1	KL{-1}L{-1}
KL1L2	KL{-1}L{-2}
KL1L3	KL{-1}L{-3}
KL1M1	KL{-1}M{-1}
KL1M2	KL{-1}M{-2}
KL1M3	KL{-1}M{-3}
KL2L2	KL{-2}L{-2}
KL2L3	KL{-2}L{-3}
KL2M1	KL{-2}M{-1}
KL2M3	KL{-2}M{-3}
KL2M4	KL{-2}M{-4}
KL3L3	KL{-3}L{-3}
KL3LM1	KL{-3}LM{-1}
KL3M2	KL{-3}M{-2}
KL3M3	KL{-3}M{-3}
KL3N	KL{-3}N

ENSDF	Translation
KLL	KLL
KLM	KLM
KM2M3	KM{-2}M{-3}
KM2N2	KM{-2}N{-2}
KM3M3	KM{-3}M{-3}
KNIGHT	Knight
KOE	kOe
KPI	K|p
KRANE	Krane
KRONIG	Kronig
KUO-BROWN	Kuo-Brown
KURIE	Kurie
KXY	KXY
L	L
L+/T	ce(L+)/(|g+ce)
L/T	ce(L)/(|g+ce)
L1	L1
L12	L12
L12C	|a(L12)
L1C	|a(L1)
L2	L2
L23	L23
L23C	|a(L23)
L2C	|a(L2)
L3	L3
L3C	|a(L3)
LA	|?<
LAMBDA	|l
LAMPF	LAMPF
LARMOR	Larmor
LASER	LASER
LBL	LBL
LC	|a(L)
LE	|<
LEGENDRE	Legendre
LI	Li
LITHERLAND	Litherland
LM	LM
LMN	LMN
LN	L(n)
LOGF1T	log| {If{+1}t}
LOGF1UT	log| {If{+1u}t}
LOGF2UT	log| {If{+2u}t}
LOGF3UT	log| {If{+3u}t}
LOGFT	log| {Ift}

ENSDF	Translation
LOHENGRIN	LOHENGRIN
LORENTZIAN	Lorentzian
LP	L(p)
LT	<
M	M
M+/T	ce(M+)/(|g+ce)
M+=	M+=
M-SHELL	M-shell
M-SUBSHELL	M-subshell
M/CE	M/total ce
M/T	ce(M)/(|g+ce)
M1	M1
M12	M12
M1C	|a(M1)
M2	M2
M23	M23
M2C	|a(M2)
M3	M3
M3C	|a(M3)
M4	M4
M45	M45
M4C	|a(M4)
M5	M5
M5C	|a(M5)
M6	M6
M8	M8
MARCH	March
MB	mb
MB/SR	mb/sr
MC	|a(M)
MC+	|a(M+..)
MEDLIST	MEDLIST
MEV	MeV
MEV**-4	MeV{E4-4}
MG/CM2	mg/cm{+2}
MHZ	MHZ
MILLI-EV	meV
MIT	MIT
ML	M+L
MNO	M+N+O
MOME2	Q
MOME3	Octupole mom(el)
MOMM1	|m
MOMM3	Octupole mom(mag)
MOMM5	2{+5} mom(mag)

ENSDF	Translation
MOMM7	2{+7} mom(mag)
MOSSBAUER	Mossbauer
MOSZKOWSKI	Moszkowski
MR	|d
MR**2	|d{+2}
MS	ms
MU	|m
MU-	|m{+-}
N*SIGMA	N|*|s
N+/T	ce(N+)/(|g+ce)
N-SHELL	N-shell
N-SUBSHELL	N-subshell
N-Z	N-Z
N/T	ce(N)/(|g+ce)
N1	N1
N12	N12
N123	N123
N1C	|a(N1)
N2	N2
N23	N23
N2C	|a(N2)
N3	N3
N3C	|a(N3)
N4	N4
N45	N45
N4C	|a(N4)
N5	N5
N5C	|a(N5)
N6C	|a(N6)
N<	N<
N=	N=
NAI	NaI
NB	I|b normalization
NB/SR	nb/sr
NBS	NBS
NC	|a(N)
NC+	|a(N+..)
NC2S	NC{+2}S
NDS	Nuclear Da Sheets
NE	|=
NE213	NE213
NG	n|g
NGG	n|g|g
NILSSON	Nilsson
NMR	NMR

ENSDF	Translation
NOTE:	Note:
NOVEMBER	November
NP	Particle normalization
NQR	NQR
NR	I|g normalization
NS*SIGMA	NS|s
NT	I(|g+ce) normalization
NU	|n
NX	NX
Ne	Ne
O	O
O/Q	O/Q
O/T	ce(O)/(|g+ce)
O1	O1
O123	O123
O1C	|a(O1)
O2	O2
O2C	|a(O2)
O3	O3
O3C	|a(O3)
O4C	|a(O4)
OCTOBER	October
ODD-A	odd-A
OMEGA	|w
OMEGA**2*TAU	|w{+2}|t
OMEGA*T	|w|t
ORNL	ORNL
OSIRIS	OSIRIS
P DECAY	p decay
P(THETA)	p(|q)
P+/T	ce(P+)/(|g+ce)
P-WIDTH	p-width
P0	P{-0}
P1	P1
P1/2	p1/2
P1C	|a(P1)
P2NG	p2n|g
PAC	PAC
PAD	PAD
PALPHA	p|a
PG	p|g
PGG	p|g|g
PHI	|F
PHI(P1)	|F(p{-1})
PHI(P2)	|F(p{-2})

ENSDF	Translation
PI	|p
PI-	|p{+-}
PIB	|p|b
PIBG	|p|b|g
PIG	|p|g
PN	P{-n}
PNG	pn|g
PRI	|DI|g(%)
PSI	|Y
PWBA	PWBA
PWIA	PWIA
Q	Q
Q(	Q(
Q+O	Q+O
Q+_	Q(|e)
Q^-	Q(|b{+-})
Q/D	Q/D
Q22	Q{-22}
Q2D	Q2D
Q2DM	Q2DM
Q3D	Q3D
QA	Q(|a)
QDD	QDD
QDDM	QDDM
QDMDQ	QDMDQ
QMG	QMG
QP	Q(g.s.)
QQSP	QQSP
QS	Q{-s}
QSD	QSD
R	R
R(DCO)	R(DCO)
R**2	r{+2}
R**4	r{+4}
R**6	r{+6}
R0	r{-0}
RDDS	RDDS
RDM	RDM
RHO	|r
RHO**2	|r{+2}
RI	I|g
RITZ	Ritz
ROSE	Rose
RPA	RPA
RUL	RUL

ENSDF	Translation
RUTHERFORD	Rutherford
RYTZ	Rytz
S VALUE	S value
S VALUES	S values
S'	S'
S(2N)	S(2n)
S(2P)	S(2p)
S(CE)	s(ce)
S-1	s{+-1}
S-FACTOR	S-factor
S-FACTORS	S-factors
S-VALUE	S-value
S-VALUES	S-values
S-WAVE	s-wave
S/	S/
S=	S=
SA	S(|a)
SAXON	Saxon
SCHMIDT	Schmidt
SD	SD
SDB	SDB
SE(LI)	Se(Li)
SELTZER	Seltzer
SEPTEMBER	September
SF	SF
SI(LI)	Si(Li)
SIGMA	|s
SIGMA(0)	|s{-0}
SIGMA*DE	|s|*|DE
SIGMAG	|s{-|g}
SIGMAN	|s{-n}
SIGMANU	|s|n
SIGNA	|s(n|a)
SIGNG	|s(n|g)
SILI	Si(Li)
SIO	SiO
SLIV-BAND	Sliv-Band
SN	S(n)
SOREQ	SOREQ
SP	S(p)
STEFFEN	Steffen
STOCKHOLM	Stockholm
SUMOF	|S\
SY	syst
Sn	Sn

ENSDF	Translation
T	T{-1/2}
T)	t)
T,	t,
T/	T/
T1/2	T{-1/2}
T20	T20
T21	T21
T22	T22
TAU	|t
TDPAD	TDPAD
TELLER	Teller
TEMP	T
TG	t|g
TH	th
THETA	|q
THETA**2	|q{+2}
THETA1	|q{-1}
THETA2	|q{-2}
THETAA	|q|a
THETAA**2	|q|a{+2}
THETAG	|q|g
THETAP1**2	|q{-p1}{+2}
THETAP2**2	|q{-p2}{+2}
TI	I(|g+ce)
TOF	tof
TPAD	TPAD
TRISTAN	TRISTAN
TRIUMPH	TRIUMPH
Ti	Ti
U	U
U2A2	U{-2}A{-2}
UB	|mb
UB*MEV	|mb|*MeV
UB/SR	|mb/sr
UG	|mg
UG/CM	|mg/cm
UK	UK
UNISOR	UNISOR
UNIV	Univ
UNIVERSITY	University
US	|ms
USA	USA
USSR	USSR
V	V
VAP	VAP

ENSDF	Translation
W	W
W(THETA)*G*WIDTH	w(|q)g|G{-|g0}
W.U.	W.u.
WEISSKOPF	Weisskopf
WIDTH	|G
WIDTH**2	|G{+2}
WIDTHA	|G|a
WIDTHA0	|G{-|a0}
WIDTHA1	|G{-|a1}
WIDTHA2	|G{-|a2}
WIDTHA3	|G{-|a3}
WIDTHA4	|G{-|a4}
WIDTHG	|G{-|g}
WIDTHG0	|G{-|g0}
WIDTHG0**2	|G{+2}\{-|g0}
WIDTHG1	|G{-|g1}
WIDTHN	|G{-n}
WIDTHN0	|G{-n0}
WIDTHP	|G{-p}
WIDTHP'	|G{-p'}
WIDTHP0	|G{-p0}
WIDTHP1	|G{-p1}
WIDTHP2	|G{-p2}
WIGNER	Wigner
WINTHER	Winther
X(	X(
X-RAY	x-ray
X-RAYS	x-rays
XG	X|g
XK	K| x ray
XKA	K|a| x ray
XKA1	K|a{-1}| x ray
XKA2	K|a{-2}| x ray
XKB	K|b| x ray
XKB1	K|b{-1} x ray
XKB13	K|b{-13} x ray
XKB1P	K|b{-1}'| x ray
XKB2	K|b{-2} x ray
XKB2P	K|b{-2}'| x ray
XKB3	K|b{-3} x ray
XKB4	K|b{-4} x ray
XKB5	K|b{-5} x ray
XKB5I	K|b{-5}\{+I} x ray
XKB5II	K|b{-5}\{+II} x ray
XKG	(K| x ray)|g

ENSDF	Translation
XKO2	K-O{-2} x ray
XKO23	K-O{-23} x ray
XKO3	K-O{-3} x ray
XL	L| x ray
XL1	L{-1} x ray
XL2	L{-2} x ray
XL3	L{-3} x ray
XLA	L{-|a} x ray
XLA1	L|a{-1}| x ray
XLA2	L|a{-2}| x ray
XLB	L{-|b} x ray
XLB1	L|b{-1}| x ray
XLB10	L|b{-10}| x ray
XLB15	L|b{-15}| x ray
XLB2	L|b{-2}| x ray
XLB215	L|b{-215}| x ray
XLB3	L|b{-3}| x ray
XLB4	L|b{-4}| x ray
XLB5	L|b{-5}| x ray
XLB6	L|b{-6}| x ray
XLB9	L|b{-9}| x ray
XLC	L{-|c} x ray
XLG	L{-|g} x ray
XLG1	L|g{-1}| x ray
XLG2	L|g{-2}| x ray
XLG3	L|g{-3}| x ray
XLG4	L|g{-4}| x ray
XLG5	L|g{-5}| x ray
XLG6	L|g{-6}| x ray
XLL	L{-{Sl}} x ray
XM	M x ray
XPYNG	xpyn|g
XX	XX
YTTRIUM	Y
Z	Z
Z>N	Z>N
[E2]	[E2]
[RI	[I|g
a0	a{-0}
|D	|D

Appendix G

ENSDF Dictionary Ordered by Output

Translation	ENSDF
(α)(ce)	ACE
(β)	(B)
(θ,H,t,T)	(THETA,H,T,T)
(θ,H)	(THETA,H)
(θ,T,H)	(THETA,T,H)
2J	2J
2Nσ	2N*SIGMA
2^5mom(mag)	MOMM5
2^7mom(mag)	MOMM7
$2\beta^-$	2B-
4π	4PI
4πβγ	4PIBG
4πβ	4PIB
4πγ	4PIG
<	LT
>	GT
A(θ)	A(THETA)
A-N	A-N
A=	A=
AAS	AAS
AB	AB
AJ	AJ
Aa_0	AA0
Alaga	ALAGA
April	APRIL
Auger	AUGER
August	AUGUST
Ay	AY
$A^{1/3}$	A**1/3
$A^{2/3}$	A**2/3
A_0	A0
A_{11}	A11
A_1	A1
A_{22}	A22
A_2/A_0	A2/A0
A_2	A2
A_2P_2	A2P2
A_3	A3
A_{44}	A44
A_4	A4
A_5	A5
A_6	A6
A_7	A7

Translation	ENSDF
B(E0	B(E0
B(E0)	BE0
B(E0)(W.u.)	BE0W
B(E1	B(E1
B(E1)(W.u.)	BE1W
B(E1)↑	BE1UP
B(E1)	BE1
B(E2	B(E2
B(E2)	BE2
B(E2)↑	BE2UP
B(E2)↓	BE2DWN
B(E2)(W.u.)	BE2W
B(E3	B(E3
B(E3)↑	BE3UP
B(E3)(W.u.)↑	BE3WUP
B(E3)	BE3
B(E3)(W.u.)	BE3W
B(E4	B(E4
B(E4)↑	BE4UP
B(E4)(W.u.)	BE4W
B(E4)	BE4
B(E5)	BE5
B(E5)(W.u.)	BE5W
B(E6)(W.u.)	BE6W
B(E6)↑	BE6UP
B(E6)	BE6
B(E7)(W.u.)	BE7W
B(E7)	BE7
B(E8)	BE8
B(EL)(W.u.)	BELW
B(EL)	BEL
B(J	B(J
B(M1)	BM1
B(M1)↑	BM1UP
B(M1)(W.u.)	BM1W
B(M2)	BM2
B(M2)↑	BM2UP
B(M2)(W.u.)	BM2W
B(M3)(W.u.)	BM3W
B(M3)	BM3
B(M4)	BM4
B(M4)(W.u.)	BM4W
B(M5)(W.u.)	BM5W

Translation	ENSDF
B(M8)↑	BM8UP
B(ML)	BML
B(ML)(W.u.)	BMLW
B/A	B/A
B=	B=
BCS	BCS
BE(L)	BE(L)
BF_3	BF3
BGO	BGO
BJ^2	BJ**2
BM(L)	BM(L)
Be	Be
Berkeley	BERKELEY
Bessel	BESSEL
Bethe	BETHE
Biedenharn	BIEDENHARN
Blair	BLAIR
Bohr	BOHR
Born	BORN
Branching	BR
Breit	BREIT
Brink	BRINK
B_4C	B4C
Bxρ	B*RHO
C	C
CCBA	CCBA
CCC	CCC
CERN	CERN
CP	CP
CRC	CRC
Ca(OH)	CA(OH)
Cerenkov	CERENKOV
Clebsch	CLEBSCH
Cm	Cm
Co	CO
Compton	COMPTON
Coriolis	CORIOLIS
Coster	COSTER
Coul	COUL
Coulomb	COULOMB
CsI	CSI
Curie	CURIE
C^2S	C2S
D)	D)
D+(Q)	D+(Q)

Translation	ENSDF
D+Q	D+Q
DCO	DCO
DCOQ	DCOQ
DPAC	DPAC
DPAD	DPAD
DSA	DSA
DSAM	DSAM
DWBA	DWBA
DWIA	DWIA
DWUCK	DWUCK
Davydov	DAVYDOV
December	DECEMBER
Doppler	DOPPLER
Dubna	DUBNA
E	E
E(ce)	ECE
E(d)	ED
E(d)	E(D)
E(e)	E(E)
E(n)	E(N)
E(n)	EN
E(p)	EP
E(p)	E(P)
$E(p_2)$	E(P2)
$E(p_1)$	E(P1)
E(t)	ET
E(t)	E(T)
E(α)	E(A)
E-E	E-E
E/ΔE	E/DE
E0	E0
E1	E1
E10	E10
E2	E2
E3	E3
E4	E4
E5	E5
E6	E6
E7	E7
E8	E8
E9	E9
EL	EL
ENDF/B-V	ENDF/B-V
ENDF/B	ENDF/B_
ENDOR	ENDOR

Translation	ENSDF
EPR	EPR
ESR	ESR
EWSR	EWSR
Ee	EE
Enge	ENGE
E	E
$E^{1/2}$	E**1/2
E^{2}	E**2
EΔE	EDE
Eα	EA
Eβ	EB
Eβ	EB_
$E\beta^{-}$	EB_
Eε	EEC
Eγ	*EG
Eγ	EG
$E\gamma^{3}$	EG**3
$E\gamma^{5}$	EG**5
F+B	F+B
F-K	F-K
F/B	F/B
FWHM	FWHM
February	FEBRUARY
Fermi	FERMI
Feshbach	FESHBACH
Fock	FOCK
Fourier	FOURIER
G-M	G-M
GDR	GDR
GM	GM
GMR	GMR
GQR	GQR
GSI	GSI
GTOL	GTOL
Gallagher	GALLAGHER
Gamow	GAMOW
Garvey	GARVEY
Gaussian	GAUSSIAN
Ge(Li)	GE(LI)
Ge(Li)	GELI
GeV	GEV
Geiger-Muller	GEIGER-MULLER
Geiger	GEIGER
H(	H(
H,	H,

Translation	ENSDF
H=	H=
HERA	HERA
HF	HF
HI	HI
HP	HP
HPGE	HPGE
Hager	HAGER
Hartree	HARTREE
Hauser	HAUSER
I	I
I(xray)	IX
I(γ+ce)	TI
I(γ+ce) normalization	NT
IAR	IAR
IAS	IAS
IBA	IBA
IBM	IBM
IBS	IBS
IGISOL	IGISOL
IMPAC	IMPAC
IPAC	IPAC
ISOLDE	ISOLDE
IT branching	IT BRANCHING
IT decay	IT DECAY
IT decays	IT DECAYS
IT=	IT=
Ice	ICE
Ice(K)	ICE(K)
Ice(N)	ICE(N)
In(	IN(
Iα	IA
Iβ	IB
Iβ normalization	NB
$I\beta^{-}$	IB-
$I\beta^{+}$	IB+
Iε	IE
Iε	IEC
Iγ	IG
Iγ	*RI
Iγ	RI
Iγ normalization	NR
IγEγ	IG*EG
J	J
JKπ	JKP
JOSEF	JOSEF

Translation	ENSDF
JULIE	JULIE
January	JANUARY
Jmax	JMAX
Jmin	JMIN
July	JULY
June	JUNE
J^2	J**2
J_0	J0
J_1	J1
J_2	J2
J_f	JF
J_i	JI
Jπ	JPI
K	K
K-O_2 xray	XKO2
K-O_3 xray	XKO3
K-O_{23} xray	XKO23
K/L+M	K/L+M
K/LM	K/LM
KLL	KLL
KLM	KLM
KL_1L_1	KL1L1
KL_1M_2	KL1M2
KL_1L_3	KL1L3
KL_1M_3	KL1M3
KL_1M_1	KL1M1
KL_1L_2	KL1L2
KL_2M_1	KL2M1
KL_2L_2	KL2L2
KL_2L_3	KL2L3
KL_2M_3	KL2M3
KL_2M_4	KL2M4
KL_3L_3	KL3L3
KL_3LM_1	KL3LM1
KL_3N	KL3N
KL_3M_3	KL3M3
KL_3M_2	KL3M2
KM_2M_3	KM2M3
KM_2N_2	KM2N2
KM_3M_3	KM3M3
KXY	KXY
Kelson	KELSON
Kelvin	KEVIN
Knight	KNIGHT
Krane	KRANE

Translation	ENSDF
Kronig	KRONIG
Kuo-Brown	KUO-BROWN
Kurie	KURIE
K xray	XK
$K\alpha_2$ xray	XKA2
$K\alpha_1$ xray	XKA1
Kα xray	XKA
$K\beta_2$ xray	XKB2
$K\beta_2'$ xray	XKB2P
$K\beta_4$ xray	XKB4
$K\beta_3$ xray	XKB3
$K\beta_1$ xray	XKB1
$K\beta_1'$ xray	XKB1P
$K\beta^{I}_{5}x$	XKB5I
$K\beta^{II}_{5}x$	XKB5II
$K\beta_{13}$ xray	XKB13
$K\beta_5$ xray	XKB5
Kβ xray	XKB
Kπ	KPI
L	L
L(n)	LN
L(p)	LP
L1	L1
L12	L12
L2	L2
L23	L23
L3	L3
LAMPF	LAMPF
LASER	LASER
LBL	LBL
LM	LM
LMN	LMN
LOHENGRIN	LOHENGRIN
Larmor	LARMOR
Legendre	LEGENDRE
Li	LI
Litherland	LITHERLAND
Lorentzian	LORENTZIAN
L_1xray	XL1
L_2xray	XL2
L_3xray	XL3
$L_l$xray	XLL
$L_\alpha$xray	XLA
$L_\beta$xray	XLB
$L_\eta$xray	XLC

Translation	ENSDF
L_{γ}xray	XLG
L xray	XL
$L\alpha_1$ xray	XLA1
$L\alpha_2$ xray	XLA2
$L\beta_3$ xray	XLB3
$L\beta_4$ xray	XLB4
$L\beta_1$ xray	XLB1
$L\beta_5$ xray	XLB5
$L\beta_2$ xray	XLB2
$L\beta_{215}$ xra	XLB215
$L\beta_9$ xray	XLB9
$L\beta_{15}$ xray	XLB15
$L\beta_6$ xray	XLB6
$L\beta_{10}$ xray	XLB10
$L\gamma_3$ xray	XLG3
$L\gamma_4$ xray	XLG4
$L\gamma_6$ xray	XLG6
$L\gamma_5$ xray	XLG5
$L\gamma_2$ xray	XLG2
$L\gamma_1$ xray	XLG1
M	M
M x ray	XM
M+=	M+=
M+L	ML
M+N+O	MNO
M-shell	M-SHELL
M-subshell	M-SUBSHELL
M/total ce	M/CE
M1	M1
M12	M12
M2	M2
M23	M23
M3	M3
M4	M4
M45	M45
M5	M5
M6	M6
M8	M8
MEDLIST	MEDLIST
MHZ	MHZ
MIT	MIT
March	MARCH
MeV	MEV
MeV{E4-4}	MEV**-4
Mossbauer	MOSSBAUER

Translation	ENSDF
Moszkowski	MOSZKOWSKI
N-Z	N-Z
N-shell	N-SHELL
N-subshell	N-SUBSHELL
N1	N1
N12	N12
N123	N123
N2	N2
N23	N23
N3	N3
N4	N4
N45	N45
N5	N5
N<	N<
N=	N=
NBS	NBS
NC^2S	NC2S
NE213	NE213
NMR	NMR
NQR	NQR
NSσ	NS*SIGMA
NX	NX
NaI	NAI
Ne	Ne
Nilsson	NILSSON
Note:	NOTE:
November	NOVEMBER
NuclearDataSheets	NDS
Nxσ	N*SIGMA
O	O
O/Q	O/Q
O1	O1
O123	O123
O2	O2
O3	O3
ORNL	ORNL
OSIRIS	OSIRIS
October	OCTOBER
Octupole mom(mag)	MOMM3
Octupole mom(el)	MOME3
P1	P1
PAC	PAC
PAD	PAD
PWBA	PWBA
PWIA	PWIA

Translation	ENSDF
Particle normalization	NP
P_0	P0
P_n	PN
Q	MOME2
Q	Q
Q(	Q(
Q(g.s.)	QP
Q(α)	QA
Q(β^-)	Q-
Q(ε)	Q+_
Q+O	Q+O
Q/D	Q/D
Q2D	Q2D
Q2DM	Q2DM
Q3D	Q3D
QDD	QDD
QDDM	QDDM
QDMDQ	QDMDQ
QMG	QMG
QQSP	QQSP
QSD	QSD
Q_{22}	Q22
Q_s	QS
R	*R
R	R
R(DCO)	R(DCO)
RDDS	RDDS
RDM	RDM
RPA	RPA
RUL	RUL
Ritz	RITZ
Rose	ROSE
Rutherford	RUTHERFORD
Rytz	RYTZ
S values	S VALUES
S value	S VALUE
S'	S'
S(2n)	S(2N)
S(2p)	S(2P)
S(n)	SN
S(p)	SP
S(α)	SA
S-factors	S-FACTORS
S-factor	S-FACTOR
S-value	S-VALUE

Translation	ENSDF
S-values	S-VALUES
S/	S/
S=	S=
SD	SD
SDB	SDB
SF	SF
SOREQ	SOREQ
Saxon	SAXON
Schmidt	SCHMIDT
Se(Li)	SE(LI)
Seltzer	SELTZER
September	SEPTEMBER
Si(Li)	SI(LI)
Si(Li)	SILI
SiO	SIO
Sliv-Band	SLIV-BAND
Sn	Sn
Steffen	STEFFEN
Stockholm	STOCKHOLM
T	TEMP
T	ISPIN
T/	T/
T20	T20
T21	T21
T22	T22
TDPAD	TDPAD
TPAD	TPAD
TRISTAN	TRISTAN
TRIUMPH	TRIUMPH
Teller	TELLER
Ti	Ti
$T_{1/2}$	T1/2
$T_{1/2}$	T
T_z	ISPINZ
U	U
UK	UK
UNISOR	UNISOR
USA	USA
USSR	USSR
Univ	UNIV
University	UNIVERSITY
U_2A_2	U2A2
V	V
VAP	VAP
W	W

Translation	ENSDF
W.u.	W.U.
Weisskopf	WEISSKOPF
Wigner	WIGNER
Winther	WINTHER
X(	X(
XX	XX
Xγ	XG
Y	YTTRIUM
Z	Z
Z>N	Z>N
[E2]	[E2]
[Iγ	[RI
°	DEG
x	*
avEβ	EAV
a_0	a0
branching uncertainty	DBR
c.m.	C.M.
ce	CE
ce(K)/(γ+ce)	K/T
ce(K)	CEK
ce(L)/(γ+ce)	L/T
ce(L)	CEL
ce(L+)/(γ+ce)	L+/T
ce(L1)	CEL1
ce(L12)	CEL12
ce(L23)	CEL23
ce(L2)	CEL2
ce(L3)	CEL3
ce(M)/(γ+ce)	M/T
ce(M)	CEM
ce(M+)/(γ+ce)	M+/T
ce(M1)	CEM1
ce(M2)	CEM2
ce(M23)	CEM23
ce(M3)	CEM3
ce(M45)	CEM45
ce(M4)	CEM4
ce(M5)	CEM5
ce(N)/(γ+ce)	N/T
ce(N)	CEN
ce(N+)/(γ+ce)	N+/T
ce(N1)	CEN1
ce(N2)	CEN2
ce(N3)	CEN3

Translation	ENSDF
ce(N45)	CEN45
ce(N4)	CEN4
ce(N5)	CEN5
ce(O)	CEO
ce(O)/(γ+ce)	O/T
ce(O)+ce(P)	CEO+CEP
ce(O1)	CEO1
ce(P+)/(γ+ce)	P+/T
ceβ	CEB
ceγ	CEG
cm^2	CM2
cm^3	CM3
configuration=	CONF=
configuration	CONF
$\cos^2\theta$	COS2TH
dE/dx	DE/DX
d^3He	D3HE
dΩ	DOMEGA
dγ	DG
dσ	DSIGMA
dσ/dΩ	DS/DW
dσ/dΩ	*DS/DW
e'(θ)	E'(THETA)
eV	EV
even-A	EVEN-A
ex.	EX.
e+	E+
e±	E+-
fm	FM
fm^{-1}	FM-1
fm^{-1}	FM**-1
fm^2	FM**2
fm^4	FM**4
g factor	G FACTOR
g factors	G FACTORS
g(2+	G(2+
g-factors	G-FACTORS
g-factor	G-FACTOR
g.s.	GS
g=	G=
gT	G*T
$gT_{1/2}$	GT1/2
$gW\Gamma_0{}^2$	G*W*WIDTHG0**2
$gw\Gamma_{\gamma 0}$	G*W*WIDTHG0
$g_1\Gamma$	G1*WIDTH

Translation	ENSDF
g_1	G1
$g_2\Gamma$	G2*WIDTH
g_2	*G2
g_2	G2
g^2_A	GA2
$g\Gamma$	G*WIDTH
$g\Gamma^2_{\gamma 0}$	*G*WIDTHG0**2
$g\Gamma^2{}_{\gamma 0}$	G*WIDTHG0**2
$g\Gamma_n$	G*WIDTHN
$g\Gamma_{\gamma 0}$	G*WIDTHG0
$g\Gamma_0\Gamma\gamma$	GWIDTH0WIDTHG
h'ω	HOMEGA
h^2	H**2
is D	ISD
kG	KG
kOe	KOE
keV	KEV
log $f^{1u}t$	LOGF1UT
log $f^{3u}t$	LOGF3UT
log $f^{2u}t$	LOGF2UT
log $f^{1}t$	LOGF1T
log ft	LOGFT
mb	MB
mb/sr	MB/SR
meV	MILLI-EV
mg/cm^2	MG/CM2
ms	MS
nb/sr	NB/SR
nγ	NG
nγγ	NGG
odd-A	ODD-A
p decay	PDECAY
p(θ)	P(THETA)
p-width	P-WIDTH
p1/2	P1/2
p2nγ	P2NG
pnγ	PNG
pα	PALPHA
pγ	PG
pγγ	PGG
r^2	R**2
r^4	R**4
r^6	R**6
r_0	R0
s(ce)	S(CE)

Translation	ENSDF
s-wave	S-WAVE
syst	SY
s^{-1}	S-1
t)	T)
t,	T,
th	TH
tof	TOF
tγ	TG
w(θ)g$\Gamma_{\gamma 0}$	W(THETA)*G*WID
x-ray	X-RAY
x-rays	X-RAYS
xpynγ	XPYNG
$\langle r^2\rangle$	AVRSQ
$\langle\beta^2\rangle^{1/2}$	BAVRSQ
$\Delta\langle r^4\rangle$	DAVRSQ4
$\Delta\langle r^2\rangle$	DAVRSQ
$\Delta\langle r^6\rangle$	DAVRSQ6
(J+½)	**(J+1/2)
$^{-1}$	**-1
$^{-3}$	**-3
$^{-4}$	**-4
$^{1/2}$	**1/2
$^{1/3}$	**1/3
^{12}Cγ	C12G
^{2}	**2
^{3}	**3
^{L}	**L
e.g.	E.G.
i.e.	I.E.
xE	*E
xIβ$^-$	*IB-
xIε	*IE
xQ	*Q
x$T_{1/2}$	*T1/2
x$\alpha^{1/3}$	*A**(1/3)
xσ	*SIGMA
$\leq$	LE
$\neq$	NE
$\geq$	GE
$\approx$	AP
$\approx<$	LA
$\approx>$	GA
∞	INFNT
Δ	Δ
Δ(HF)	DHF

Translation	ENSDF
Δ(logft)	DFT
Δ(β-normalization)	DNB
Δ(γ-normalization)	DNR
Δ(γ+ce-normalization)	DNT
ΔA	DA
ΔA_2	DA2
ΔA_4	DA4
ΔE	DE
ΔI(γ+ce)	DTI
ΔIα	DIA
ΔIβ	DIB
ΔIε	DIE
ΔIγ	DRI
ΔIγ(%)	PRI
ΔJ	DJ
ΔJπ	DJPI
ΔK	DK
ΔL	DL
ΔN	DN
ΔQ(ε)	DQ+
$\Delta Q(\beta^-)$	DQ-
ΔQ(α)	DQA
ΔS	DS
ΔS(n)	DSN
ΔS(p)	DSP
ΔT	DISPIN
$\Delta T_{1/2}$	DT
$\Delta T_{1/2}$	DT1/2
Δ	DELTA
Δα	DCC
Δ™	DMR
Δπ	DPI
Φ	PHI
$\Phi(p_2)$	PHI(P2)
$\Phi(p_1)$	PHI(P1)
Γ	*WIDTH
Γ	WIDTH
$\Gamma^2_{\gamma 0}$	WIDTHG0**2
Γ^2	WIDTH**2
Γ_n	WIDTHN
Γ_{n0}	WIDTHN0
Γ_{p0}	WIDTHP0
Γ_{p1}	WIDTHP1
Γ_p	*WIDTHP
$\Gamma_{p'}$	WIDTHP'

Translation	ENSDF
Γ_{p2}	WIDTHP2
Γ_p	WIDTHP
$\Gamma_{\alpha 4}$	WIDTHA4
$\Gamma_{\alpha 1}$	WIDTHA1
Γ_γ	WIDTHG
$\Gamma_{\gamma 1}$	WIDTHG1
$\Gamma_{\alpha 2}$	WIDTHA2
$\Gamma_{\alpha 0}$	WIDTHA0
$\Gamma_{\gamma 0}$	WIDTHG0
$\Gamma_{\alpha 3}$	WIDTHA3
Γα	WIDTHA
Σ	*SUMOF
Σ	SUMOF
Ψ	PSI
α	ICC
α	ALPHA
α	CC
α decay	ADECAY
α decays	ADECAYS
α syst	ASYST
α'	A'
α's	ALPHAS
α(K)exp	*EKC
α(K)exp	EKC
α(K)	KC
α(L)exp	ELC
α(L)	LC
α(L12)exp	EL12C
α(L12)	L12C
α(L1)exp	EL1C
α(L1)	L1C
α(L2)	L2C
α(L23)exp	EL23C
α(L23)	L23C
α(L2)exp	EL2C
α(L3)exp	EL3C
α(L3)	L3C
α(M)exp	EMC
α(M)	MC
α(M+..)	MC+
α(M1)	M1C
α(M1)exp	EM1C
α(M2)	M2C
α(M2)exp	EM2C
α(M3)	M3C

Translation	ENSDF
α(M3)exp	EM3C
α(M4)	M4C
α(M4)exp	EM4C
α(M5)	M5C
α(M5)exp	EM5C
α(N)exp	ENC
α(N)	NC
α(N+..)	NC+
α(N1)exp	EN1C
α(N1)	N1C
α(N2)exp	EN2C
α(N2)	N2C
α(N23)exp	EN23C
α(N3)	N3C
α(N3)exp	EN3C
α(N4)exp	EN4C
α(N4)	N4C
α(N5)	N5C
α(N6)	N6C
α(O1)	O1C
α(O2)	O2C
α(O3)	O3C
α(O4)	O4C
α(P1)	P1C
α(exp)	ECC
α-decay	A-DECAY
α-syst	A-SYST
α_0	ALPHA0
α_1	ALPHA1
α_2	ALPHA2
α_3	ALPHA3
αα	AA
αγ	AG
β	BETA
β	B
β's	BETAS
β(GT)	BGT
β(IS	B(IS
β-vibrational	B-VIBRATIONAL
βR	B*R
βR	BETA*R
βc	BC
βce	BCE
βe^-	BE-
βn	BN

Translation	ENSDF
βp	BP
β^+	B+
$\beta^+\varepsilon$ Decay	BECDECAY
β^-2n	B-2N
β^-	B-_
β^-n	B-N
β_0	B0
β_{04}	B04
β_{03}	B03
β_{02}	B02
β_{00}	B00
β_{12}	B12
β_1	B1
β_{20}	B20
β_{24}	B24
β_{22}	B22
β_2R	B2*R
β_2	B2
β_3	B3
β_3R	B3*R
β_{30}	B30
β_4	B4
β_{42}	B42
β_4R	B4*R
β_5	B5
β_5R	B5*R
β_6	B6
β_6R	B6*R
β_7	B7
β_L	BL
$\beta_L RA^{1/3}$	BL*R*A**(1/3)
β_L^2	BL**2
β_LR	BL*R
βα	BA
ββ	BB
βγ	BG
βγn	BGN
βγγ	BGG
δ	MR
δ^2	MR**2
ε	EPSILON
ε	EC
ε2p	EC2P
εB	EPSILONB
εB(E2)↑	EBE2UP

Translation	ENSDF
εB(E3)↑	EBE3UP
εK	CK
εK(exp)	ECK
εL	CL
εL(exp)	ECL
εL1(exp)	ECL1
εL2(exp)	ECL2
εL3(exp)	ECL3
εM	CM
εN	CN
εp	ECP
εα	ECA
γ	GAMMA
γ	G_
γ/α	G/A
γX	GX
γce	GCE
γe^-	GE-
γn	GN
γp	GP
γp'	GP'
γp(t)	GP(T)
γ±	G+-
γ_0	G0
γβ	GB
$\gamma\beta^-$	GB-
γγ	GG
γγn	GGN
$\gamma\gamma^\Gamma$	GGT
γγγ	GGG
χ	CHI
χ^2	CHI**2
εM(exp)	ECM
εN(exp)	ECN
κ	KAPPA
λ	LAMBDA
μ	MOMM1
μ	MU
μb	UB
μb/sr	UB/SR
μbxMeV	UB*MEV
μg	UG
μg/cm	UG/CM
μs	US
μ^-	MU-

Translation	ENSDF
ν	NU
π	PI
π^-	PI-
πβ	PIB
πβγ	PIBG
πγ	PIG
θ	THETA
θ^2	THETA**2
θ_1	THETA1
θ_2	THETA2
$\theta_{p1}{}^2$	THETAP1**2
$\theta_{p2}{}^2$	THETAP2**2
θα	THETAA
$\theta\alpha^2$	THETAA**2
θγ	THETAG
ρ	RHO
ρ^2	RHO**2
σ	SIGMA
σ(nγ)	SIGNG
σ(nα)	SIGNA
σ_0	SIGMA(0)
σ_n	SIGMAN
σ_γ	SIGMAG
σxΔE	SIGMA*DE
σν	SIGMANU
Γ	*TAU
Γ	TAU
ω	OMEGA
$\omega^2\Gamma$	OMEGA**2*TAU
ωΓ	OMEGA*T

Appendix H

ENSDF Policies

GENERAL POLICIES - Presentation of Data

The Nuclear Data Sheets are prepared from the Evaluated Nuclear Structure Data File (ENSDF), a computer file maintained by the National Nuclear Data Center on behalf of the International Network for Nuclear Structure and Decay Data Evaluations. See page iii for a list of the members of this network and their evaluation responsibilities. The presentation of material in the Nuclear Data Sheets reflects the organization of ENSDF, which is a collection of "data sets". For each nuclear species, these data sets present the following types of information:

The adopted properties of the nucleus.

The evaluated results of a single type of experiment, such as a radioactive decay, a single nuclear reaction, or the combined results of a number of similar types of experiments, such as (HI,xnγ) reactions. The data given in ENSDF are primarily derived from experimental information.

The general policies and conventions followed in the preparation of these data sets and in the presentation of material in the Nuclear Data Sheets (NDS) are discussed below.

General

The following policies apply to the adoption or presentation of data. Deviations from these policies will be noted by the evaluator.

1. The excitation energies of levels connected by γ transitions are from a least-squares fit to the adopted γ energies.

2. Dominant decay branches (*i.e.*, for the decay of ground states and isomeric states) are rounded off to 100 when the competing branches total less than approximately 0.001%. When only one branch has been observed and no estimate can be made for expected competing branches, the observed branch is given as ≤100 and the competing branch(es) as "%branching=?".

3. Total internal-conversion coefficients (α) for each transition are theoretical values corresponding to the listed radiation character (*i.e.*, multipolarity) and mixing ratio (δ). For a transition of mixed character (two or more multipolarities) and unknown mixing ratio, α is the average of the possible extremes and the uncertainty overlaps the full range of values.

In all calculations by the evaluator involving internal-conversion coefficients, a 3% uncertainty is assumed for the theoretical coefficients.

4 The cross reference flags (XREF), defined in the Adopted Levels table are given for each adopted level. When a level in an individual reaction or decay data set may correspond to more than one adopted level, the flag for that data set is given in lower case. In case of ambiguity, the energy from a particular data set is given as a comment.

Adopted Levels, Gammas data set

The Adopted Levels and γ radiations tables in the NDS are generated from an Adopted Levels, Gammas data set in ENSDF. This data set represents the best values for the level and γ properties as determined by the evaluator on the basis of all the available information.

The following information is included in an Adopted Levels, Gammas data set.

For the nuclide:

1. **Q** (β^-): β^- decay energy [always presented as Q(β)=M(A,Z)–M(A,Z+1)] and α decay energy [Q(α)] for the ground state.
2. **S(n) and S(p)**: Neutron and proton separation energies.
3. **XREF**: Cross-reference symbol assignments for the various experimental data sets.

For each level:

1. **E(lev)**: Excitation energy (relative to the ground state).
2. $\mathbf{J^{\pi}}$: Spin and parity with arguments supporting the assignment.
3. $\mathbf{T_{1/2}}$ **or Γ**: Half-life or total width in center of mass.
4. **Decay branching** for the ground state and isomers (an isomer is defined as a nuclear level with $T_{1/2} \geq 0.1$ s or one for which a separate decay data set is given in ENSDF).
5. **Q**,μ: Static electric and magnetic moments.
6. **XREF Flags** to indicate in which reaction and/or decay data sets the level is seen.
7. **Configuration assignments** (*e.g.*, Nilsson orbitals in deformed nuclei, shell-model assignments in spherical nuclei).
8. **Band assignments** and possibly band parameters (*e.g.*, rotational bands in deformed regions).
9. Isomer and isotope shifts (usually only a literature reference is given).
10. Charge distribution of ground states (usually only a literature reference is given).
11. Deformation parameters.
12. **B(E2)↑,B(M1)↑**,..: Electric or magnetic excitation probabilities when the level half-life or the ground-state branching is not known.

For γ-ray and E0 transitions:

1. **Placement** in level scheme.
2. **Eγ**: Measured γ-ray or E0 transition energy.
3. **Iγ**: Relative photon intensity from each level.
4. **Mult**,δ: Electric or magnetic multipole character, the mixing ratio, and nuclear penetration parameter.
5. **CC**: Total internal-conversion coefficient (when significant).
6 **(EL)(W.u.),B(M1)(W.u.)**,..: Reduced transition probabilities in Weisskopf units.

GENERAL POLICIES - Presentation of Data (cont.)

Reaction and decay data sets

These data sets include information about different types of experiments and may include data sets for β decay, α decay, isomeric transition (IT) decay, Coulomb excitation, charged-particle reactions [such as (d,p) and (t,p)], heavy-ion reactions [such as ^{40}Ar,xnγ)], (γ,γ'), and mesonic atoms.

The following policies apply to the presentation of data in reaction and decay data sets. Any deviation from these policies will be noted by the evaluator.

1. The J^{Π} values in the decay data sets and reaction data sets with gammas are taken from the associated Adopted Levels, Gammas data set. For other reaction data sets the J^{Π} values are from the reaction data. The J^{Π} value to the capture state in thermal-neutron capture is assigned assuming s-wave capture.
2. The character of a γ ray and its mixing ratio are from the associated Adopted γ radiation table.
3. The term "absolute intensity" has the same meaning as the term "emission probability", and the term "relative intensity" is equivalent to "relative emission probability" or "relative emission rate." The former are given as intensities per 100 decays.
4. Beta and electron-capture intensities are per 100 decays of the parent and are usually deduced from γ intensity imbalance for the levels fed. The separation of $I(\varepsilon+\beta^+)$ into $I(\varepsilon)$ and $I(\beta^+)$ is based on theoretical ε/β^+ ratios. The log *ft* values for nonunique transitions are calculated as for allowed transitions.
5. Particle transition intensities (other than β's) are per 100 particle decays. The total particle branching is given both in the drawings and in the tables.
6. Tabular γ-ray intensities are relative values. The normalization factor to convert them to absolute intensities [photons per 100 decays of the parent for decay data sets, or photons per 100 neutron captures for (n,γ) data sets, *etc*.] is given in a footnote.
7. Radiations from the decay of neutron or proton resonances are not presented. The energies and other level properties for bound levels deduced from resonance experiments are included. Primary as well as secondary γ's following thermal-neutron capture are generally included.
8. BEλ, BMλ for the excitation of levels are generally given.
9. Up to three references that make major contributions to the information in a specific data set are given in the data set heading. These major references also appear in the drawings.

Organization of material

Within each A chain, information is presented by nuclides which are arranged in order of increasing Z. There is an index for each evaluation which is followed by an isobaric diagram. A table of properties for the ground state and isomeric levels for all nuclides of the A chain is given following or with the isobaric diagram.

For each nuclide, ^{A}Z, the arrangement of material and conventions for inclusion in tables are described below.

1. Adopted levels in ^{A}Z - All adopted level properties are shown for each level, together with explanatory comments.
2. Adopted γ radiations in ^{A}Z.
3. Band structure is shown where known.
4. Levels and radiations in ^{A}Z from radioactive decays - Decays are ordered by increasing A, Z, and excitation energy of the parent.
   a. Table of levels deduced from the decay.
   b. Tables of radiations observed in the decay.
   c. Decay Scheme
5. Levels and γ rays in ^{A}Z from nuclear reactions - Reactions are ordered by increasing A, Z of the target, then by increasing A, Z of the incident nucleus. A heading is given for each reaction.
   a. Table of levels deduced from the reaction.
   b. Table of γ rays observed in the reaction, if any.
   c. Level Scheme, if γ rays were observed and placed.

GENERAL POLICIES – "THEORY"

A reference "Theory 1967Xy01" indicates theoretical predictions computed by the authors of 1967Xy01. A reference "Theory" alone indicates a determination by the evaluator of theoretical predictions described below.

Internal Conversion Coefficients

Theoretical conversion coefficients are obtained by spline interpolation (1968Ha53) from tables of Hager and Seltzer (1968Ha53) for the K–, $L_{1...3}$–, $M_{1...5}$–shells and of Dragoun, Plajner, and Schmutzler (1971Dr11) for the (N+O+...) –shells. For the $N_{1...5}$–subshells, values are obtained by graphical interpolation from tables of Dragoun, Pauli, and Schmutzler (1969Dr09). For K–, $L_{1...3}$ shells, conversion coefficients for transitions outside the E_γ, A, or Z ranges of Hager and Seltzer are obtained as follows: for $E_\gamma \leq 6000$ keV and for Z=3,6,10 and $14 \leq Z \leq 30$ interpolation from tables of Band, *et al.* (1976Ba63); for $E_\gamma > 2600$ keV, by graphical interpolation from tables of Trusov (1972Tr09). For E0 transitions, K/L_1 and L_1/L_2 ratios are obtained by graphical interpolation from tables of Hager and Seltzer (1969Ha61).

Angular Distribution and Correlation Coefficients

The coefficients required for analysis of directional correlation, polarization correlation, directional distribution, and polarization distribution data are obtained as described by Steffen (1971St47, 1971St48). In particular, we adopt the phase convention for the mixing ratio, δ, defined by Krane and Steffen (1970Kr03). Particle parameters required for the analysis of correlation and distribution data involving conversion electrons are obtained by graphical interpolation from tables of Hager and Seltzer (1968Ha54). The expression for the deorientation coefficient required to account for intermediate unobserved mixed radiations is given by Anicin (1972An20).*
A tabulation of gamma-gamma directional-correlation coefficients is given by Taylor, *et al.* (1971Ta32). These authors use the Steffen phase convention.

Penetration Parameters

Penetration parameters required for the analysis of internal conversion data and angular correlation or distribution data involving electrons are obtained by graphical interpolation from tables of Hager and Seltzer (1969Ha61).

Internal Pair Conversion Coefficients

Theoretical internal pair conversion coefficients for Λ=E1, M1, E2 are obtained by graphical interpolation in Z, E from tables of Lombard, *et al.* (1968Lo16).

* As pointed out by these authors, most earlier references which discuss this coefficient define it incorrectly.

β-Decay Rate Probabilities

Log *ft* values, capture-to-positron ratios, and electron-capture ratios for allowed, first-forbidden unique, and second-forbidden unique transitions are obtained as described by Gove and Martin (1971Go40). This reference also contains a tabulation of log *ft* values and total capture-to-positron ratios for allowed and first-forbidden unique transitions.

Atomic Processes

X-ray fluorescence yields are obtained from Bambynek, *et al.* (1972Bb16) for $Z \leq 92$ and from Ahmad (1979Ah01) for Z>92. Electron binding energies for Z<84 are taken from Bearden and Burr (1967Be73) and from Porter and Freedman (1978Po08) for Z>84.

α-Decay Hindrance Factors

The α-hindrance factors (the ratio of the measured partial half-life for α-emission to the theoretical half-life) are obtained from the spin-independent equations of Preston (1947Pr17). The nuclear radius for each even-even nucleus is determined by defining, for the g.s. to g.s. α-transition, the hindrance factor (HF)□1. For odd-A and odd-odd nuclei, the radius parameters are chosen to be the average of the radii for the adjacent even-even nuclei (1998Ak04). In cases where only one adjacent even-even radius is known, the extrapolated/interpolated value for the unknown radius is used in the calculation. A survey of the dependence of α-hindrance factors on asymptotic quantum numbers and the variation of α-hindrance factors within rotational bands is given for A□229 in 1972El21.

Electromagnetic Transition Rates

The Weisskopf single-particle estimates for the half-lives of electric and magnetic multipole radiation of energy E_γ are (1952Bl97)

$$T_{1/2W}(EL)=0.190 \left(\frac{L}{L+1}\right)\left(\frac{3+L}{3}\right)^2 \frac{[(2L+1)!!]^2}{A^{2L/3}}\left(\frac{164.44}{E\gamma\ (MeV)}\right)^{2L+1} \text{x}10^{-21}\ \text{s}$$

$$T_{1/2W}(ML)=3.255\ A^{2/3}\ T_{1/2W}(EL)$$

for a nuclear radius of $1.2\ A^{1/3}\text{x}10^{-13}$ cm.

Unweighted and Weighted Averages

If $x_1 \pm \Delta x_1$, $x_2 \pm \Delta x_2$, ... $x_n \pm \Delta x_n$ are n independent measurements of a given quantity, Δx_i being the uncertainty in x_i, then the weighted average of these measurements is $\bar{x} \pm \Delta\bar{x}$, where

$$\bar{x} = W\Sigma x_i/(\Delta x_i)^2,$$
$$W = 1/\Sigma\ (\Delta x_i)^{-2},$$

and $\Delta\bar{x}$ is the larger of
$(W)^{1/2}$
and $[W\Sigma(\Delta x_i)^{-2}(x-x_i)^2/(n-1)]^{1/2}$.

The unweighted average of these same measurements is given by $\bar{x} \pm \Delta\bar{x}$, where

$$\bar{x} = \Sigma x_i/n,$$
$$\Delta\bar{x} = [\Sigma\ (\bar{x}-x_i)^2/n(n-1)]^{1/2}.$$

SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS

PROPOSITIONS ON WHICH STRONG ARGUMENTS ARE BASED

Ground States

1. The ground state of an even-even nucleus has $J_\pi = 0^+$.
2. Spin determinations by such techniques as atomic-beam resonance, paramagnetic resonance, electron-spin resonance, and optical spectroscopy give correct values.

Gamma Transitions

3. The agreement of the measured value of a single conversion coefficient with the theoretical value for a multipolarity which is well separated from the value for any other multipolarity determines the transition multipolarity.
4. In all other cases if there is no other evidence for multipolarity, agreement of two or more measured conversion coefficients or ratios with theoretical values is necessary in order to establish the multipolarities of a transition and its mixing ratio.
5. Since an E0 transition can proceed only by conversion or pair production, pure E0 is ruled out if photons are observed.
6. Recommended upper limits for γ-ray strengths (Γ_γ/Γ_w,Γ_w-Weisskopf stimate) for various A values are given below.

	Γ_γ/Γ_W (Upper Limit)		
Character*	A=6–44[a§]	A=45–150[b,c]	A>150[d]
E1 (IV)	0.3[#]	0.01	0.01
E2 (IS)[e]	100	300	1000
E3	100	100	100
E4	100	100[†]	
M1 (IV)	10	3	2
M2 (IV)	3	1	1
M3 (IV)	10	10	10
M4		30	10

* 'IV' and 'IS' stand for isovector and isoscalar
† Γ_γ/Γ_w(Upper Limit)=30 for A=90–150
# Γ_γ/Γ_w(Upper Limit)=0.1 for A=21–44
§ Γ_γ/Γ_w(Upper Limit)=0.003 for E1 (IS),
10 for E2 (IV), 0.03 for M1 (IS), 0.1 for M2 (IS)
[a] From 1979En05
[b] From 1979En04
[c] From 1981En06
[d] Deduced from **ENSDF** by M. J. Martin
[e] In super-deformed bands the E2 transitions can have Γ_γ/Γ_w>1000.

Beta Transitions§

7. If log *ft* < 5.9, the transition is allowed: ΔJ=0 or 1, Δπ=no (no change in parity). Superallowed (ΔT=0) $0^+ \square 0^+$ transitions have log *ft* in the range 3.48 to 3.50. Isospin forbidden (ΔT=1) $0^+ \square 0^+$ transitions have log *ft*>6.4. If 3.6<log *ft*<6.4, the transition is not $0^+ \square 0^+$.
8. If log $f^u t$<8.5 (log $f't$ < 7.4), ΔJ=0,1; Δπ=yes or no.
9. If log *ft*<11.0, ΔJ=0,1; Δπ=yes or no or ΔJ=2, Δπ=yes.
10. If log *ft*<12.8, ΔJ=0,1,2; Δπ=yes or no.
11. If log $f^u t \geq$8.5 (log $f't \geq$ 7.4) and if the Fermi plot has the curvature corresponding to a shape factor (p^2+q^2), then the transition is first-forbidden unique (ΔJ=2, Δπ=yes).

See "β-Decay Rate Probabilities" on page vii.
Note that log $f^u t$=log $f't$+1.079.

Note: For nuclei at, or very near to, closed shells values may be smaller. For example, in the mass region around Z=82, the upper limit of 5.9 given in #7 above could be 5.1.

§ See 1973Ra10

γγ Directional Correlation

$$W(\theta) = \sum_{\text{k-even}} A_k P_k (\cos\theta)$$

12. If a gamma-gamma directional-correlation experiment yields $A_2 \approx +0.36$ and $A_4 \approx +1.1$, then the spin sequence is $0 \square 2 \square 0$.
13. Results of γγ(θ) are strong evidence for excluding spin sequences for which the theoretical A_2 or A_4 falls well outside the experimental range.

βγ Directional Correlation

$$W(\theta) = \sum_{\text{k-even}} A_k(\beta)A_k(\gamma)P_k(\cos\theta)$$

14. If $|A_2(\beta)| \geq 0.1 (A_4=0)$, the transition is not allowed. The converse is not true.
15. If $A_4(\beta) \neq 0$, the transition is neither allowed nor first forbidden.
16. If $A_4(\beta)=0$, the transition is allowed or first forbidden.

βγ Polarization Correlation

$$P(\theta) = \frac{\sum_{k-\text{odd}} A_k(\beta)A_k(\gamma)P_k(\cos\theta)}{W(\theta)}$$

17. In allowed transitions,

β^-	$A_1(\beta)<0$ if $J_i=J_f$
β^+	$A_1(\beta)>0$ if $J_i=J_f$
β^-	$A_1(\beta)\geq 0$ if $J_i=J_f+1$
	$A_1(\beta)<0$ if $J_i=J_f-1$
β^+	$A_1(\beta)\leq 0$ if $J_i=J_f+1$
	$A_1(\beta)>0$ if $J_i=J_f-1$

18. If $A_3(\beta) \neq 0$, the β-transition is not allowed. The converse is not always true.

γ Angular Distribution

19. In the angular distribution of gamma rays from deexcitation of states populated in high-spin reactions (for a typical value of σ/J=0.3, where σ is the magnetic substate population parameter):

a. If $A_2 \approx +0.3$ and $A_4 \approx -0.1$, the transition is generally ΔJ=2 (stretched quadrupole). (The same A_2 and A_4 values are possible for ΔJ=0, D+Q transitions also, but such transitions are N less common. A_4=0 for ΔJ=0, dipole transition).
b. If $A_2 \approx -0.2$ and $A_4 \approx 0$, the transition is generally ΔJ=1 (stretched dipole).
c. If $A_4>0$ ($A_2 \approx +0.5$ to -0.8), the transition is ΔJ=1, D+Q.

γ DCO Ratio

In the angular correlation (DCO) of gamma rays from deexcitation of states populated in high-spin reactions (for a typical value of σ/J=0.3, where σ is the magnetic substate population parmeter):
20. For ΔJ=2, stretched quadrupole as a gating transition:

a. R(DCO)≈1.0, the transition is generally ΔJ=2 (stretched quadrupole). (The same value is possible for ΔJ=0, dipole but such transitions are less common).
b . If R(DCO)≈0.5, the transition is generally ΔJ=1 (stretched dipole).
c . If R(DCO) differs significantly from ≈0.5 or ≈1.0, the transition is ΔJ=1 (or 0), D+Q

SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS – continued

PROPOSITIONS ON WHICH STRONG ARGUMENTS ARE BASED continued

γ DCO Ratio continued

21. For ΔJ=1, stretched dipole as a gating transition:
a. If R(DCO)≈2.0, the transition is generally ΔJ=2 (stretched quadrupole). (The same value is possible for ΔJ=0, dipole transitions, but such transitions are less common).
b. If R(DCO)≈1.0, the transition is generally ΔJ=1 (stretched dipole).
c. If R(DCO) differs significantly from ≈2.0 or ≈1.0, the transition is ΔJ=1 (or 0), D+Q.

Reactions

22. Low-energy Coulomb excitation is predominantly E2 excitation.
23. Coulomb excitation determines J^π if the excitation probability agrees with the calculated values of Alder (1960Al23).
24. The spin of the compound nuclear state resulting from thermal-neutron capture is equal to the spin of the target nucleus plus or minus 1/2.
25. Primary γ's from neutron capture are E1, M1, E2, or M1+E2.
26. If the angular distribution in a single-nucleon transfer reaction can be fitted with a unique L value, the spin of the final state J_f is related to the spin of the initial state J_i by

$$\vec{J}_f = \vec{J}_i + \vec{L} + \vec{1/2}$$

with parity change if L is odd.
27. If the vector analyzing power for a single-nucleon transfer reaction shows a clear preference between J=L+1/2 and J=L–1/2 and if the L value is known, then the J value is determined.
28. Generally for the states populated in high-spin reactions, spins increase with increasing excitation energy. This is a result of the fact that these reactions tend to populate yrast or near yrast states.
29. If the angular distribution can be fitted with a unique L-value the J^π of the final state is related to the J^π of the initial state by $\vec{J}_f = \vec{J}_i + \vec{L}$, $\pi_f\pi_i = (-1)^L$, for the following cases
   a. A strong group observed in (p,t), (t,p), and (^{3}He,n) reactions (strong groups are assumed to result from two identical nucleons transferred in a relative s state)
   b. A strong group observed in the α-particle transfer reaction (^{6}Li,d).
   c. (e,e') and (α,α') inelastic scattering.
30. In reactions with $J^\pi = 0^+$ target, projectile, and ejectile, if the yield of a group at 0º or 180º is
   a. non-zero, the parity of the final state is $(-1)^{J_f}$
   b. zero at several uncorrelated energies, the parity of the final state is $(-1)^{J_f+1}$
31. In reactions with a polarized $J^\pi = 1$ projectile in the m=0 substate, with $J^\pi = 0^+$ ejectile and target, if the yield of a group at 0º or 180º is
   a. non-zero, the parity of the final state is $(-1)^{J_f+1}$
   b. zero at several uncorrelated energies, the parity of the final state is $(-1)^{J_f}$

Regions of Strong Nuclear Deformation

The systematic occurrence of rotational-band structure in the strongly deformed nuclides can be a considerable help in making Jπ assignments, since one can also use the level energy as one of the considerations. This frequently makes it possible to assign a Jπ value to a level with confidence from data which, absent such structure, might yield an ambiguous assignment.

32. Level-energy considerations. If the couplings among the states are not too strong, the energies of the lower members of a band can be expressed by the relatively simple relation (see, *e.g.*, 1971Bu16 and references therein):

$$E(J,K)=AX+BX^2+CX^3+...$$
$$+(-1)^{J+K}\prod_{i=1-K}^{K}(J+i)\{A_{2K}\}+B_{2K}X+...\} \quad (1)$$
where $X=J(J+1)-K^2$

The **inertial parameter**, A, exhibits a systematic behavior in the various regions of strongly deformed nuclei, which can be helpful in assigning levels to rotational bands. In some instances (*e.g.*, strong Coriolis coupling) where the A values depart significantly from systematic trends, this observation can itself be useful, since it can help establish the presence of such effects and, hence, provide evidence for the relevant nucleonic configurations.

For the case of K=1/2 bands, the **decoupling parameter**, a, which is characteristic for each such band, is given by the ratio A_1/A in (1). Establishing a value for the decoupling parameter of a proposed band can be useful in assigning a nucleonic configuration to it - and *vice-versa*.
33. Allowed-unhindered beta transitions. In this region, beta transitions having log *ft* values <5.0 are classified as "allowed unhindered" (*au*). Such transitions take place between one-quasiparticle orbitals having the same asymptotic quantum numbers. In the "rare-earth" region ($90 \leq N \leq 112$, $60 \leq\approx Z \leq\approx 76$), four such orbital pairs are known: [532], near the beginning of this region; [523], near the middle of this region; [514], above the middle of this region; and, at the high end, [505]. Observation of an *au* transition is definitive evidence for the presence of the particular pair of orbitals.
34. Coulomb excitation. If a sequence of levels having "rotational-like" energy spacings is found to be excited with enhanced probabilities, this is evidence that this sequence (at least below the first "backbend") forms the ground-state rotational band for the nuclide involved. If the E2 transition probabilities involved are large (tens of Weisskopf units or larger) and comparable to each other, then this is definitive evidence for both a band structure and the sequence of Jπ values, assuming one of the spins Nis known.
35. Alpha decay. Observation of a "favored" α transition (HF<4) indicates that the two states involved have the same nucleonic configuration. If a sequence of levels having "rotational-like" energy spacings is associated with the level fed by this favored transition and these levels have HF's that vary according to the established trend within rotational bands (1972El21), then this sequence can be considered to form a rotational band whose nucleonic configuration is the same as that of the alpha-decaying state. If the Jπ value of this latter state and its configuration are known, then the corresponding quantities can be considered to be known for the band in the daughter nuclide or *vice versa*.
36. Single-nucleon-transfer reactions (light-ion-induced). For a single-nucleon transfer reaction induced by light ions (^{4}He and lighter), the characteristic pattern of cross sections among rotational-band members ("fingerprint") can be used to assign a set of levels as specific Jπ members of a band based on a particular Nilsson configuration, if the fingerprint agrees well with that predicted by the Nilsson-model wavefunctions and is distinct from those expected for other configurations in the mass region. (This method is even stronger if angular distributions giving unique L values, or vector analyzing powers, support the assignments for one or more of the levels.)

SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS – continued

PROPOSITIONS ON WHICH STRONG ARGUMENTS ARE BASED continued

High-spin states

In the decay of high-spin states, commonly produced in heavy-ion induced compound nuclear reactions or in highly excited nuclides created as products of nuclear fission or in Coulomb excitation, the multipolarities of the deexciting γ transitions and the relative spins and parities of the levels are generally determined from angular distributions, angular correlations (DCO ratios), linear polarizations and internal-conversion coefficients. In addition, relative energy-level spacings and the increase of γ intensity with decreasing excitation energy are important clues.

37. For a well-deformed nucleus when a regular sequence of ΔJ=2 (stretched quadrupole) transitions is observed at high spins as a cascade, the sequence may be assigned to a common band with E2 multipolarity for all the transitions in the cascade. A similar but somewhat weaker argument holds for less deformed nuclei where a common sequence of levels is connected by a regular sequence of ΔJ=2 (stretched quadrupole) transitions in a cascade.

38. For near-spherical nuclei, when a regular sequence of ΔJ=1 (stretched dipole) transitions is observed at high spins as a cascade, then the sequence may be assigned to a common band with (M1) multipolarity for all the transitions in the cascade. (Cascades of ΔJ=1, E1 transitions occur in rare cases of nuclides which show alternating-parity bands or reflection asymmetry.)

39. In the absence of angular distribution/correlation data, a regular sequence of transitions in a cascade may be assigned to a common structure or a band if (a) the low-lying levels of this structure have well established spin and parity assignments and (b) there is good evidence that, at higher energies and spins, the band has not changed in its internal structure due to band crossings or other perturbations.

Alpha Decay

40. The hindrance factor for an α transition from the ground state of an even-even nucleus to the ground state of the daughter nucleus is 1.0 by definition. For odd-A and odd-odd nuclei, hindrance factors ≤4 identify favored α transitions, and these connect states having the same spin, parity and configuration.

41. For α-decay between two states, one of which has J=0, the parity change is given by $\Delta\pi=(-1)^{\Delta J}$.

PROPOSITIONS ON WHICH WEAK ARGUMENTS ARE BASED

1. In cases where gammas of one multipolarity "cluster" in one time region in the half-life vs. energy plot, as is true for M4's, other γ's whose half-lives fall in this cluster may be assigned the corresponding multipolarity.
2. In cases where a cluster of two multipolarities, *e.g.* M1 and E2 occupies one time region, a new gamma of which the half-life falls in this region may be assigned one of the two multipolarities or a mixture of the two.
3. Whenever ΔJ≥2, an appreciable part of the gamma transition proceeds by the lowest possible multipole order.

This statement is based on the scarcity of counter-examples and the observation that few E2 γ's are as slow as M3's, few E2's as slow as E3's, *etc*.

4. The spin and parity of a parent state may be inferred from the measured properties of its assumed isobaric analog resonance, and vice versa.
5. Low-lying states of odd-A nuclei have shell-model spins and parities, except in the regions where deformations appear. This argument is much stronger when supported by expected cross-section strengths (C^2S) in single-nucleon transfer reactions.

It is recognized that some shell-model predictions are stronger than others. For example, the shell model would mildly deny that the ground-state J^π of the 39th proton be $3/2^-$, but emphatically deny its being $3/2^+$. However, we have not included this distinction here and consider all shell-model arguments to be weak.

6a. For low-lying states of odd-odd spherical nuclei, the Nordheim Nrules (1950No10):

$J = j_p + j_n$, if $j_p=l_p + -1/2$ and $j_n = l_n + -1/2$;
$J = |j_p - j_n|$, if $j_p = l_p + - 1/2$ and $j_n=l_n -+ 1/2$.

may be helpful in obtaining the ground-state spins and parities, if there is supporting evidence.
6b. For excited states of strongly deformed odd-odd nuclei, the Gallagher-Moszkowski rules (1958Ga27) may be helpful in deducing the relative positions of the two two-quasiparticle states formed by the two different couplings of the quasiparticle constituents, if there is supporting evidence. Here, the state corresponding to the parallel alignment (Σ=1) of the projections (=1/2) of the intrinsic spins of the two odd particles is expected to lie lower than that produced by the antiparallel (Σ=0) alignment. This can be particularly useful in establishing the ground state Jπ values and nucleonic configurations forn odd-odd nuclei.

(In the strongly deformed even-even nuclei, the opposite is expected to obtain, i.e., the Σ=0 coupling should lie lower than that with Σ=1. In these nuclei, however, the experimental situation is less clear since the two-quasiparticle excitations occur at or above the pairing gap, where the level densities are high and couplings to vibrational excitations can affect the two two-quasiparticle states differently.)
7. Statements similar to 5 and 6 based on other models.
8. Statements based on interpolation or extrapolation of regional trends, such as shown in 1971Bu16, 1972El21, 1977Ch27, 1990Ja11 and 1998Ja07 for the rare-earth and heavy-mass regions.
9. All statements connected with the nonobservation of expected transitions.
10. Rules extracted in the survey by 1972El21 for unfavored α transitions can be used to deduce the configuration of the parent or the daughter level, if the configuration of the other is known.
11. For magnetic moments, the extreme rarity of pure single-particle states and observation of large deviations from free-nucleon g-factors in nuclei means that comparison between the experiment and the 'Schmidt Limit' estimates (based on such pure states) is not a sound basis for spin or parity assignment. The magnetic moments or g-factors, however, can give supporting, and in some cases decisive, evidence for assignments where predictions for possible alternatives, using g-factors based on local systematics of measured moments, differ widely.

For excited states, the 'collective' aspects of the state frequently make substantial contribution to the magnetic moment. The correct g-factor for this contribution, however, is a matter of detailed theory and any potential assignment based on assumed g(collective)=Z/A must be viewed with caution.

CONVENTIONS USED IN NUCLEAR DATA SHEETS

Units
Energies keV
Cross Sections barns
Magnetic dipole moments nuclear magnetons (μ_N)
Electric quadrupole moments barns
B(EL) e^2b^L
B(ML) $\mu_N^2 b^{L-1}$

Uncertainties ("Errors") The uncertainty in any number is given one space after the number itself:
4.623 *3* means 4.623 $\pm$0.003
4.6 h *12* means 4.6 $\pm$1.2 h
$5.4x10^3$ *2* means 5400 $\pm$200
4.2 *+8–10* means $4.2\ ^{+0.8}_{-1.0}$
–4.2 *+8–10* means $-(4.2\ ^{+10}_{-8})=-4.2\ ^{+0.8}_{-1.0}$

? Question Mark given after a quantity often indicates doubt as to the existence or the value of the quantity. For example, a "?" given after the $T_{1/2}$ value indicates that the assignment of that half-life to the associated level is not certain.

( ) Parentheses have the following interpretation for different quantities in the tabular data:

Quantity	Meaning of parentheses
Jπ	Jπ based upon weak arguments. See SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS.
L transfer or Mult.	Possible value but not definitely established experimentally.
Other	Value deduced (*i.e.*, is not directly measured) or taken from other sources.

Examples:

$J^{\pi}=(1/2,3/2)^-$
Weak arguments limit the spin to 1/2 or 3/2. Strong arguments indicate negative parity.

$J^{\pi}=4^{(+)}$
Strong arguments show the spin is 4; weak arguments suggest positive parity.

L=(3)
L value tentatively established as 3.

Mult.=(M1)
Radiation character tentatively established as M1.

Mult.=M1(+E2)
Radiation character includes E2 with a mixing ratio, |δ|, that may be >0.

[ ] Brackets

$7/2^-[2514]$ Nilsson asymptotic quantum numbers, K^{π} [N n_z Λ]

`Assumed quantity, e.g., [M1+`

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A	mass number*, A=Z+N
A_2, A_4	coefficients of Legendre polynomials in angular- correlation or angular-distribution measurement
av	average
B(EL), B(ML)	reduced EL, ML transition probability in $e^2x(barn)^L$, μ_N^2 $x(barn)^{L-1}$
calc, CA	calculated, calculation
CCBA	coupled-channel Born approximation
ce	conversion electron
chem.	chemical separation
circ	circular
c.m.	center of mass
coef	coefficient
coin	coincidence
Coul. ex .	Coulomb excitation
CP	circular polarization
cryst	crystal-diffraction spectrometer
C^2S, C^2S'	one-nucleon spectroscopic strength for pickup, stripping reactions
d	day
D	dipole
DSA	Doppler shift attenuation
DWBA	distorted-wave Born approximation
DWIA	distorted-wave impulse approximation
E	energy
E(ε)	energy of electron-capture transition(endpoint of γ-continuum + K-electron eparation nergy of daughter)
E1, E2, EL	electric dipole, quadrupole, 2^L-pole
excit	excitation function
expt	experiment, experimental
F	fission
F-K	Fermi-Kurie (plot)
FWHM	energy resolution, full width at half maximum
g	gyromagnetic ratio*
GDR	giant dipole resonance
GQR	giant quadrupole resonance
g.s.	ground state
h	hour
H	magnetic field
HF	hindrance factor
hfs	hyperfine structure
HI	heavy ion
I	intensity
IAR	isobaric analog resonance
IAS	isobaric analog state
IBS	internal bremsstrahlung spectrum
IMPAC	ion implantation perturbed angular correlation technique
inel	inelastic
ion chem.	chemical separation by ion exchange
IT	isomeric transition
J	total angular momentum quantum number*
K	projection of nuclear angular momentum J on nuclear symmetry axis
K, L, M	K-, L-, M-shell internal conversion
K/L	K-, L-conversion electron ratio
L	(1)orbital angular momentum quantum number*, (2)multipolarity
L(n), L(p)	L-transfer in neutron, proton transfer reaction
min	minute
M+	M+N+O+...
M1, M2, ML	magnetic dipole, quadrupole, 2^L-pole
mag spect	magnetic spectrometer
max	maximum
Moss	Mossbauer effect
ms	(1)mass spectrometer, (2)millisecond
mult	multipolarity/character
N	neutron number*, N=A-Z
NMR, NQR	nuclear magnetic, quadrupole resonance
norm	normalization
PAC	perturbed angular correlation
pc	proportional counter
p,γ(θ)	angular distribution of γ-rays with respect to a proton beam
p,γ(t)	time distribution of photons with respect to a pulsed proton beam
pol	polarized, polarization
priv comm..	private communication
PWBA	plane-wave Born approximation
Q	(1)reaction energy*, (2)disintegration energy*, (3)quadrupole moment*, inunits of barns, (4)quadrupole
Q(ε)	total disintegration energy in ε decay
Q(β-)	total disintegration energy in β- decay
Q(α)	total disintegration energy in α decay, E(α) + E(recoil)
R	$r_oA^{1/3}$, nuclear radius*
RDM	recoil distance measurement
RUL	recommended upper limit for γ-ray strength
rel	relative
res	resonance
s	second
S	spectroscopic factor
S'	$[(2J_f+1)/(2J_i+1)]S$
S(n) or S_n,	energy necessary to separate a
S(p) or S	neutron, proton from nucleus
scatt	scattering
scin	scintillation counter
semi	semiconductor detector
SF	spontaneous fission
Spall	spallation
Sr	steradian
syst, SY	systematics
t	triton
T	(1)isobaric spin, (2)temperature
Tz	Z-Component of isobaric spin, (N-Z)/2
$T_{1/2}$	half-life*
th	thermal
thresh	threshold
tof	time-of-flight measurement
vib	vibrational
W.u.	Weisskopf single-particle transition speed
Y	year
Z	atomic number*, Z=A-N
α	total γ-ray internal conversion coefficient N(ce)/N(γ)*
α(K), α(L)	γ ray internal conversion coefficient for electrons ejected from the K-, L-shell
αγ,βγ,γγ,	coincidences of α's and γ's, β's and γ's, γ's and γ's
αγ(θ,H,t)	αγ-, βγ-, γγ-coincidences as
βγ(θ,H,t),	function of angle, magnetic γγ(θ,H,t) field, time
$β_2$, $β_3$, βL	quadrupole, octupole, 2^L-pole nuclear deformation parameter
βγ(pol),	polarization correlation of γ's
γγ(pol)	in coinc idence with β's,γ's
Γ, Γ(γ), Γ(n)	level width*, partial width for γ-, n-emission
γ(θ,H,T)	γ-intensity as function of angle, magnetic field, temperature
γ±	annihilation radiation
δ	ratio of reduced matrix elements of (L+1)- to L-pole radiation with sign convention of Krane and Steffen, Phys.Rev. C2, 724 (1970)
ε	electron capture
εK, εL, εM	electron capture from K-, L-, M-shell
ε(γ)B(E2) ,	partial B(E2) for photon,
ε(ce)B(E2)	conversion electron detection
θ	indicates angular dependence
λ	(1)projection of particle angular momentum on nuclear symmetry axis, (2)radiation type, e.g., M1, M2..

Nuclear Data Sheets Symbols and Abbreviations - continued

μ	magnetic moment of particle*, given in nuclear magnetons (μ_n)
v	neutron shell-model configuration
π	parity, proton shell-model configuration
σ	cross section*
$\Sigma(\gamma\gamma)$	coincidence summing of γ-rays
$\omega(K)$, $\omega(L)$	K, average-L fluorescence yield

%α	percent α branching from level
%β-	percent β- branching from level
%β+	percent β+ branching from level
%ε	percent ε branching from level
%IT	percent (γ+ce) branching from level
%SF	percent spontaneous fission from level
$\langle r^2 \rangle$	root-mean-square of nuclear radius

Prefixes*

T	tera	($=10^{12}$)	μ	micro	($=10^{-6}$)
G	giga	($=10^{9}$)	n	nano	($=10^{-9}$)
M	mega	($=10^{6}$)	p	pico	($=10^{-12}$)
k	kilo	($=10^{3}$)	f	femto	($=10^{-15}$)
c	centi	($=10^{-2}$)	a	atto	($=10^{-18}$)
m	milli	($=10^{-3}$)			

Symbols for Particles and Quanta*

N	neutron	π	pion
p	proton	μ	muon
d	deuteron	e	electron
t	triton	ν	neutrino
α	α-particle	γ	photon

Recommended by Commission on Symbols, Units, and Nomenclature of International Union of Pure and Applied Physics

12.

ENSDF Analysis and Utility Codes

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ENSDF Analysis and Utility Codes

Presentation for the ICTP-IAEA Workshop on Nuclear Structure and Decay Data: Theory and Evaluation

Trieste-08

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ENSDF Analysis and Utility Codes

- Platforms
- Overview of the Programs
- Programs Used for Various Types of ENSDF Datasets
  - All Types of Datasets
  - Adopted
  - Decay
  - Reaction
- Additional Notes on Some of the Codes
- *Introduction to the CD-ROM*

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ENSDF Analysis and Utility Codes
Platforms

- Most of the programs are available for the following:
  - ANSI standard Fortran 77 or Fortran 95
  - LINUX and UNIX (gnu f77 FORTRAN, INTEL FORTRAN 90, or Lahey/Fujitsu FORTRAN 95)
  - Windows 95/98/ME/NT/2000/XP/VISTA (COMPAQ/DEC Visual Fortran)
- Executables are also provided for LINUX, UNIX, and Windows.

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ENSDF Analysis and Utility Codes
Overview

- ADDGAM — adds gammas to an adopted dataset
- ALPHAD — calculates α R_0, Hindrance Factors and theoretical $T_{1/2}(\alpha)$
- *BrIcc/HSICC* (Band-Raman Internal Coefficients/Hager-Seltzer Internal Conversion) — interpolates internal conversion coefficients – BrIcc adopted
- COMTRANS (Comments Translation) — translates comment records in ENSDF dataset to a "rich text" format
- DELTA — analyzes angular correlation data
- ENSDAT (Evaluated Nuclear Structure Drawings and Tables) — produces high quality drawings and tables in the Nuclear Data Sheets style

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ENSDF Analysis and Utility Codes
Overview - 3

- RadList (Radiation Listing) — calculates atomic and nuclear radiations, and checks energy balance
- RULER — calculates reduced transition probabilities
- TREND (Tabular Representation of ENSDF) — tabular display of ENSDF data

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ENSDF Analysis and Utility Codes
All Types of Datasets

- Applicable programs are FMTCHK, ENSDAT, PANDORA and TREND
- FMTCHK should be run after any manual changes to the file
- ENSDAT may be used to check the data visually
- If you are considering combining several datasets (*e.g.*, from XUNDL), PANDORA may be useful
- TREND may be used to check the data visually

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ENSDF Analysis and Utility Codes
Adopted Levels, Gamma Datasets — 1

- Applicable programs are ADDGAM, GTOL, Brlcc, PANDORA and RULER
- ADDGAM and PANDORA are useful in constructing the dataset
- PANDORA used iteratively to aid in physics decisions, checking assignments, and updating source datasets based on changes in the adopted data
- GTOL useful only in obtaining the least-squares adjustment of the level energies
  - Matrix may occasionally be singular

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ENSDF Analysis and Utility Codes
Adopted Levels, Gamma Datasets — 2

- RULER may be used in two modes:
  - comparison mode to provide additional information in obtaining γ-multipolarity assignments
  - should also be run to provide the BEλWs and BMλWs
  - Brlcc/HSICC should be run before RULER
- Brlcc should be run to provide the internal conversion coefficients
  - there is no need to delete the "S G" records generated by code

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ENSDF Analysis and Utility Codes
Decay Datasets — 1

- Applicable programs are ALPHAD (for α decay), GABS, GTOL, BrIcc, LOGFT (for $\beta^{\pm}/\varepsilon$ decay), RadList and RULER
- ALPHAD should be used to obtain the hindrance factors, and R_0 for even-even ground-state nuclei - an R_0, must be supplied for other nuclei
- GABS may be used to combine the data from up to three sources to obtain I_γ-normalization (NR), the branching ratios (BR) and absolute I_γs.
  - BrIcc should run on the input data, or the αs from the adopted dataset should be used

ENSDF Analysis and Utility Codes
Decay Datasets — 2

- GTOL may be used:
  - provide a least-squares adjustment of the level energies
  - check the uncertainties and placement of the γs
  - obtain the intensities of particles feeding the levels
    - should be done before ALPHAD and LOGFT are employed
  - may be useful in deriving I_γ-normalization (NR)
- BrIcc may be used:
  - check experimentally measured αs against theory
  - if the adopted αs are not used, to produce this information for the data set

ENSDF Analysis and Utility Codes
Decay Datasets — 3

- LOGFT is required to obtain the log *ft*s, $I_{\beta+}$ and I_{ε}, and partial electron-capture fractions
  - should be done before using RadList.
  - if not using measured intensities, GTOL should be used to obtain $I_{\beta-}$ and $I_{\varepsilon+\beta+}$
- RadList should be used:
  - check the calculated energy deposited with that based on the Q-value and branching ratio
  - to compare to experimentally obtained X-ray intensities
  - check results against integral measurements (*e.g.*, $<E_{\beta\pm}>$)
  - unresolved discrepancies should be noted in the dataset
  - Brlcc and LOGFT should have been used before doing these checks

ENSDF Analysis and Utility Codes
Decay Datasets — 4

- RULER may be used to check or further limit multipolarities based on other methods (*e.g.*, from experimental conversion coefficients)

ENSDF Analysis and Utility Codes
Reaction Datasets — 1

- Applicable programs are GTOL, BrIcc and RULER.
  - RadList may also prove of use for (thermal n,γ) datasets
- primary use of GTOL is to do a least-squares adjustment of the level energies and to check the uncertainties and placement of the γs
  - if ΔE_γ values are not given and a good estimate cannot be obtained, may be better to use the authors' level energy values
  - also useful in checking for intensity imbalance problems if relative intensities are given

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ENSDF Analysis and Utility Codes
Reaction Datasets — 2

- BrIcc may be used to check experimentally measured αs against theory
  - very useful to include αs and partial αs for (thermal n,γ) datasets
- RadList may be used to check the energy balance of (thermal n,γ) datasets by tricking the code
  - change the DSID on the ID record to indicate IT decay
  - add an appropriate Parent record (E_{level}=S_n)
  - add a BR of 1.0 on the Normalization record

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ENSDF Analysis and Utility Codes
Additional Notes - 1

- ALPHAD
  - ΔR_0: five values are calculated and reported:
    $R_0(T_{½},E)$, $R_0(T_{½}+\Delta T_{½},E)$, $R_0(T_{½}-\Delta T_{½},E)$, $R_0(T_{½},E+\Delta E)$, $R_0(T_{½},E-\Delta E)$
    $\Delta R_0=\sqrt{(((|R_0(T_{½}+\Delta T_{½},E)-R_0(T_{½}-\Delta T_{½},E)|)/2)^2 + ((|(R_0(T_{½},E+\Delta E)-R_0(T_{½},E-\Delta E)|)/2)^2)}$
  - if either the value or the Δ for E_{parent}, Q_α, or E_{level} is non-numeric and E_α and ΔE_α are numeric, E_α and ΔE_α are used in the calculations
  - order of precedence for non-numeric uncertainties: limits (*e.g.*, "GT" or "LT"), "AP", "CA", and "SY"

ENSDF Analysis and Utility Codes
Additional Notes - 2

- COMTRANS
  - should **not** be run on ENSDF or XUNDL files submitted to the NNDC
    ^A4 → A4 → A{-4} → a{-4}
    T→T{-1/2}→T{-1/2}T{-1/2}→T{-1/2} T{-1/2}T{-1/2}T{-1/2}→ …
  - useful to run before using Isotope Explorer 2 or ENSDAT
- ENSDAT
  - keynumber list generated by ENSDAT may be used to check the keynumbers
  - layout commands may be embedded in the input
    - see ENSCOMDS.TXT
    - need to be removed before submission to the NNDC
  - "View" option available if you have a PostScript viewer such as GhostView installed

ENSDF Analysis and Utility Codes
Additional Notes - 3

- NSDFLIB — subroutine package used in all programs, except DELTA, GABS and LWEIGHT
  - ANSI standard FORTRAN77
  - ANSI standard FORTRAN95 with a couple of exceptions
- RadList
  - calculated uncertainties may be overestimated.
    - total energy deposited by γs calculated as $\Sigma BR \times NR \times E_\gamma \times I_\gamma$ instead of $BR \times NR \Sigma E_\gamma I_\gamma$
  - uses the first partial conversion coefficient found
    - If EKC is encountered before KC, EKC will be used in the calculations

ENSDF Analysis and Utility Codes
Additional Notes - 4

- RULER — some problems in the uncertainties when calculating BEλWs and BMλWs.
  - $1/T_{1/2}$, $1/(1+\alpha)$, or $1/(1+\delta^2)$ may result in asymmetric uncertainties
  - possible covariances between α and E_γ or δ or between I(γ+ce) and ΣI(γ+ce)
  - first order Taylor expansion may not be valid (*e.g.*, for $E\gamma^5$)
  - an asymmetric $T_{1/2}$ may result in a symmetric $1/T_{1/2}$.
  - Lyon's method should probably be used for non-physical results (*e.g.*, BE2W-ΔBE2W<0)

LOGFT

Calculates vital β^- decay and $\beta^+ + \varepsilon$ decay information (allowed, 1U, 2U transitions only)

Input (also uses information on N and P records):

1st forbidden unique: col 78-9

Iε+Iβ+: col 65

Iβ-: col 22

```
 81SR  B          3.0                                    1U
169YB  E                                          0.88   22
```

Output:

Log *ft*

I(β+)

I(ε)

```
81SR   B          3.0                    8.5                1U
81SRS  B EAV=3127 15
169YB  E          0.013 3   0.87 22     8.84  11 0.88  22
169YBS E EAV=409.3 14$CK=0.8147 2$CL=0.13091 4$CM+=0.03
953 1
```

Warning: output is from allowed calculation for all but 1U and 2U cases!

C. Baglin, Trieste2008

Why do we need log*ft*, I(β+), EAV, CK, *etc.*?

Log *ft* systematics (see Jπ guidelines and review by 1998Si17):

- may enable Jπ assignments

  (if log*ft* ~3.5, < 5.9, <12.8 or log$f^{1U}t$<8.5, *etc.)*

- may allow useful limits to be set on branch to g.s., *e.g.*,
  - TI < … if log*ft* > 5.9 (for a 1st-forbidden branch), or
  - TI < … if log$f^{1u}t$ > 8.5 for a 1st-forbidden unique branch

I(β+):

- theoretical capture to positron ratio enables decay scheme normalization when I(annihilation) has been measured

EAV, CK, CL…:

- information needed by RADLST

(comparison of I(x-ray) from RADLIST with measured I(x-ray) can provide a useful check on the decay scheme)

C. Baglin, Trieste2008

ENSDF Analysis and Utility Codes

Their Descriptions and Uses

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Summary

The ENSDF analysis and checking codes are briefly described, along with their uses with various types of ENSDF datasets. For more information on the programs, see "Read Me" entries and other documentation associated with each code: (http://www.nndc.bnl.gov/nndcscr/ensdf_pgm/).
The current status and platform availability may be obtained at: http://www.nndc.bnl.gov/nndcscr/ensdf_pgm/code_status.html.

Table of Contents

How to Use the Programs

FMTCHK

FMTCHK should be run every time the ENSDF formatted file has been manually changed before executing any of the other programs. All fatal errors (indicated by "<F>") should be corrected. If possible, all errors (indicated by "<E>") should be corrected. Warning messages (indicated by "<W>") should be checked to see if there are problems that may need correction. For small input files, use of the default options is recommended. For larger files, the user may wish to make several iterations, starting with fatal errors only. This program should also be run on the final version before submittal to the NNDC.

Notes:

1. It is sometimes difficult to judge whether a message should be flagged as an error or warning. If you disagree with an error message, please indicate this along with your reasons on submittal or before. In some instances, error messages are given because of the possible effects on other programs. Two examples are:
   a. It is considered an error when a mixing ratio is given and there is no associated mixed multipolarity. This is a problem since programs such as RULER or BrIcc/HSICC will be unable to perform the proper calculations. Note that the converse (*i.e.*, a mixed multipolarity given with no mixing ratios) may be addressed by assuming a 50%-50% admixture of the two multipolarities.
   b. It is considered an error when an "FL=" is not given and there are no final levels with a certain limit or there are more than one level which may be considered the final level based on E_{level}-E_{γ}. This is a problem, particularly for complex level schemes such as in the adopted dataset, for level scheme programs such as ENSDAT or Isotope Explorer and programs such as GTOL, which do a least squares adjustment of the level energies, or programs such as PANDORA.

ENSDAT and TREND

ENSDAT produces level schemes, bands and tables in a format similar to that of the *Nuclear Data Sheets* and may be used to inspect the results visually. TREND provides a simpler ASCII presentation of the tabular data that does not require a PostScript printer or viewer. One should also be able to copy the list of keynumbers generated by ENSDAT into the clipboard and paste into the keynumber form of the NNDC Web NSR to obtain the NSR entries corresponding to these keynumbers.

As well as ENSDAT, FMTCHK and TREND, other programs applicable to these datasets are ADDGAM, GTOL, BrIcc/HSICC, PANDORA and RULER. ADDGAM and PANDORA are useful in constructing the dataset. In addition, PANDOR may be used iteratively to aid in physics decisions, checking assignments, and updating source datasets based on changes in the adopted data. GTOL is useful only in obtaining the least-squares adjustment of the level energies; for complex datasets, the matrix to be inverted may be singular (see Additional notes under GTOL for methods of handling this problem). RULER may be used in the comparison mode to provide additional information in obtaining γ-multipolarity assignments. BrIcc/HSICC and RULER should also be run to provide the internal conversion coefficients, and BEλWs and BMλWs, respectively; note that BrIcc/HSICC should be executed before RULER. BrIcc/HSICC should also be run to provide the internal conversion coefficients. There is no need to delete the "S G" records generated by BrIcc/HSICC; the publication program suppresses these records automatically when the evaluation is prepared for submission to Academic Press. Figure 1 shows the approximate order in which the programs are run. This is an iterative process and, as changes are made, various programs will need to be rerun (in particular, FMTCHK).

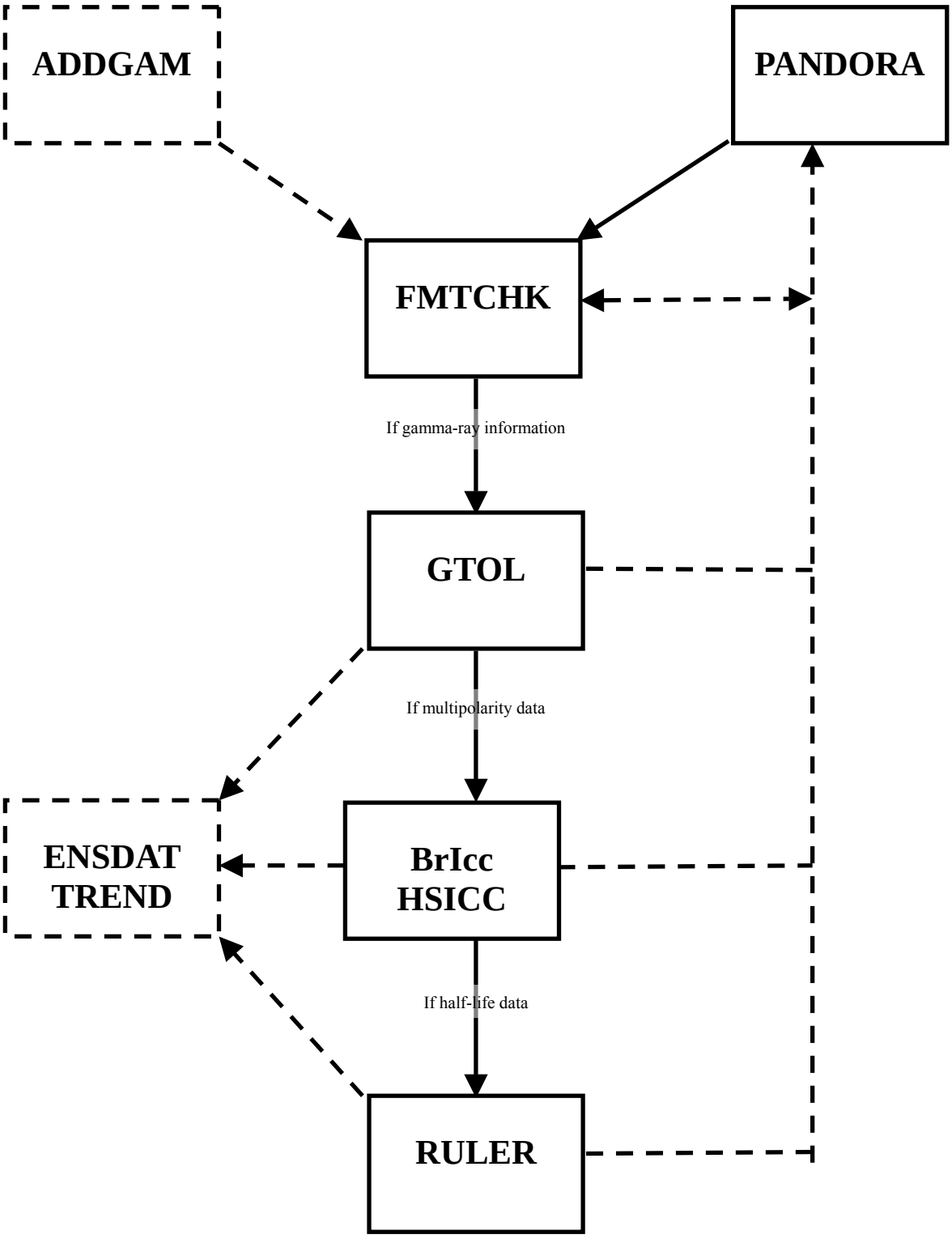

Figure 1: Flowchart of programs for Adopted Levels, Gammas datasets

Decay Datasets

Along with ENSDAT, FMTCHK and TREND, other programs applicable to these datasets are ALPHAD (for α decay), GABS, GTOL, BrIcc/HSICC, LOGFT (for $\beta^{\pm}/\varepsilon$ decay), RadList and RULER. Figure 2 shows the approximate order in which the programs are run - this is an iterative process and, as changes are made, various programs will need to be rerun (in particular, FMTCHK).

1. ALPHAD should be used to obtain the hindrance factors and, for even-even ground-state nuclei, r_0. For other nuclei, r_0 must be supplied.
2. GABS may be used to combine the data from up to three sources to obtain I_γ-normalization (NR), the branching ratios (BR), and absolute I_γ's. BrIcc/HSICC should be run on the input data, or the internal conversion coefficients from the adopted dataset should be used.
3. GTOL may be used to provide a least-squares adjustment of the level energies to check the uncertainties and placement of the γs. If there are a large number of γs and few whose energies deviate from the calculated energies, the experimental uncertainties may be overestimated; on the other hand, if there are a large number of deviations, the uncertainties may be underestimated. Also, for any deviation of over ≈3σ, the placement of the transition should be carefully checked. GTOL should also be used to obtain the intensities of particles feeding the levels, and this should be undertaken before ALPHAD and LOGFT are employed, and may also be useful in deriving the I_γ-normalization (NR).
4. BrIcc/HSICC may be used to check experimentally measured internal conversion coefficients against theory. If the adopted internal conversion coefficients are not used, BrIcc/HSICC should be executed to produce this information for the data set. This should be carried out before GABS, GTOL, or RadList are used.
5. LOGFT is required to obtain log *ft*s, $I_{\beta+}$ and I_ε, and partial electron-capture fractions before using RadList. If one is not using measured intensities, GTOL should be used to obtain $I_{\beta-}$ and $I_{\varepsilon+\beta+}$.
6. RadList should be used to check the calculated energy deposited with that predicted by the Q-value and branching ratios. If X-ray intensities or integral measurements (*e.g.*, 4πβ) were performed, these should be compared to those calculated by the program. If discrepancies cannot be resolved, they should be noted in the dataset. ALPHAD, BrIcc/HSICC and LOGFT should have been used before doing these checks.
7. If $T_{½}$s have been measured, RULER may be used to check or further limit multipolarities based on other methods (*e.g.*, from experimental conversion coefficients).

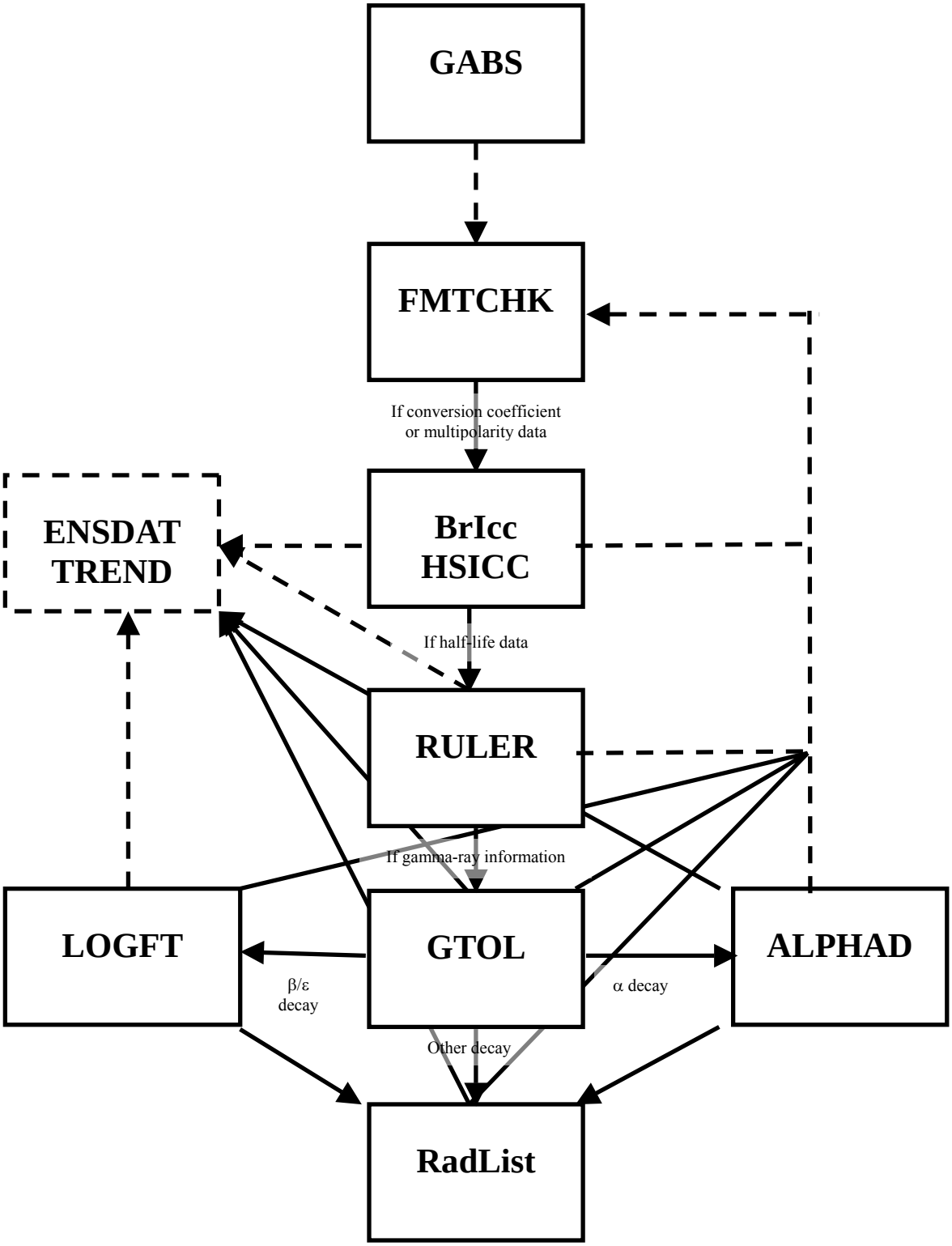

Figure 2: Flowchart of programs for decay datasets

Reaction Datasets

In addition to ENSDAT, FMTCHK and TREND, other programs applicable to these datasets are GTOL, BrIcc/HSICC, and RULER. RadList may also prove of use for (thermal n,γ) datasets,. Figure 3 shows the approximate order in which the programs are run. This is an iterative process and, as changes are made, various programs will need to be rerun (in particular, FMTCHK).

1. The primary use of GTOL is to undertake a least-squares adjustment of the level energies and to check the uncertainties and placement of the γs as described above. Authors do omit Δγs; if the evaluator cannot obtain a good estimate of these uncertainties, the author's level energy values may be a better source of these data. Checks of intensity imbalance problems may also be useful if relative intensities are given, for which the total conversion coefficients may need to be provided.
2. BrIcc/HSICC may be used to check experimentally measured internal conversion coefficients against theory. While not necessary to include the conversion and partial conversion coefficients for reaction datasets, they are very useful for (thermal n,γ) datasets.
3. If half-lives ($T_{½}$) have been measured, RULER may be used to check or further limit multipolarities based on other methods (*e.g.*, from experimental conversion coefficients).
4. RadList may be used to check the energy balance of (thermal n,γ) datasets by tricking the program into believing the dataset is for IT decay. This is done by changing the DSID on the ID record, adding an appropriate Parent record (level energy equal to the neutron separation energy), and a BR of 1.0 on the Normalization record.

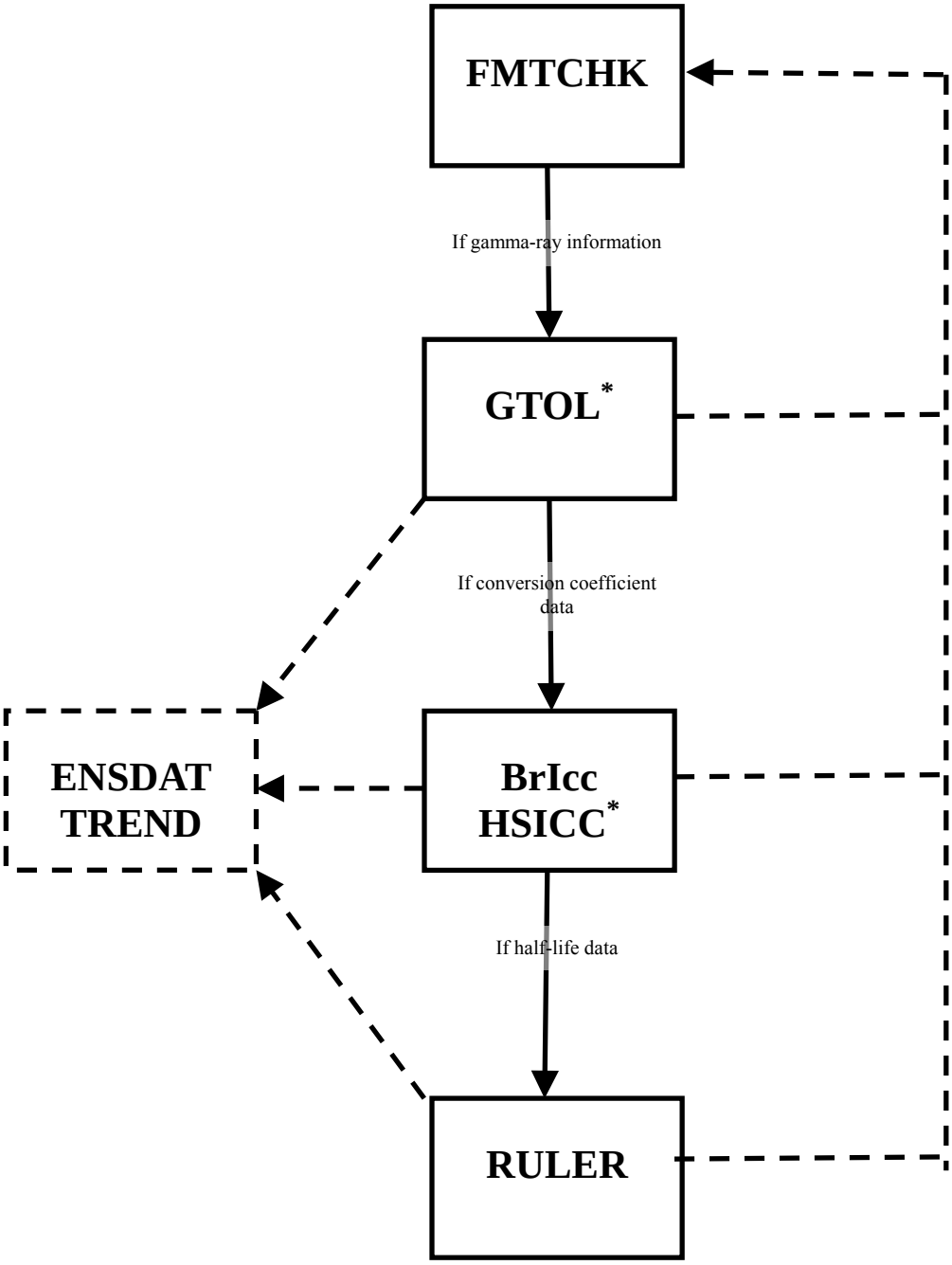

Figure 3: Flowchart of programs for reaction datasets
*if relative intensities are to be checked, the order of these steps should be reversed

Internal Conversion Coefficient Programs

The International Network of Nuclear Structure and Decay Data Evaluarors adopted BrIcc 2.0, which uses the "frozen-orbital" approximation, in May 2005 as a replacement for the HSICC program for ENSDF evaluations. A brief comparison of BrIcc 2.0, an earlier no-hole version of BrIcc, and HSICC is given in Table 1.

	BrIcc 2.0	**BrIcc 1.3**	**HSICC**
Source	2005KIZT	2002Ba85, 2005KIZW	1968Ha52, 1971Dr11
Shells	K – P1 and internal electron-positron pair formation	K – R2 and internal electron-positron pair formation	K – M5 & N+O+…
Multipolarity	*E0*[1], E1 – E5 and M1 – M5		E1 – E4 and M1 – M4
Energy Range (keV)	ε_I+1 to 6000		ε_I+1 to 1500
ΔE_γ	Included in $\Delta\alpha$		Attempts to warn
Elements	Z = 10 – 95	Z = 10 – 126	Z = 30 – 103
Theory	Frozen orbitals	No hole	Hole included
Estimated Uncertainty	1.4%	2%	3%

Table 1 Comparison of Internal Conversion Coefficient Programs

As can be seen in Table 1, version 2.0 of BrIcc has a maximum of Z = 95. For elements above this value either BrIcc 1.3 or HSICC should be used. The no-hole approximation may underestimate conversion coefficients, and therefore if Z≤103, a better option may be to use HSICC. If an internal conversion coefficient code other than the current adopted version of BrIcc is used, this choice should be noted in the ENSDF evaluations.

[1] Requires new ENSDF formats before full implementation.

ADDGAM

Version 1.4 [7 Feburary 2001]

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This program adds γs to the Adopted Levels when all γs come from one data set. If γs come from more than one data set but are non-overlapping, the program may be run successively with different γ data sets as input.

Input files (ENSDF format):

1) Data set containing the adopted levels. Sample input file: ADDGAML.DAT
2) Data set containing the gammas to be added. Sample input file: ADDGAMG.DAT

Output file: Merged set containing the information in (1) and the γs from (2). Sample output file: ADDGAM.NEW

Terminal dialogue: The user will be asked to provide the file names for the data set containing the adopted levels, the file for the gammas to be added, and the file for the new data set.

Compilation and loading instructions: This program requires subroutines from the `NSDFLIB` package.

Additional documentation: None.

ALPHAD

Version 2.0a [6 November 2006]

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Original Authors: H.V. Michels, Y. Sanborn, R.C. Ward.

This program calculates the α hindrance factors and theoretical $T_{½}$ and, for even-even ground state to ground state transitions, r_0 using Preston's spin-independent equations (M.A. Preston. Phys. Rev. 71, 865 (1947)).

The program reads an ENSDF-formatted file and produces a report of the hindrance factors, theoretical $T_{½}$s, and r_0s calculated by the program. This report will also summarize any problems encountered or assumptions made. There is an option to produce a new file containing the HFs calculated. The r_0 values may be specified on an ALPHA comment record by "HF" in columns 10 and 11 and a dollar sign ("$") in column 12 or blanks in columns 12 through 19. The first value and uncertainty in columns 20 through 80 preceded by an R ("R") and an equal sign ("=") or approximate sign ("AP") will be taken as r_0.

Sample input file: ALPHAD.DAT

Sample output files:
1. ALPHAD.RPT - Report of calculations.
2. ALPHAD.NEW - New ENSDF file containing the hindrance factors (HFs) calculated by the program.

Terminal dialogue:
1. **Input data file (Default: ALPHAD.DAT):**
2. **Output report to file (Y/N):**
   The default is "Y". If NO is answered, the report will be displayed on the terminal. If YES is answered, the following query will appear:
   Output report file (Default: ALPHAD.RPT):
3. **Echo input (Y/N):**
   The default is "Y". The input file in this case will be copied to the report file.
4. **Rewrite input with hinderance factor (Y/N):**
   The default is "Y". If YES is answered, the following query will appear:
   Output data set file (Default: ALPHAD.NEW):

If the report output is to a file, the terminal output will note the progress in the calculations and report warning messages.

Compilation and loading instructions: This program requires subroutines from the `NSDFLIB` package.

Additional notes:

1. Calculation of Δr_0: Five values are calculated: $r_0(T_{½}(\alpha),E_\alpha)$, $r_0(T_{½}(\alpha)+\Delta T_{½}(\alpha),E_\alpha)$, $r_0(T_{½}(\alpha)-\Delta T_{½}(\alpha),E_\alpha)$, $r_0(T_{½}(\alpha),E_\alpha+\Delta E_\alpha)$, and $r_0(T_{½}(\alpha),E_\alpha-\Delta E_\alpha)$.
   $\Delta r_0 = \sqrt{(((|r_0(T_{½}(\alpha)+\Delta T_{½}(\alpha),E_\alpha)-r_0(T_{½}(\alpha)-\Delta T_{½}(\alpha),E_\alpha)|)/2)^{**}2 + ((|(r_0(T_{½}(\alpha),E_\alpha+\Delta E_\alpha)-r_0(T_{½}(\alpha),E_\alpha-\Delta E_\alpha)|)/2)^{**}2)}$. r_0 and Δr_0 as calculated are output in the report file and so are $r_0(T_{½}(\alpha)+\Delta T_{½}(\alpha),E)$, $r_0(T_{½}(\alpha)-\Delta T_{½}(\alpha),E)$, $r_0(T_{½}(\alpha),E+\Delta E)$ and $r_0(T_{½}(\alpha),E-\Delta E)$.
2. If either the value or the uncertainty for E_{parent}, Q_α, or E_{level} is non-numeric and E_α and ΔE_α are numeric, E_α and ΔE_α are used in the calculations. NOTE: For systematic uncertainties in Q_α from the Audi-Wapstra Mass Tables, the input data should be modified to use the estimated uncertainty and the new output edited to change DQP back to "SY".
3. If there is more than one non-numeric uncertainty involved, the order of precedence is limits (*e.g.*, GT or LT), and then "AP", "CA", and "SY" for the new output.

Additional documentation: None.

Acknowledgements: I thank Y. Akovali and M.J. Martin for many useful discussions on the physics involved, for their many suggestions on improving the output, and for testing various versions of this code.

BrIcc Program Package
(Band-Raman Internal Conversion Coefficients)

Version 2.2 [2 April 2008]

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`BrIcc` can be used in different ways: as an interactive tool to interpolate conversion coefficients and E0 electronic form factors, and as an ENSDF evaluation tool. As an evaluation tool, the program will prepare new ENSDF records (GAMMA and GAMMA continuation) and may also be used to merge the new records into existing ENSDF data sets.

Sample input and output files: None available at present.

Terminal dialogue: See BrIcc Manual (BrIccManual.pdf)

Additional documentation: BrIccManual.pdf

COMTRANS (COMment TRANSlation)

Version 7.1 [24 November 2003]

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The COMTRANS program is a nuclear structure evaluator tool for translating comments in the Evaluated Nuclear Structures Data File (ENSDF) from the all upper case form to the upper/lower case form. In addition, translations of code words found in the NSD dictionary are made into a rich text type of format (*e.g.*, |a replaces ALPHA and {+56}Fe replaces 56FE). These comments no longer need to be used with the NSD dictionary. However, evaluators should note that adding a code word to such a translated comment means they must change the lower case comment flag (c or t) in column 7 to an upper case comment flag (C or T) or rerun the file using COMTRANS. Otherwise, ENSDAT and the publication code (which do not translate lower case comment (c or t) cards) will output the code word unchanged. Finally, the input file is converted into a Y2K compliant form if not already in that form. All keynumbers are changed from the old six-character Keynumber (85AU01) into the new eight-character keynumber (1985AU01). The keynumber fields of the ID and Q cards are also changed to comply with the Y2K formats.

The program asks for an input file name, an output file name and options. The ENSDF translation dictionary file must be in the same directory from which the program is executed. The input and output files may include a disk and directory path.

Program files:
1. comtrans_sl.exe
2. ensdf_dic.exe - dictionary creation program.

Text files:
1. ensdf_dic.dat - sequential text file of the dictionaries used to create ra_ensdf_dic.dat.

Input files:
1. An ENSDF formatted file. Sample input file: comtrans.tst
2. ra_ensdf_dic.dat (direct access binary file) contains the ENSDF translation dictionaries used by ENSDAT and COMTRANS; must be in the execution directory.

Sample output file: comtrans.out (Y2K compliant)

Terminal dialogue: The program will request the following information:
1. Input
2. Output

Compilation and loading instructions: Only the executable is supplied.

Additional notes:

1. Should **not** be run on ENSDF or XUNDL files submitted to the NNDC.
   ^A4 → A4 → A{-4} → a{-4}
   A4 A_4 a_4
2. Useful to run before using Isotope Explorer 2 or ENSDAT.
   a. Isotope Explorer 2 assumes that the comments have been translated into a "rich text" format and does not carry out a dictionary lookup.
   b. ENSDAT may be faster since a dictionary lookup does not have to be performed for the comments.

DELTA

Version 1.01 [15 April 1993]

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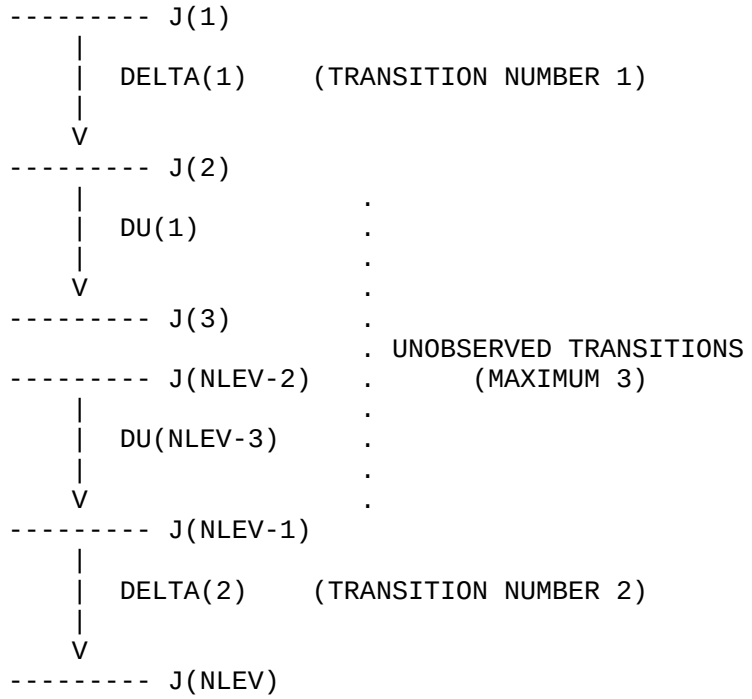
This program analyses angular correlation and conversion coefficient data, and calculates the best mixing ratios. The sign convention is that of Krane and Steffen, Phys. Rev. C2, 724 (1970).

The gamma-gamma cascade studied is:



DELTA(1) and DELTA(2) can be varied. The mixing ratios of the unobserved transitions are fixed. Possible data items are:

1. A_2 and A_4 for $\gamma\gamma$-correlation (corrected for solid angle effects).
2. δ values from other independent measurements ($\tan^{-1}(\delta)$ is used internally).
3. Conversion coefficient or conversion ratio data.

All data items are treated as independent, and uncertainties as statistical. A measured A_2 gives very little information if both mixing ratios are unknown, a measured internal conversion coefficient helps a lot! δ values may be suspect when the minimum is not approximately parabolic. The default step size in $\tan^{-1}(\delta)$ is 2 degrees - this is normally small enough, but for very accurate data a smaller step size (set with option ST) may be necessary.

Limitations:

1. No triple correlations.

2. Spins up to 20 are allowed, except when unobserved transitions are involved. The maximum spin is 10 for unobserved transitions. These limitations are valid if the computer can handle double precision reals of up to 10^{76}.

3. Effects of internal conversion on the deorientation coefficients for mixed transitions are neglected. See Anicin *et al.,* Nucl. Instrum. Meth.103, 395 (1972) for this usually very small effect.

Except for the changes made in input and output units and to conform to ANSI-77 standard, this code is as provided by the author.

Input file: All records have the following format:

COL. 1-2 Symbol that determines type of card.

COL. 3-72 Free format reals or integers. Separator: any character different from '0-9', '.' and '-'. Everything following a '$' is ignored, and therefore can be used for comments on the data cards. Only DATA and GO cards are necessary. Uncert. = 0 for δ means that δ is kept fixed; new data with same name as existing data replace the latter.

Options (parameters in () are optional):

CL	Clear data
DU	Dump common blocks (for debugging)
OU A	A = 0 short output (default) A > 0 FULL OUTPUT
ST ST1(,ST2)	Step size (in degrees) for $\tan^{-1}(\delta_1)$ and $\tan^{-1}(\delta_2)$, respectively
EN	End of run
GO RJ1,RJ2(,RJ3)	Read spins and go. RJs are reals or integers. (*e.g.*, 5/2- = -2.5, 2+ = 2, 0- = -0) Maximum 6 spins.
HE ANY TEXT	Header
LI A,B,C,D	Limits $\tan^{-1}(\delta_1)$ to A to B and $\tan^{-1}(\delta_2)$ to c to d
UN (DU(1), DU(2), DU(3))	Unobserved transitions, δs. Defaults = 0.0
Correlation and DELTA data	
A2 A2,DA2	A_2, ΔA_2
A4 A4,DA4	A_4, ΔA_4
D NTR (,DELTA,DDELTA)	Transition number, δ, Δδ. Defaults: none, 0, 0

Conversion coefficient data (maximum 5 items)	
** NTR, EXP, DEXP, L1, H1(,L2,H2)	where ** is any unique combination of symbols (e.g., CC, AK) NTR The number of the transition (1 or 2) EXP Experimental value DEXP Uncertainty L1 Theoretical value for the lower multipole (SHELL1) H1 Theoretical value for the higher multipole (SHELL1) For ratios SHELL1/SHELL2: L2 Theoretical value for the lower multipole (SHELL1) H2 Theoretical value for the higher multipole (SHELL2)

Sample input data set: DELTA.DAT

Output file (short output marked with an asterisk (*)):

For each spin combination (each GO card):
* Option and data cards read
* Header
* Data
Header
χ^2 and best theoretical values of data (step in δ_1)
* Best δ_1
Header
* Plot of χ^2 *versus* $\tan^{-1}(\delta_1)$
Header
χ^2 and best theoretical values of data (step in δ_2)
* Best δ_2
* Plot of χ^2 *versus* $\tan^{-1}(\delta_2)$
* 'END OF ANALYSIS FOR THIS SPIN COMBINATION'

Optionally a dump of common block variables can be obtained.

Sample output: DELTA.RPT

Terminal dialogue: The user will be requested to supply the input file name and the output file name.

Compilation and loading instructions: No special instructions.

Additional documentation: DELTA - a computer program to analyze gamma-gamma correlations from unaligned states. L.P. Ekstrom. Nuclear Physics LUNFD6/(NFFR-3048) 1-27, Lund University, 1983.

ENSDAT (Evaluated Nuclear Structure Drawings and Tables)

Version 12.23 [25 July 2007]

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The ENSDAT program (Evaluated Nuclear Structure Drawings And Tables) is similar to the production program for the Nuclear Data Sheets, but more limited in application. Only ENSDF data files can be used as input and a PostScript file, list of keynumbers in NSR, and a report file are output. As the default, all possible tables, band drawings, and gamma drawings are produced for each dataset encountered in the input file. However, one or more of these groups of output can be selected (see below). In addition, the default tables and drawings can be modified by adding commands to the input file using control cards (see the file enscomds.txt). A final page is output to the PostScript file, which gives a listing of all the keynumbers, encountered in the input file.

Program files:
1. ensdat.exe
2. ensdf_dic.exe - dictionary creation program.

Text files:
1. enscomds.txt - instructions for using commands in the input file.
2. ensdf_dic.dat -sequential text file of the dictionaries used to create ra_ensdf_dic.dat.

Input files:
1. An ENSDF formatted file. Sample input file: adopted.186.
2. ra_ensdf_dic.dat - contains the translation dictionaries. ensdf_dic.exe must be run to create the ISAM files used by ENSDAT and COMTRANS.

Outputs:
1. PostScript file of tables and drawings in a form similar to Nuclear Data Sheets.
2. Report file summarizing work done and any errors noted.
3. File listing the keynumbers (NSR) found in the input file.

Sample output files: ad_186.log and ad_186.ps.

Terminal dialogue: The program will request the following information:
1. Input - input file specification.
2. Output - output file name.
3. Options - one or more of the following options can be entered, separated by a blank:

TABLE Level, gamma, and radiation information will be output in tabular format.
BAND Band drawings will be output. Radplot type drawings are also output.
DRAW Gamma drawings will be output.
NOAUTO No drawings or tables will be generated except those that are specified by

the user on control cards, added to the input file.

If none of these options are used, all tables, band drawings (if any), and gamma drawings (if any) will be output to the PostScript file.

4. View output - Yes or No (optional - see installation instructions for details)

Command Line dialogue: ENSDAT *input output [option]*
Compilation and loading instructions: Only the executable is supplied.

Additional documentation: Following the output file name, several options are available to the user. The output file name must be followed by a blank and then, if desired, one or more of the following options:

TABLE	Level, gamma, and radiation information will be output in tabular format.
BAND	Band drawings will be output.
DRAW	Gamma drawings will be output.
NOAUTO	No drawings or tables will be generated except those specified by the user on control cards added to the input file.

As before, if none of these options are used, all tables, band drawings (if any), and gamma drawings (if any) will be output to the PostScript file.

FMTCHK (Format and Syntax Checking)

Version 10.3a [28 September 2007]

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Original author: Bruce J. Barton.

This program analyzes the format of an ENSDF formatted file to verify conformation to "Evaluated Nuclear Structure Data File. A Manual for Preparation of Data Sets" by J.K. Tuli, Brookhaven National Laboratory Report BNL-NCS-63155-01/02 (2001) and subsequent memos.

Input file (ENSDF format): Sample input file is DATA.TST

Output file: A report file indicating possible errors or warnings is generated. Sample output file: FMTCHK.RPT. Brief explanations of the fatal error (prefix <F>), error (prefix <E>), warning (prefix <W>), and informational (prefix <I>) messages are given in `README-FMTCHK.TXT` or `README-FMTCHK.HTML`

Terminal dialogue: The user will be asked to supply the input and output file names, if errors only should be reported or the complete file reported (default: errors only), if continuation records should be checked (default: check continuation records), if only fatal errors should be reported (default: no), if warning messages should be suppressed (default: no suppression - this query will be suppressed if only fatal errors are to be reported), and if the checking of the XREF *versus* DSID should be suppressed.

As the data sets in the input file are processed, this activity will be indicated on the terminal. After each data set is processed, the total number of fatal error, error and warning messages will be reported. If both adopted data sets and "source" data sets are in the file, the X records and IDENTICATION records will be compared and any discrepancies listed.

Compilation and loading instructions: This program requires subroutines from the `NSDFLIB` package.

Additional documentation: None.

Additional notes:

1. For level energies of the form X, Y, Z, *etc.* or E + X, E + Y, E + Z, *etc.*, an arbitrary energy is assigned to the first occurrence of the character based on the energy of the previous level energy. This assignment is reported as an informational message in the report file, and is used to see if the levels are in the proper energy order.

GABS

Version 9.2 [7 Febuary 2001]

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GABS calculates absolute gamma-ray intensities and a decay-scheme normalizing factor (NR) for converting relative intensities to absolute values per 100 decays of the parent nucleus. The program calculates the decay mode branching ratios (BR) for radionuclides that decay through several decay modes, and determines the uncertainties in all these quantities.

Input file: GABSPC reads up to three data sets (ENSDF format). See the documentation for modifications to the standard ENSDF format for use by this program. Sample input: GABS.IN

Output files:
1. Report file summarizing the results of the calculations (default: GABSPC.RPT).
2. New ENSDF formatted file containing the results of the calculations (may not already exist). Sample output: GABS.OUT

Terminal dialogue: The program will ask for an input file name, a report file name, if a new file should be created ("Y"; default is no; case insensitive), and, optionally, the name of the output file.

Compilation and loading instructions: This program requires subroutines from the `NSDFLIB` package.

Additional documentation: PROGRAM GABSPC (Version 9, May 2000). Edgardo Browne, Lawrence Berkeley National Laboratory. Adapted for IBM PC by Coral M. Baglin (September 1991).

GTOL (Gamma to Level)

Version 7.2e [1 June 2007]

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Original authors: W.B. Ewbank, Nuclear Data Project, Oak Ridge National Laboratory; B.J. Barton, National Nuclear Data Center, Brookhaven National Laboratory; and L.P. Ekstrom and P. Andersson, Department of Nuclear Physics, Lund University.

Gamma-ray energies are used to derive a set of least-squares adjusted level energies. The net feeding at each level is calculated from the input γ intensities and conversion coefficients. Unplaced or questionable γs, or γs with an ambiguous or unknown final level are ignored.

The program parses the DSID of each data set and skips them, if there is no indication of possible gamma records within the data set. In addition, the program will not calculate the intensity balancing for adopted data sets.

Input file: An ENSDF formatted file with the following optional information:

An option record with 'OPTION' in col. 1-6 may precede any data set and contain any of the following options in free format:

Option	Meaning
NOREC	No recoil correction, *i.e.*, recoil correction has already been applied to E_γ
RECOIL	Perform recoil correction (DEFAULT)
MARKED	Process only data sets preceded by a card with '*GTOL' in col. 1-5
ALL	Process all data sets (DEFAULT)
DEG=	For the current data set, override default assumption of 1 keV where no uncertainty on the gamma energy is given. Following the equal sign may be either a number or a number followed by a percent sign. A number alone indicates the uncertainty on E_γ in keV, while a number followed by a percent sign indicates the fractional percent uncertainty to be assigned.
DRI=	For the current data set, assume a default uncertainty for the relative I_γ when none given. A number alone indicates the uncertainty on I_γ in the current relative units, while a number followed by a percent sign indicates the fractional percent uncertainty to be assigned.

DTI=	For the current data set, assume a default uncertainty when none given. A number alone indicates the uncertainty on $I_{\gamma+ce}$ in the current relative units, while a number followed by a percent sign indicates the fractional percent uncertainty to be assigned.

An option card resets the defaults.

A level energy can be held fixed by adding the letters 'F' or 'G' somewhere in the energy field (columns 10 - 21). If 'G', is used, the uncertainty of the fixed level energy will be added in quadrature with that derived from the least-squares adjustment. If the output option to create a new file containing the adjusted level energies is chosen, 'F' or 'G' will be removed and a level documentation record will be added (LEVEL ENERGY HELD FIXED IN LEAST-SQUARES ADJUSTMENT).

If DRI= or DTI= are specified on an OPTION record, the assumed uncertainty may be overridden for an individual intensity, by adding an "E" separated from the intensity in either the RI or TI fields.

If DEG=, DRI=, or DTI= are specified on an OPTION record and a new file is created, FOOTNOTE COMMENTS will be generated and inserted as necessary.

Sample input file: gtol.inp

Output files:

1. Report file. The report file will contain a summary of the data input and actions taken by the program (*e.g.*, unplaced or questionable γs ignored), and the following optional outputs for each data set:
   a. Comparison of input gamma energies to those calculated on the basis of the adjusted level energies.
   b. Comparison of calculated net feedings to each level with values input on B, E, or A records.
      If the calculated net feeding overlaps zero within three standard deviations, the program will calculate estimated upper limits (90% confidence level) using two methods suggested by Louis Lyons in Statistics for Nuclear and Particle Physicists (Cambridge University Press), and report these estimates if they differ by more than 0.01. The two methods are:
      i. (Integral of gdB from 0 to Bl)/(Integral of gdB from 0 to infinity) = 0.9 where g is the normal (Gaussian) distribution.
      ii. $Bl < Bm + 1.28\sigma$.
   c. If a new file is generated, a comparison of the old and new records will also be generated.

   Sample output file: gtol.rpt
2. New file containing the adjusted level energies (optional). Sample output file: `gtol.out`

Terminal dialogue: The program will request the input and report file names and ask if you wish a new file to be created (default: no new file) and for the new file name - suppresses the gamma-energy comparison (default: no suppression), and intensity comparison (default: no suppression). There will also be a query as to what value to

adopt for the theoretical uncertainty on $\Delta\alpha$(tot). The progress of the program will be noted on the terminal as well as possible problems.

Compilation and loading instructions: This program requires subroutines from the `NSDFLIB` package.

Additional documentation:

B.J. Barton and J.K. Tuli. Physics analysis programs for nuclear structure evaluation. Brookhaven National Laboratory Informal Report BNL-NCS-23375/R (1977).

L.P. Ekstrom and P. Andersson. FORTRAN 77 versions of string handling subprograms and the programs GTOL and MEDLIST. Nuclear Physics Report LUNFD/(NFFR-3049)/1-27, Lund University, Sweden, 1983.

Additional notes:

1. If the level energies are of the form X, Y, Z, *etc.* or E + X, E + Y, *etc.*, the least-squares fit is carried out separately for each group of states and merged back into the final results. Similar to FMTCHK, an arbitrary energy is assigned to the level based on the energy of the previous energy, and is used to sort the levels in the energy comparison but is not used when creating the new output file.
2. FMTCHK should be rerun if a new file is created since the order of the level energies may have changed as a result of the least-squares adjustment. This may occur when there are two closely lying levels or if there is a series of levels with unknown energies (*e.g.*, E + X) interspersed with levels of known energy.
3. If the connecting information is too sparse, the matrix created may be singular and cannot be inverted (generally occurs for adopted datasets and other datasets where there are levels with no de-exciting γs). In such instances, check the report file for levels that do not de-excite and fix these levels.
4. As noted above, uncertainly-placed γs are ignored in the least-squares fit and intensity balance calculations. This means possible additional iterations to obtain an estimate of the excitation energies and their possible contributions to the uncertainties of the intensity balances:
   a. To obtain an estimate of the excitation energies of levels only connected by such transitions, modify the input by removing the "?" in column 80 of the relevant gamma records and adding "F" in the energy fields of any connected level records which are also fed or de-excited by other γs. Factor the results of the new least-squares fit into the original file.
   b. To obtain an idea of the effect of uncertainly-placed γs on the intensities, modify the input file by removing all "?" in column 80 of the gamma records. By comparing the original intensity balance calculations with the new date, you will be able to estimate the effect of these transitions on the balance uncertainties.

HSICC (Hager-Seltzer Internal Conversion Coefficients) Program Package

The HSICC program package consists of the following programs: HSICC (calculates internal conversion coefficients), HSMRG (merges new gamma records created by HSICC with the original input data), BLDSHST (builds a direct access file of the internal conversion coefficient table), and SEQHST (recreates a sequential file of the internal conversion table from the direct access file). These are described separately on the following pages.

BrIcc has replaced HSICC as the recommended program to use for ENSDF evaluations.

Compilation and loading instructions: HSICC requires subroutines from the `NSDFLIB` package; the others do not.

HSICC Program Package — HSICC

Version 11.13f [9 October 2001]

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This program calculates internal conversion coefficients by spline (cubic) interpolation of tabulated values from Hager and Seltzer for the K, L, and M shells and from Dragoun, Plajner and Schmetzler for the N + O+... shells.

Input files:
1. ENSDF formatted file. Sample input file: DATA.TST. The input data should not be modified before running the HSMRG code.
2. ICC index file (created by the BLDHST program).
3. Binary file of ICCs (created by the BLDHST program).

Output files:
1. Complete report of calculations. Sample output file: HSCALC.LST.
2. New G/2G records generated by the program are used as input to the HSMRG program Sample output file: CARDS.NEW.
3. Comparison of new and old G/2G records. Sample output file: COMPAR.LST.

Terminal dialogue: The program will ask for the following information:
1. Input files
   a. Name of input ENSDF file (default: DATA.TST)
   b. Name of ICC index file (default: ICCNDX.DAT)
   c. Name of ICC binary table file (default: ICCTBL.DAT)
2. Output files
   a. Name of file from complete report (default: HSCALC.LST)
   b. Name of file containing new G/2G records (default: CARDS.NEW)
   c. Name of comparison file (default: COMPAR.LST)

Additional documentation:

R.S. Hager and E.C. Seltzer. Internal Conversion Tables. Part 1: K-, L-, M-Shell Conversion Coefficients for Z = 30 to Z = 103. Nucl. Data A4, 1 (1968).

O. Dragoun, Z. Plajner and F. Schmutzler. Contribution of Outer Atomic Shells to Total Internal Conversion Coefficients. Nucl. Data Tables A9, 119 (1971).

B.J. Barton and J.K. Tuli. Physics analysis programs for nuclear structure evaluation. Brookhaven National Laboratory Informal Report BNL-NCS-23375/R (1977).

Additional notes: If E_γ is near the threshold for internal conversion, new records are not created.

HSICC Program Package — HSMRG

Version 7.1a [17 September 2001]

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Original author: Bruce J. Barton.

This program merges the new (corrected) G-records created by HSICC with the input dataset file to create an updated dataset file.

Input files:
1. Input data file (ENSDF format) - must be the same input file used by HSICC. Sample input file: DATA.TST
2. Correction file of G-records created by HSICC. Sample input file: CARDS.NEW

Output file: Updated file (ENSDF format). Sample output file: CARDS.MRG

Terminal dialogue: The program will ask for the names of the input file used by HSICC (default: DATA.TST), the correction file created by HSICC (default: CARDS.NEW), and the merged data file (default: CARDS.MRG).

Additional documentation: none.

HSICC Program Package — BLDHST

Version 3.6 [9 Feburary 2001]

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Original author: Bruce J. Barton.

This program builds the Hager-Seltzer direct access table plus index from a sequential file.

Input file: A sequential access symbolic file of 80 character records (Z, SHELL, EG, E1, E2, E3, E4, M1, M2, M3, M4) = (I3, A2, F7.2, 8E8.2). Data file includes ICCSEQ.DAT. Four additional files (H1.DAT through H4.DAT) are included for MS-DOS, covering Z = 3 - 34, Z = 35 - 59, Z = 60 - 82, and Z = 83 - 103, respectively.

Output files:

1. Direct access table consisting of a binary file of 11 word (44 bytes) records. 13004 records in the file if ICCSEQ.DAT is used as input.
2. An index consisting of a direct access binary file of one-word (4 bytes) records. The Z^{th} record is the integer record number pointer to the direct access table.

Terminal dialogue: The program will first ask for the sequential input file name (default: ICCSEQ.DAT) and then the output table and index file names (defaults: ICCTBL.DAT and ICCNDX.DAT).

Additional documentation: none.

HSICC Program Package — SEQHST

Version 3.4 [9 Febuary 2001]

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Original author: Bruce J. Barton.

This program converts the Hager-Seltzer direct access table to a sequential text file format.

Input file: The direct access table is a binary file of 11 word records with 13004 records in the file.

Output file: The text file is a sequential access symbolic file of 80 character records (Z, SHELL, EG, E1, E2, E3, E4, M1, M2, M3, M4) = (I3, A2, F7.2, 8E8.2). Data file includs ICCSEQ.DAT.

Terminal dialogue: The program will first ask for the binary table file name (default: ICCTBL.DAT) and then the sequential output file name (default: ICCSEQ.DAT).

Additional documentation: none.

LOGFT

Version 7.2a [20 March 2001]

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Original authors: N.B. Gove and M.J. Martin, Nuclear Data Project, Oak Ridge National Laboratory, and B.J. Barton, National Nuclear Data Center, Brookhaven National Laboratory.

This program calculates log *ft* for beta decay, the partial capture fractions for electron capture, the electron capture to positron ratio for positron decay, and the average beta energies. Special calculations can also be performed for first and second forbidden unique; all other categories are treated as allowed.

Input files:
1. ENSDF formatted file. Sample input includes DATA.TST
2. Radial wave function data. Data file includes LOGFT.DAT

Output files:
1. Report file. Sample output includes LOGFT.RPT
2. New ENSDF formatted file with appropriate values for B and E cards updated. Sample output includes LOGFT.NEW

Terminal dialogue: The program will ask for the names of the input data file (default: DATA.TST), the report file (default: LOGFT.RPT), the file containing the wave function data (default: LOGFT.DAT), and the file to be created (default: LOGFT.NEW).

Compilation and loading instructions: This program requires subroutines from the `NSDFLIB` package.

Additional documentation: N.B. Gove and M.J. Martin. Log-f tables for beta decay. Nuclear Data Tables A10, 206 (1971).

Additional notes:
1. New records will not be created if there are non-numeric parent or level energies, Q-values, or associated uncertainties.
2. If Lyon's method 1 has been used to estimate the intensity, LOGFT should also be run using the original values.

NSDFLIB (Evaluated Nuclear Structure Data File Library)

This library consists of subprograms used by many of the ENSDF Analysis and Utility Programs. FORTRAN77, and FORTRAN90/95 versions of the library exist. Both contain string processing, which extend the capabilities of ANSI standard FORTRAN, number to string and string to number, and mathematical subprograms. The FORTRAN90/95 version also has command-line interpreter, time and date, and sorting subprograms.

NSDFLIB (FORTRAN 77)

Version 1.5d [28 June 1999]

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This subroutine package consists of three subroutine packages F77STR (Fortran77 String Processing Library), NSDCNV (Fortran77 Conversion Routines), and NSDMTH (Fortran 77 Mathematical Routines). All elements of the package have been written to conform to the ANSI standard for Fortran77 and are therefore machine independent. The version number and date above is for F77STR.

Input file: none.

Output file: none.

Terminal dialogue: none.

Compilation and loading instructions: This subroutine package is required by most of the ENSDF analysis and utility codes, and should be compiled and linked as necessary with them.

Additional documentation: Internal National Nuclear Data Center memo
NSDFLIB-MEM.TXT

NSDFLIB95 (FORTRAN 90/95)

14 October 2005

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The `NSDFLIB95` subprogram library contains FORTRAN95 versions of the NSDLIB subprogram library and additional subprogram libraries. With the exception of the `GET_COMMAND_LINE`, `OPEN_SORT_INPUT` and `OPEN_SORT_OUTPUT` subroutines, all subprograms in this library are written to conform to the ANSI standard for FORTRAN95 and are, therefore, generally machine independent.

Input file: none.

Output file: none.

Terminal dialogue: none.

Compilation and loading instructions: This subroutine package is required by newer versions of the ENSDF analysis and utility codes and should be compiled and linked as necessary with them.

Additional documentation: Internal National Nuclear Data Center memo `nsdflib95.html` or `nsdflib95.pdf`.

PANDORA (Physics Analysis of Nuclear Data to Outline Required Adjustments)

Version 7.0b [1 May 2007]

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This program provides the following physics checks for an ENSDF file.

1. Decay data sets have a P-card.
2. An L-CARD with T1/2 > 0.1 S should have MS FLAG.
3. Check consistency of spin/parity of levels with multipolarity connecting transitions.
4. J = L+-1/2 for a transfer reaction with even-even target.
5. No parity change for $3.6 < \log ft < 5.9$, $J^{i-1} \le J^f \le J^{i+1}$. Parity change for 1U in cols. 78-79 and $\log ft \ge 8.5$ $J^f=J^{i\pm2}$.
6. Alpha decay: if the mass is odd and HF < 4, $J^f=J^i$, no parity change; if J^f or $J^i = 0$, parity change = $(-1)^{(Jf-Ji)}$.
7. Levels out of order.

Input files: ENSDF formatted file. Sample input file: pandin.dat.

Output files:

1. file.err. Errors and warnings about the input data. Sample output file: file.err
2. file.gam. Report of the γs in the input file arranged by A, Z, E_γ and DSID. Sample output file: file.gam
3. file.gle. Report of the γs in the input file arranged by A, Z, $E_{(\text{parent level})}$, E_γ and DSID. I_γ given are branching ratios ($I_{(\text{strongest }\gamma)} = 100$). Sample output file: file.gle
4. file.lev. Report of the levels in the input file arranged by A, Z, E_{level} and DSID. Sample output file: file.lev
5. file.rad. Report of β/ε in input file arranged by A, Z, $E_{\beta/\varepsilon}$ and DSID. Sample output file: file.rad
6. file.rep. Reports ignored records, levels that have no match in adopted levels, frequency of XREF symbols, new XREF symbols, *etc*. Sample output file: file.rep
7. file.xrf. Reports the cross-reference records. The cross-reference symbols are also given in file.lev. Sample output file: file.xrf
8. New ENSDF formatted file with XREFs added or modified. Sample output file: pandor.out

Generation of the files reporting on gammas, levels, and radiations and the new ENSDF formatted file is optional. There is no option to specify file names for the FILE.* outputs.

Terminal dialogue: The program will ask for the input file name and then query if the user wishes the level, gammas and radiation reports (default: 0 for no) and a new file generated (default: 0 for no). If new output is specified, the user will be asked for the output file name. As generation of the various output files is completed, this fact will be noted on the terminal.

Compilation and loading instructions: This program requires subroutines from the `NSDFLIB` package.

Additional documentation: Internal document (`pandor.ps`).

RadList (Radiation Listing)

Version 5.5 [5 October 1988]

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This program is designed to calculate the nuclear and atomic radiations associated with the radioactive decay of nuclei. Nuclear decay data are used as the primary input in ENSDF format. Listings or computer files containing the energies, intensities and dose rates for various nuclear radiations are produced. These outputs also contain the energies, intensities, and dose rates of the associated atomic radiations. Optionally the continuum spectra for $\beta^{\pm}$ decay and for internal bremsstrahlung associated with $\beta^{\pm}$ and electron-capture decay may be calculated.

Input files:

1. ENSDF formatted file. The following optional records are allowed as defined in cols. 1-9 of the record:
   a. MERGE/ENDMERGE specifies that the radiations from the data sets contained between them will be merged on output (ignored if the data-base option is selected).
   b. PAGE causes the radiation listing output to begin on a new page for the following data set.
   c. PARAMETER - various parameters affecting the calculations or output of the program may be given in cols. 10 - 80 of this record which immediately precedes a data set and only affects that data set. These parameters are:
      i. ALLGAM to override the minimum intensity cutoff for radiations and output all gammas. No value should be given for this parameter.
      ii. MAXEC specifies the number of electron-capture branches to be listed in the radiation listing (default = 0).
      iii. MAT specifies a material number for ENDF-6 output (default is based on the Z and A of the parent).
      iv. RIMIN specifies the minimum intensity cutoff (in percent) for radiations (default = 0.001% except for the data-base option [10^{-12}%]).
      v. WEIGHT specifies an arbitrary weighting fraction, but not allowed with database and ENDF-6 options.

Sample input file: `radlst.inp`. See the report for an explanation of what is tested within this sample input.

2. Atomic electron binding energies, fluorescence and Auger-electron yields: One of the following two data files must be present:
   a. Direct access binary file (`atomic.dat`) - the program will generate this file if non-existant and the following file is available.
   b. Sequential file (default name: `mednew.dat`) - data file provided with distribution.
3. Atomic mass data: if neither of the two following files is present, the program will calculate atomic masses based on the Garvey-Kelson formalism.
   a. Direct access binary file (`wapstb.dat`) - the program will generate this file if non-existant and the following file is available.
   b. Sequential file (default name: `radmas.dat`) - data file provided with distribution.

Output files: With the exception of the report file, these files are options.

1. Report file: input data are listed in cols 2-81 and messages reporting possible problems or assumptions are given in cols 82-133; possible severe errors are noted on a line following the record in question.
   After all relevant radiation data have been analyzed, there will be a summary of the energy deposited by the radiations and recoiling nuclei and a comparison between the sum of these deposited energies and the energy expected from the branching ratios and Q values.
2. Radiations listing: Fortran-formatted file containing the nuclear and atomic radiations obtained by the program - see the report for additional details.
3. Database file: presents the data generated by the program in a fixed computer-readable format - see the report for additional details.
4. ENDF-6 format file: MT = 1, MF = 451 (comments) and MT = 8, MF = 457 (decay data) sections are generated.

Either the ENSDF-6 file or the database file may be generated, but not both.

Terminal dialogue:

1. The program will ask which output files should be generated (defaults: radiation listing; no ENDF-like file or database file).
2. Unless the database option is chosen, the user will be asked if the continua should be calculated (default: no).
3. The names of the input and report files will be requested (defaults: RADLST.INP and RADLST.RPT).
4. If the binary data files are not present, the user will be asked for the names of the sequential files.
5. The user will be asked the names of the various output files to be generated (defaults: ENSDF.RPT, NUDAT.OUT, and ENDF.RAW).
6. The source of the atomic data and mass data will be noted.
7. As each data set or group of data sets are processed, a summary of the results will be displayed on the terminal.

Sample terminal dialogs and outputs: Following are descriptions of the sample files included in the distribution. This list supersedes Appendix B of the report. The various outputs in these files are separated by "%%%%%" followed by the type of output, and in some cases only show those outputs where there are major differences.

1. `radlst1.out`: normal options
2. `radlst2.out`: ENDF option

3. `radlst3.out`: database file option
4. `radlst4.out`: continua with bremsstrahlung chosen
5. `radlst5.out`: ENDF with both continua and bremsstrahlung chosen

Compilation and loading instructions: This program requires subroutines from the `NSDFLIB` package.

Additional documentation: T.W. Burrows. The program RADLST. Brookhaven National Laboratory Report BNL-NCS-52142 (1988).

RULER

Version 3.2a [6 August 2007]

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This program either calculates the reduced electromagnetic transition strengths and compares these to the Recommended Upper Limits (RUL), or calculates BEλW and BMλW for inclusion in ENSDF data sets. Primarily designed to work on ADOPTED LEVELS, GAMMAS datasets, but will process any dataset whose DSID indicates the presence of gammas.

Input file: ENSDF formatted file. Sample input file: `ruler.in`

Output files:

1. The report file will list the datasets and note any problems or assumptions by the program. Comparison mode shows the calculations, and compares the results with the RULs, noting possible violations. Calculation mode, shows the calculations and compares the old and new values for BELWs and BMLWs. Sample output files: `ruler1.rpt` (comparison) and `ruler2.rpt` (calculation).
2. Optionally a new file will be created containing the calculated BEλWs and BMλWs. Sample output file: `ruler.out`.

Terminal dialogue: The program will request the input and report file specifications, the mode of operation (answer is case insensitive), and, optionally, the new file specifications.

Compilation and loading instructions: This program requires subroutines from the `NSDFLIB95` package.

Additional documentation: Distribution memo (`ruler.ps`).

TREND
(Tabular Representation of ENSDF)

Version 8.3 [7 Febuary 2001]

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Other author: Bruce J. Barton.

This program generates ENSDF data tables report, and allows the user to view and control the output file on the screen.

Input file: An ENSDF formatted file. Sample input file: `data.tst`

Outputs: Tabular representations of the ENSDF data similar in organization to the Nuclear Data Sheets are generated either as a report file or as a file capable of being viewed interactively on an ANSI (VT100 equivalent) or VT52 terminal.

Sample output file: `trend.rpt` (132 columns; 66 lines per page)

Terminal dialogue: The program will request the following information:
1. Input file name.
2. Output file name.
3. If the output file exists, does the user wish to view it?
4. 80 or 132 column display (no defaults).
5. Lines per page (defaults: 60 if 80 column display; 66 if 132 column display) - user should specify 24 for screen display.

If the user has specified "TT:" or "TTY:" (case insensitive) as the output file name, answered yes to viewing an existing file or 24 lines per page, the tables will be displayed on the screen with a prompt line at the bottom. The user may scroll up and down through the tables.

Compilation and loading instructions: This program requires subroutines from the `NSDFLIB` package.

Additional documentation: None.

13.

GUIDELINES FOR EVALUATORS

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April, 1988

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CONTENTS

GUIDELINES FOR DECAY AND REACTION DATA SETS

A. Extraction of Data

1. In any experiment, the author's basic measured quantities should be quoted, unless these data can be converted to more usual or convenient forms by applying known numerical factors (for example, mean-life to half-life, BE2(sp) to BE2).

Quote what was actually measured in an experiment and not necessarily what the authors quote in cases where these are different.

> Note: A measurement of $I\gamma/\Sigma I\beta$ might be quoted by an author as $I\beta(gs)$, which, for the author's decay scheme should be equivalent to the absolute $I\gamma$ determination, but is not as fundamental a quantity. If the decay scheme is changed, the $I\beta(gs)$ could change, whereas the absolute $I\gamma$ measurement should still be valid. Failure to make such an important distinction is a particularly common source of confusion when normalization conditions are being stated.
>
> A measurement of $I\gamma^{+-}/I\gamma$ might be quoted by an author as $I\beta^{+}/I\gamma$. The ratio should be expressed in terms of the annihilation radiation, since $I\beta^{+}/I\gamma$ could imply that the positron spectrum was measured.

2. Document any and all changes made in data quoted from an author. When correcting an author's value for a quantity, for example an error due to a misprint, give the corrected value in the appropriate field, and mention the uncorrected value in a comment. Do not give the uncorrected value in the field, and rely on the comment to define and explain the correct value.

3. When extracting data from an author's paper, note any assumptions, standards, or constants that enter into a derived value, and correct the data for any changes in these assumed values. For example, an ε/α ratio for one nucleus might depend on the value assumed for another nucleus, or a conversion coefficient might be normalized to a standard value. Data should be presented in such a way that the effect of changes in any of the assumed values is clearly displayed; thus, "α_k = 0.0324 12 if α_k = 0.0324 12 for $\alpha_k(^{137}Cs)$-……". Better values for the assumed quantities might be available at the time the mass chain is being revised.

4. Check the bibliography in each article against the reference list provided by BNL. This action is a valuable cross-check to help ensure that references have not been overlooked. Also, authors will sometimes quote data received as private communications; these data should be tracked down if possible if they seem important.

5. Do not rely on an author to extract older data correctly. Even if an author collects such data in a table, the original article should be checked. This checking procedure is especially important in view of 3, above.

6. Be sure to distinguish between values measured by an author and those deduced by the same author. For example, in a transfer reaction, an author might adopt L values for some transitions based on known $J\pi$ in order to extract values for other levels. Such a distinction should be made clear.

B. Manipulation and Presentation of Data

1. Comments

(a) For data sets in which the data appear in two or more separate sections in the data sheets output, namely decay data sets and reaction data sets involving gammas, the comments should always be written in such a way that they are clearly separated into general comments, comments on levels, comments on gammas etc. This "separation" of comments avoids the problem of having comments appear where they are not appropriate (of course these comments can be edited out where they are not appropriate, but this is a step that should be avoided).

> Note 1: A single comment such as "the level scheme is that of . . . based on. . . the Eγ and Iγ are from …, with Iγ normalized so that... The Iβ are from the I(γ+ce) imbalance at each level" should be rewritten as separate general comments on levels, gammas and betas, or as specific data-type comments on Eγ, Iγ, Iβ, as appropriate.

> Note 2: Comments on γγ(θ), γγ(t), γ(θ,H,T) etc. in a given data set should normally be given with levels rather than with gammas, since usually under the levels listing one wants to see comments on the values of J, T½, or μ etc., deduced in that data set from measurements of these types. If the γγ(θ) data also yield δ values, the comment on δ in the gamma listing can simply state that the relevant γγ(θ) data are discussed in the levels listing.

(b) General comments of a descriptive nature at the head of individual data sets should be kept to a minimum. In particular, comments for each keynumber that describe what was measured (such as Eγ, Iγ), or what detection method was used (such as semi, Ge(Li)) are not required, but can be given at the evaluator's discretion. The only required comments are the specification of bombarding energy and energy resolution for reaction data sets. Projectile energy and experimental resolution should be given for each reference from which data are quoted, even if not a major source. Such information may also be useful for other references. For grouped reactions, such as (HI, xnγ) or Coulomb excitation, the bombarding particle would of course also need to be specified for each keynumber. In addition, for Coulomb excitation, the distinction between particle detection, (x, x'), and gamma detection, (x, x'γ) should be made. Examples are given in (e) below.

> Note 1: The bombarding energy and resolution for reference "A" are of interest in a case where, although most of the excitations energies are from some other source, reference "A", whose data are not otherwise included, reports a level not seen by the other sources, and the evaluator chooses to include this level. In many cases, evaluators refer to reference "A" only in a comment on the specific level in question; however, reference "A" should be included explicitly with the other references in the heading.

> Note 2: The specification of "s" for spectrometer is an example of the additional type of information that is probably not worth giving, since such an entry conveys only partial information on the experimental setup while giving the reader information that photographic plates and aluminum absorbers, for example, were used may be of equal importance. In most cases it would be very difficult to write exhaustive comments such that the reader would not have to look at the paper to obtain the necessary experimental details, so there is no strong reason for giving just part of the picture. The specification of "semi" or "Ge(Li)" is also not really needed. Few modern papers contain "scin" data. Probably useful to specify "cryst", since such measurements can be very precise, and the calibration uncertainties are then known to be proportional to Eγ.

Note 3: Specific comments such as "Eγ are weighted averages from 77Sc02 and 79Fell. Others: 72Go04, 78Hi23" specify the important references for Eγ, and are more informative than a set of keywords presented uncritically.

Note 4: The specification of the angular range might be useful in a case such as the assigning of L = 0 as opposed to L = 2 in (α, α') for a giant resonance. This assignment requires knowledge of the angular yield variation at angles near zero. An indication that this range was measured lends credence to an author's conclusion that L = 0. However, the same information could be given instead in a comment discussing the author's conclusion.

c) Do not put E = … on the ID record, except when needed to distinguish otherwise identical data sets, for example, (n, γ) E = th and (n, γ) E = res. The bombarding energy should be put in a comment; see examples in (e) below.

d) Except for even-even targets, Jπ(target) should be given for particle transfer reactions in which L values were determined. A general comment such as "Jπ(^{139}La) = 7/2^{+}" is recommended; see examples in (e) below.

e) For readability of the comments referred to above, each keynumber followed by the appropriate comments should be given on a separate line with the keynumber first. The following are some examples.

^{208}Pb Levels from ^{208}Pb(d, d'), (pol d, d')

71Un0l E = 13 MeV, FWHM = 3-10 keV, θ = 125°-150°
80Mo18 E = 86 MeV, FWHM = l x l0^{-3}
80Wi12 E = 108 MeV, θ = 4°-14° (partial data also reported in 80Dj02)
Others: 62Jo05, 68Hi09

^{208}Pb Levels from Coulomb Excitation

69Ba51 (x, x') X = α, E = 17-l9 MeV; x = ^{16}0, E = 69.1 MeV
71Gr3l (x, x'γ) x-α, E = 15,18 MeV

^{208}Bi Levels from ^{207}Pb(^{3}He, d), (α, t) 71Al05

E(^{3}He) = 30 MeV, FWHM AP 20 keV, θ = 10°-70°
E(α) = 30 MeV, θ = 20°, 50°
Jπ(^{207}Pb) = 1/2^{-}

^{208}Bi Levels from ^{208}Pb(p, n), (p, np') IAS

(p, n)	74Fi14	E - 25.8 MeV	
	80Ho21	E = 120 MeV, FWHM AP 670 keV; 160 MeV, FWHM AP 1200 keV	
	Others:	72Wo23, 71Wo04	
(p, np')	73Wo04	E = 30.5 MeV	
	77Bh02	E = 25 MeV, n-p' coin	
	Others:	79LiZU, 71Wo04	

2. Combining data sets

Do not combine reactions that are fundamentally different in character, for example (p, p') and (n, n'), or one-and two-particle transfer reactions.

Except for Coulomb excitation, separate data sets should be created for particle and gamma reactions, for example (d, p) and (d, pγ), or (p, p') and (p, p'γ). Attempting to combine the different types of information usually presented in the two reactions leads to confusion in the presentation. Typically, one wants to present the L (and/or J) and S information from the particle work, and adopted Jπ for the gamma drawings.

The reaction (X, X') is intended to include (X, X); there is no need to include explicitly the special case of elastic scattering.

> Note: We do not generally include the type of information extracted from elastic scattering in the data sheets, so the (X, X) reaction will rarely appear alone. One exception is in the case of resonance work, where information on resonances in the compound nucleus can be obtained and may be of importance (see Section F, below). Information on nuclear shapes and charge densities, etc., deduced from elastic scattering can be given, or referred to, in adopted levels without the need for the (X, X) source data set.

3. Sources of data

Sources of data for all headings, for example E(level), Iγ, δ, L, S, should be given unless "obvious". The final decision as to whether a source is obvious or not will reside with the editors. Keep in mind that each evaluator has the responsibility to ensure that the data presented are traceable to their source.

When more than one keynumber is included on an ID record, the keynumber from which the individual pieces of data are taken should be stated. If a reader wants to check an E, Iγ, or S, for example, that reader should be able to go directly to the relevant reference or references.

> Note: A comment on Iγ, stating "from X" or "weighted average of data from X and Y" is preferable to requiring the reader to deduce the sources of data based on the keywords in the general comments described in (1) above.

4. Placement of gamma records

Gammas should be placed in order of increasing energy following each level for consistency in presenting drawings (and for convenience in reading data bank listings). This same order should be followed in the unplaced gammas listing.

5. Significant digits

When converting values from one set of "units" to another (for example, half-life to mean-life, or renormalizing Iγ values), enough digits should be retained so that the inverse operation will reproduce the original values. Note that for some cases this exercise will result in more digits being quoted in the converted value than in the original value. This procedure is especially important when dealing with quantities determined with fairly high precision. For example, from BE2 = 0.384 4, one should report T1/2 = 7.27 ps 8, not 7.3 ps 1, and from a mean-life of 32 ps 1, one should report T1/2 = 22.2 ps 7, not 22 ps 1. Another way of stating this principle is that the fractional uncertainty in the original value should be preserved (to the same number of significant digits) in the converted value.

When taking a weighted or unweighted average, quote a sufficient number of digits to correspond to our round-off procedure; that is, whenever possible, quote two digits for uncertainties up to 25. For example, a weighted average of 6.0 1 and 6.1 1 should be quoted as 6.05 7.

6. Multiplets

(a) Unless a complex peak in a reaction spectrum is resolved in a given experiment, a single "level" entry should be made. For example, in the case of a peak suspected of being made up of two levels with Jπ = a and Jπ = b, respectively, on the basis of work from other experiments, a single level with "Jπ = a and b" in the Jπ field should be introduced. Inclusion in this data set of two levels involves making an explicit assumption that is not necessary. The probable level association can be adequately explained in a comment; this same approach should be used with gammas. A multiply-placed transition seen as a single peak in the spectrum should appear in the output as one transition with multiple placements. Do not introduce additional transitions (with artificially altered energies, or energies taken from the level scheme).

> Note: If the intensity of a gamma multiplet is not divided among the several placements, the full intensity, with uncertainty, should be given for each placement, along with "&" in column 77. Do not enter the intensities as limits in source data sets; converse is true in adopted gammas, where multiply-placed Iγ should be entered as upper limits; see note under Section E. 2. in GUIDELINES FOR ADOPTED LEVELS. If the intensities are divided, for example on the basis of γγ, "@" should be entered in column 77. These entries will automatically generate footnotes explaining that the transitions are multiply-placed and that the intensities are not divided (for "&"), or are suitably divided (for "@").

(b) If a gamma transition or a peak in a reaction spectrum is claimed to be a multiplet, the basis for this claim should be given. For example, the gamma peak might be broad, or coincidence data might suggest that a peak is a multiplet. In the case of a peak in a reaction spectrum, experimental arguments such as "peak is broad" should be distinguished from theoretical arguments such as "C2S is too large for a single level on the basis of shell model expectations".

(c) Consider gamma-ray multiplets where Iγ (peak) in a specific data set cannot be decomposed on the basis of data available in that data set, but branches involving one or more members of the multiplet are available from other data sets; Iγ for members of the multiplet should be deduced where possible using such branchings. Appropriate comments, such as "Iγ: From Iγ(326γ)/Iγ(432γ) in Adopted Gammas", are of course required, and "@" should be entered in column 77.

d) A multipolarity determined for a multiplet will not necessarily be correct for each, or perhaps even any member of the multiplet. For example, depending on the relative strengths of the components, I(γ) and I(cek) for a doublet consisting of an El and Ml component could yield mult = E2. The multipolarity for the doublet should be given in a comment, but should not be entered in the multipolarity field of the individual components, unless additional information is available that justifies the assignments.

> Note: When I(γ) but not I(cek) (or vice-versa) is resolved, and the multipolarity of one component of a doublet is known from other sources, the multipolarity for the other component may possibly be deduced.

7. Cross sections and analyzing-power should not be given explicitly - sufficient simply to mention that such measurements were made, in the context of justifying any conclusions based on this type of data. The conclusions themselves should be given.

Note: If an evaluator feels that the angular distribution coefficients do need to be given, they should be defined in the form A2, A4, not A2/Ao, A4/Ao; i.e., we define the angular distribution function as $W(\theta) = 1 + A2P2(\cos\theta) + ...$, not as $Ao + A2P2(\cos\theta) + ...$

8. (γ, γ') experiments

Some confusion and a lack of consistency in the presentation of data exists in experiments on resonant fluorescence. Scattering experiments are the most common type of measurement that, for the case of photons scattered elastically from a thin target, yields the quantity $gW(\theta)\Gamma(\gamma 0)^2/\Gamma$, where $g = (2J + 1)/(2Jo + 1)$, with J-resonance level spin, Jo = ground state spin, and W is the angular correlation function. For inelastic scattering, the term $\Gamma(\gamma 0)^2$ in the numerator should be replaced by $\Gamma(\gamma 0)\Gamma(\gamma i)$ where $\Gamma(\gamma i)$ refers to the de-exciting transition to an excited level with J = Ji. The quantity $gW\Gamma(\gamma 0)^2/\Gamma$, or just $\Gamma(\gamma 0)^2/\Gamma$, should be given in this type of experiment. When J and W are known, the adopted value for $\Gamma(\gamma 0)/\Gamma$ (= $I(\gamma 0)/\Sigma I(\gamma)$ in the case of bound states) should be used where available to deduce the level width (or T1/2). The corresponding intensity ratio $I(\gamma i)/\Sigma I(\gamma)$ would be needed for the inelastic case.

Note 1: Measurements are usually undertaken at 127° where W = 1 for all dipole transitions, independent of Jo, J, or Ji ($P2(\cos\theta) = 0$ at this angle). For mixed transitions, W depends on the mixing ratio and on the J values.

Note 2: Occasionally, self-absorption experiments are performed to yield $gW\Gamma(\gamma 0)/\Gamma$.

The quantity $\Gamma(\gamma 0)^2/\Gamma$ can be given in the "S" field, with the field suitably relabelled (see Section G. 1. below). This procedure eliminates considerable typing at the input stage. The quantity $\Gamma(\gamma 0)/\Gamma$ can be given in the RI field for the relevant γ or as a comment on the corresponding level.

9. BEλ and $\beta\lambda$

Consider Coulomb excitation and (e, e'), where electromagnetic excitation probabilities can be determined, in which the quantities BE2, BE3, etc. should be quoted on continuation level records. Data quoted as matrix elements should be converted to BE2, etc. A matrix element has been determined and this fact could be added as a comment. Note that $BE\lambda = (2Jo + I)^{-1}|\langle ME\lambda\rangle|^2$, where $\langle ME\lambda\rangle$ is the matrix element, and Jo is the target spin.

Note: Do not give BEλ data with the gammas. BEλ(down) data, as provided by an author for gammas, should be converted to BEλ(up) and given with the corresponding level. The appropriate place for BEλ(down) data is in adopted gammas where such values are given in single-particle units based on adopted T1/2, branching, etc., data.

For inelastic reactions other than those governed by the electromagnetic interaction, the appropriate interaction strengths to quote are the deformation parameters, $\beta\lambda$ or $\beta\lambda R$. Authors sometimes convert the deformation parameters to BEλ, but this is a model-dependent procedure and unless the authors quote only BEλ the deformation parameters should be entered into ENSDF.

10. Delayed gammas

For an in-beam reaction in which both prompt and delayed Iγ from level X are available, there are two methods of accounting for the data.
(a) If only one reaction (or more than one but grouped together such as in (HI, xnγ)) contains data on the delayed transitions from level X, two data sets can be created: one labelled with the modifier "prompt gammas" and the other with the modifier "delayed gammas".

(b) Preferred method is to create an IT decay data set for level x.
This alternative is especially recommended if there is more than one source of data. A single IT data set which combines the results from all the relevant reactions is preferable to creating several delayed-gamma data sets from the several reactions for the same level X.

> Note: The prompt data should always be presented; however, the separation into prompt and delayed data sets can be particularly useful when the delayed-gamma intensities are used to obtain multipolarities based on intensity balance arguments.

If the delayed data are rather sparse, and the results from the data, such as multipolarity information or T1/2, can be conveniently quoted in the prompt data set, (for example "Mult: from α deduced from intensity balance in the delayed spectrum"), the evaluator may choose to combine all the data in a single data set.

11. Data sets without level information

Separate data sets for reactions studied, but for which no specific level information is given, can be included at the evaluator's discretion if the experiment yielded some useful information. Such a data set would consist only of comments. The following are examples.

^{208}Po from ^{204}Pb(^{16}O, ^{12}C) 76Da18

E = 93 MeV
The authors deduce Γ(α) for the ^{208}Po ground state and compare with the corresponding α-decay value via R-matrix theory using the same target-plus-α nuclear potential.

^{208}Pb from ^{208}Pb(p, n) 74Sc0l,74Sc3l

E = 25.8 MeV
Authors deduce rms neutron/proton radius ratio = l.07 3

> Note: The information contained in such data sets in many cases could also be included as comments in adopted levels. This is especially true for the second example; however, unless a data set is created for a reaction, there is no convenient way to search and retrieve that reaction, nor to indicate to the reader that such a reaction was studied. If a reaction was studied but no "useful" information is available, the best approach would be to simply list the reaction under "Other reactions" in a comment on adopted levels.

12. β- and ε + β + feedings, and logft

Logft values should be made consistent with the deduced β^- or $\varepsilon + \beta^+$ feedings. In particular, when $I \pm \Delta I$ is consistent with zero (for example 3% 3), the corresponding logft should be expressed as a lower limit corresponding to a feeding of $I + \Delta I$(6% in this case). Branches that overlap zero (for example, - 3% 6), should be shown with the feeding given as an upper limit (< 3%), with the corresponding logft given as a lower limit.

> Note 1: The above holds for cases where the feeding can be expected to be non-negligible, i.e., where the transition is $\Delta J = l$, $\Delta\pi$ = yes or no, or $\Delta J = 2$, $\Delta\pi$ = yes. Where $J\pi$ change implies negligible feeding, this feeding should be set to zero. Any deduced feeding not consistent with zero should be commented on, and an explanation for the inconsistency given if possible.

An exception to this policy of omitting "unphysical" branches occurs when the initial or final Jπ is in question; there is no clear evidence whether Jπ or the feeding is in error. Under such circumstances , the β^- or $\varepsilon + \beta^+$ branch should be shown, perhaps with "?", and the problem should be pointed out in a comment.

Note 2: Summed feeding to two levels connected by a transition whose TI is not known, or is known only as a limit, can sometimes be determined even though the feeding cannot be divided between the two levels. Such combined feedings should be given in a comment.

13. Normalization

The normalization condition should always be given. Be sure to account for both NR and BR.

Note 1: If the normalization condition involves a measured quantity for which no uncertainty is quoted by the authors (for example, $I(\beta^-$ gs) = 30%), try to assign an uncertainty. If you can not do so, or choose not to do so, the resulting NR (or NR x BR) should be given as approximate. If NR is given with no uncertainty, GTOL will generate level feedings, and MEDLIST will generate absolute intensities that reflect only the uncertainties in the relative intensities. If $\Delta I(\beta^-)$ is assigned in the given example, the uncertainty can be explicitly added to $I(\beta^-)$ in the listing, with an appropriate comment, or simply referred to within the normalization statement, for example, "NR:...the evaluator has assigned an uncertainty of x% to the intensity of the gs β^- branch in order to derive an overall uncertainty for NR". The former approach is recommended. Note that when the gs branch has a small intensity (say a few percent), even a large assigned uncertainty can result in a rather precise NR as calculated from $\Sigma TI(gs) = 100 - I\beta^-(gs)$.

Note 2: When Iγ in the RI field already include all the uncertainty appropriate for absolute intensities, such as when an author determines and quotes absolute values (including absolute uncertainties), NR and BR should introduce no additional uncertainty and be listed on the "N" record with no uncertainty (there is no requirement that the uncertainty in BR, as given in adopted levels, be carried over to the "N" record in a decay data set, although the value must be the same).

14. Parent records

Fields where data are known should be completed in the parent record, and the data should be the same as in the adopted data set. Comments on the "P" record should not be given unless necessary. The appropriate place for comments on any of the quantities appearing on the "P" record is in the adopted data set for the parent nuclide.

15. Miscellaneous

(a) Symbol "/" should not be used when proportionality of more than two values is defined. The expression K/L/M is mathematically equivalent to KM/L, even though few readers would interpret the term in this way. Use ":" instead to give K:L:M.

(b) Do not replace numerical values with large uncertainties by approximate values.

Note: An "isomer" energy of 230 300 keVallows for the possibility that the isomer may lie below the "ground state" by 70 keV. If the energy is replaced by ~230 keV, this possibility (while not ruled out) will not be conveyed to most readers.

(c) Try to resolve discrepancies - if they cannot be resolved, state this lack of resolution.

Note: If $\delta = +0.38$ is adopted for a certain transition, the value $\delta = +2$ appears in one of the source data sets, and the reason for the discrepancy cannot be determined, the evaluator should comment on the discrepancy. These comments can be logged in the source data set by pointing out that the value differs from the adopted value, or in adopted γs where the discrepant value can be mentioned in a comment. If something of this nature is not done, the reader might think that the discrepant value had been overlooked and may question the adopted value. If there are several such "discrepant" δ values in a certain data set, a general comment rather than a comment on each case could be given.

(d) Use the word "uncertainty" rather than "error" to refer to what we call the standard deviation in a measured quantity. The word "error" should be reserved for mistakes, such as in the sentence "The authors apparently made an error when they ...".

(e) Note that TI is translated as I(γ+ce), not I($\varepsilon+\beta^+$), even though the fields have the same name in ENSDF. When I($\varepsilon+\beta^+$) is meant, this definition must be spelt out.

(f) A level designated as an isomer in one data set should be treated as an isomer in all data sets (i.e., columns 78 and/or 79 should be completed).

(g) Do not comment on correction factors for a quantity when such correction factors are negligible relative to the uncertainty quoted for the quantity. For example, $\mu = +3.8$ 5 does not require a comment stating “diamagnetic correction has not been applied".

(h) Avoid the use of "CA" in the uncertainty field when a numeric uncertainty can be calculated.

Note: If Iγ is calculated from TI and α, the uncertainty in Iγ (from the uncertainty in TI and α), rather than "CA", should be placed in the uncertainty field.

(i) When calculating or correcting quantities that depend on other properties (for example, calculating conversion coefficients which depend on Eγ, calculating T1/2 from BE2 which depends on Eγ, branching, δ, and α, or correcting g factors for their dependence on T1/2), adopted values of all other relevant quantities should be used.

(j) When working with an author's proposed decay scheme, the evaluator should make a search for possible alternative gamma placements between known levels.

(k) Enter data in E(ε) or E(β^-) fields only when they are of sufficient accuracy that, in the evaluator's judgement, they should be considered as input to the mass adjustment. Values that are of somewhat lesser accuracy but still "significant" could be mentioned in comments. Very imprecise values are probably not worth recording. All the network analysis programs that require these energies obtain them from the appropriate Q-value and level energy.

Note: A measurement of β^+ endpoint must be entered as $E(\varepsilon) = E(\beta^+) + 2mc^2$. For example, a comment such as "E(ε): From E(β^+)=...(keynumber)" would be appropriate.

(l) Alpha-decay data sets: if the energies of the daughter levels being fed are not known, E(level) = 0 + X style should be used, rather than listing the alphas as unplaced. With this procedure, relative level energies can be presented in the daughter-nucleus mass chain. Alternatively, a level energy from systematics can be given (see Section C. (c), below). Note that there is no such thing as an unplaced alpha, unless one is referring to an alpha with uncertain parent assignment.

(m) Measurements of $P_k\omega_k$ (= I(K-x ray)) should be given. Adopted values can be entered on a continuation "E" record. These quantities are of direct interest to some researchers, and provide a direct measurement of the K-x rays, either for ε branches to individual levels, or an average for the

whole decay scheme. When possible, $P_k\omega_k$ should be compared with I(K-x ray) as calculated by RADLIST.

(n) If numerical data are quoted in comments, the uncertainty should be included unless the value is only being used as a label; thus, "T1/2: From BE2 = 0.240 6", or "μ: From g = 1.62 3 in (α, 2nγ)". Even though the actual numerical value is not needed in all cross references, the uncertainty should be included.

(o) When changing the sign of a mixing ratio which has an asymmetric uncertainty, note that $\delta = A + a\text{-}b$ becomes $\delta = -A + b\text{-}a$ (not $-A + a\text{-}b$).

(p) The ground state should be included in all data sets of the type (X, X'), i.e., inelastic scattering.

C. Systematics

Use should be made of systematics whenever possible, the extent to which they can be applied in any given case being determined by their reliability. The evaluator is usually in a better position to know how and when to apply systematics of a given quantity than the typical reader who is generally looking at just one or perhaps a few mass chains at a time.

> Note: Network evaluators make extensive use of systematics. Strong arguments for Jπ assignments which rely on logft values, strong arguments for multipolarities that rely on RUL, and extrapolations from the measured data in the mass adjustment (which are called systematics values) are prime examples.

One area in which systematics are particularly valuable is the estimation of ground and isomeric state branching ratios.

(a) Plots of log T1/2(α) vs log E(α) for nuclides with the same Z are usually linear. For a nuclide whose alpha branching has not been experimentally determined, use of T1/2(α) vs E(α) systematics can sometimes yield a reliable estimate of T1/2(α) which, along with the measured total T1/2, yields the alpha branching. On more than one occasion, such an estimate has been invoked to show that an experimental value must be incorrect; see also (c), below.

(b) Gross beta decay T1/2(β^-) and T1/2($\varepsilon + \beta^+$) estimates from (for example) Takahashi et al., Beta-Decay Half-lives Calculated on the Gross Theory, At. Data Nucl. Data Tables 12 (1973) 101, can be used to estimate β^- or $\varepsilon + \beta^+$ branching fractions. These estimates are considered to be reliable to better than a factor of approximately 3; thus, while an estimate of $\%\beta^- \approx 50$ and branching for the alternate modes of ≈50% should be considered as very approximate, an estimate of $\%\beta^- \approx 0.1$ can be used to assign the alternate mode(s) as essentially 100% with a high degree of reliability.

Additional areas where systematics arguments should at least be explored include the following.

(c) Systematics of alpha-decay hindrance factors can be used to deduce a variety of quantities (depending on what is known about the decay branch). These quantities include Jπ and configurations, total alpha branching and branchings of individual groups, and the excitation energy of the level fed in the daughter nucleus. Each evaluator (or centre) responsible for a mass region in which alpha decay occurs is encouraged to build up such a set of systematics. See Schmorak, Systematics of Nuclear Level Properties in the Lead Region, Nucl. Data Sheets 31 (1980) 283, and Schmorak, α-Decay Hindrance Factors in the ENSDF procedures manual for further discussion of these and other types of systematics.

(d) When a certain pair of shell- or Nilsson-model orbitals gives rise to the appearance of an isomeric transition over a reasonably large mass range, the reduced transition probabilities for the isomeric transition usually fall within a narrow range of values. Such data can be used to estimate properties for the "same" transition where one piece of information is missing, such as T1/2, IT branching, or Eγ.

(e) When a ground-state β^- branch is not known and there is no other way to determine the gamma normalization, logft values for similar transitions may exhibit local systematics. Even if the evaluator decides not to give an explicit normalization factor, a comment would be of value to the reader that points out what this factor would be if the transition had a logft value similar to other such transitions in the same region.

> Note: From $\log f^{lu}t > 8.5$ one might derive $I\beta^-(gs) < l0\%$. While this estimate might be the best one can do, systematics of $\log f^{lU}t$ values for other transitions of similar type (i.e., transitions between similar configurations) might suggest that the probable intensity is < 5%, or even close to zero. In such cases, the evaluator can adopt the systematics value for the limit on the β^- feeding in order to obtain the normalization. Justification for the chosen value must be stated. The systematics value could also be entered directly in the Iβ field, with an explanation for the source of that parameter instead of (or in addition to) the value derived from the normalization factor.

D. Uncertainties

1. Estimation of uncertainties.

When an experimental value is quoted by an author without an uncertainty, the evaluator should attempt to estimate and assign an uncertainty to that quantity if that quantity is required in further calculations, or if that value is a quantity that needs to be adopted and no other value is available.

> Note 1: The normalization of a decay scheme may sometimes involve a measurement quoted with no uncertainty; see Note 1 in Section B. 13, above, for a discussion of a ground-state beta transition with no quoted uncertainty that is needed for the normalization of the decay scheme.
>
> Note 2: When one or more excitation energies in a reaction data set (quoted with no uncertainty) need to be included in the adopted levels, the evaluator should attempt to estimate the uncertainty for these excitation energies. Uncertainties can sometimes be estimated by comparing the author's values with adopted energies in regions where there is overlap. Occasionally, comparison with data for other nuclei included in the paper can also be helpful.

2. Adoption of uncertainties

Weighted-average GTOL program and all other analysis programs that calculate uncertainties when individual values with uncertainties are combined, treat the individual uncertainties as statistical in nature. When the uncertainties are known to have a significant systematic component, the output from the above programs should be modified as necessary, particularly in cases where the quoted uncertainty is mainly and clearly systematic (due to a calibration uncertainty) so that the adopted uncertainty should be no smaller than the smallest of the input uncertainties. No result obtained from a weighted - or unweighted-average program or by any other method can have an uncertainty smaller than the uncertainty (or uncertainties) in the calibration standard(s) used to determine the input values.

3. All uncertainties in extracted data (for example, Eγ, Iγ, E(level) and T1/2) should be accounted for, either explicitly or in comments. Authors occasionally quote peak-fitting uncertainties and then state that an additional x% should be included to account for other sources of uncertainty, or they quote the value for some quantity relative to a standard value.

> Note 1: Consider Iγ in which these additional uncertainties, if independent of Eγ or Iγ, can either be included in NR, or explicitly combined for each transition with the partial uncertainties given by the authors. Since the intensity ratios of transitions close in energy may be nearly independent of the additional uncertainties, there may be an advantage in accounting for these through their inclusion in NR, although additional uncertainties that have been folded in can always be folded out if necessary.

> Note 2: Additional uncertainties should be included explicitly in the case of data describing other quantities, at least for quantities that are used in adopted levels and gammas. Neither network analysis nor listing programs are capable of making use of a comment such as "an additional uncertainty of x eV should be added in quadrature to the Eγ to account for uncertainties in the calibration". If an author quotes a value of T1/2 or a g factor relative to a standard, the uncertainty in the standard should be included when the value is adopted or combined with other measurements.

4. When undertaking calculations, the evaluator should attach an uncertainty to all theoretical α values (3% is recommended). For example, calculations of TI = Iγ(l+α) (or Iγ = TI/(l+α) or T1/2 from BE2) should include this uncertainty. The contribution of this uncertainty to the total uncertainty is negligible in many cases, but in normalizing 100% IT decay to Iγ(l+α) = 100, or normalizing a decay scheme in which only a single transition feeds the ground state and Iγ for this transition is given by the authors with no uncertainty, the uncertainty in α will be the only uncertainty in the normalized Iγ (assuming that the decay scheme is known with confidence). A comment should be included to explain what was done, and this uncertainty should not be entered in the Δα field. Our analysis programs already assign 3% uncertainty to α when performing calculations involving this quantity.

5. Numerical uncertainties larger than 25 should, normally be rounded off.

> Note: Data should be quoted in units such that this round-off convention can be applied. For example, T1/2 = 250 ps 50 should be quoted as 0.25 ns 5, and a set of Iγ data given by an author normalized to $I_{\gamma I}$ = l000 70 should be renormalized to $I_{\gamma i}$ = 100 7. Energies: since the standard energy unit is keV, values such as Q^- = 2000 150 keV, or E(β^-) = 2450 80 keV do not have to be converted to 2.00 15 MeV, or 2.45 8 MeV.

E. Resonances

Although the data coverage in ENSDF is limited to the bound-state region, any properties of the bound levels deduced from resonance work should be included. Eγ and 1γ data from (p, γ) and (n, γ) reactions do not need to be included in ENSDF except as noted below.

> Note: A typical case of interest involves the study of average resonance neutron capture in which Jπ values have been deduced on the basis of reduced transition intensities. The resulting data set needs to contain only the bound levels fed from the resonances, along with the deduced Jπ values; Iγ presented typically as Iγ/Eγ are not required. In fact, such data should not be given since they are just average quantities, and are only significant from the point of view of ENSDF for their use in deducing Jπ (in this sense, they are analogous to angular distribution coefficients).

Resonance data should be included in the following cases.

a) Isobaric analogue resonance data should be included; they should also be included in adopted levels.

b) Giant resonance data should be included, although data of this type are available for only a few nuclides.

c) Eγ, Iγ (and other relevant data) from thermal neutron capture should be included.

Note: Excitation data for isobaric analogue resonances should appear with the nucleus in which the resonances occur. Branchings to daughter levels (for example, in (p, np')), should also be given. Comments that include the deduced energies of the parent states (energies relative to E = 0 for the analogue of the ground state), or comments labelling the resonance with the appropriate parent level are useful.

Other situations may arise where the inclusion of resonance data is important (for example, near closed shells where the resonances occur at excitation energies low enough that they may "overlap" adjacent bound states that have been studied). The inclusion of data in this and other special cases is at the evaluator's discretion.

Note: Energies for resonance data can be entered in the form SN+X, SP+X, where X is the neutron- or proton-resonance energy, usually given in laboratory units (lab, or c.m. coordinates should be specified in either case). These resonances should be converted to excitation energies in the adopted levels.

F. L Transfers

1. A brief comment is required on the method used for obtaining L values; for example, L values "from DWBA analysis" should be distinguished from L values obtained "from comparison of σ(θ) with shapes for levels with known Jπ".

2. Parentheses are used to denote questionable or uncertain values. As described in the introductory section, square brackets can be used to indicate an assumed value, i.e., a value adopted by an experimenter (or by an evaluator) on the basis of known Jπ. This procedure might be adopted for the purpose of extracting S, or for determining empirical angular distribution shapes so that L values for other levels can be determined.

Note: When quoting L values, the evaluator has the option of quoting the author's values and then applying his/her own judgement as to their reliability when incorporating them into Jπ assignments, or of quoting the author's values as modified by the evaluator. For example, an author's L = 2 which in the evaluator's judgement should be L = (2), could appear as L = 2 in the source data set, but as L = (2) if used as a J1I' argument. Alternatively, a value of L = (2) could be entered in the source data set. In either case, a comment is required explaining that the evaluator feels that the L assignment is tentative.

G. Spectroscopic Factors

1. The exact label for the given quantity should be defined by using the "LABEL=name" format described in the manual; thus, "LABEL = C2S".

2. An explicit definition of S should be given if there is any ambiguity about what is meant; thus, "S is defined by “dσ/dΩ(exp) = Nsdσ/dΩ(DWBA) with N=..."

3. The method for obtaining the scale of S should be given, and it is important to distinguish between absolute and relative values. Thus, a comment should be given, such as "from DWBA", which implies that the values are "absolute", or "from DWBA normalized to X for the y level" for relative S values.

4. The shell-model (or other) orbital involved in the transfer should be specified if needed for the extraction of S.

> Note: This orbital can usually be specified in terms of a general comment such as "L-l, 2, and 3 are assumed to be p3/2, d5/2, and f5/2 except where noted otherwise". An alternative method is to give Jπ for the relevant levels along with a comment such as "Jπ: value assumed by the authors for the extraction of S"; the former approach is preferred when practical.

5. When Jπ adopted by an author differs from the evaluator's value, the S value (which will be incorrect) should not be entered in the S field, but given only in a comment. The reason for recommending that the incorrect value be given at all is that a knowledgeable reader can often estimate the value for the correct orbital from the value calculated for the incorrect orbital .

H. Jπ

1. Jπ values from adopted levels should be included where known; the introductory section states that this is our standard policy. For reaction data sets with no gammas, Jπ values should not be given unless they are determined for the reaction in question, or unless they are important in explaining some other aspect of the experiment. Jπ values should be given in reaction data sets with gammas. The introductory section states that Jπ values appearing in the γ reaction data set are adopted values unless noted otherwise.

> Note 1: Reactions that do not involve gammas - Jπ values, such as from L values and analyzing powers in (d, p) reaction, should be given in the Jπ field along with a comment stating how they were determined. Jπ values that come directly from the L values, such as $J = L \pm 1/2$ for single-particle transfer on an even-even nucleus, or L = J in (p, t) on an even-even target, are redundant, and should not be routinely given. Exceptions occur, for example, where the evaluator wishes to indicate the Jπ value used to extract the spectroscopic factor, or to show explicitly the band structure.
>
> Note 2: Reactions involving gammas, e.g., average resonance neutron capture - deduced Jπ values can be given in the Jπ field, or in comments. The latter procedure is recommended since adopted Jπ can then be placed in the Jπ field, in line with the accepted policy of including adopted Jπ values for any reaction data set involving gammas.

2. Arguments used in the Jπ assignments in adopted levels must be documented in the source data sets. The following represent a few examples.

	Jπ	argument
a)	3/2-	L(d, p) = l, 392γ to 5/2- is Ml
b)	1-	Average Resonance (n, γ), γ to 0+
c)	3+	El γ to 2-, γγ(θ)
d)	(5/2)+	L = 2, C2S in (d, p)

(a) (d, p) data set should contain the relevant L value, with any explanation deemed necessary to justify or clarify the adoption. Recommended γ data set should contain the justification for the Ml assignment to the 392γ.

(b) Average resonance (n, γ) data set should contain the value deduced in that data set (Jπ = 0-, l- in the present case), given in either the Jπ field, or as a comment; see also Note 2 under 1, above.

(c) Enough detail of the γγ(θ) experiment should be given in the source data set to justify the conclusions. Briefly, this section should mention the assumptions (i.e., what J values for other levels and what δ values for relevant gammas in the cascade were adopted, and should clearly state which values of J are allowed and which are ruled out. For the above example: only necessary to state that γγ(θ) is consistent with J = 3, and rules out J = l and 2.

(d) (d, p) data set should contain L and C2S values for the level in question, and a comment justifying the basis for the C2S argument. For example: "d3/2 strength exhausted by known 3/2+ levels. C2S for the L = 2, E=...level suggests d5/2".

I. Iγ, TI

1. Relative TI data (or absolute, for example, for (n, γ) in preference to branching ratio data) should be given when available.

> Note: If both relative Iγ and branching ratios are available, and if the branching ratios are more accurately known than the relative TI, both sets of data should be given. Relative Iγ should be given in the RI field, and the branching ratios can be given as comments on the relevant levels.

2. Reaction γs: projectile energy and angle at which the quoted Iγ were measured should be specified unless obvious from the keywords given in the general comments. Relative Iγ values measured under different experimental conditions, such as at a different bombarding energy or angle, should not be combined in the RI field, except where an Iγ from level "X" is deduced from branches relative to other transitions from level "X".

3. Gamma intensities reported as upper limits are important data measurements; and should be included (a comment to the effect that the transition was not seen could be included). Iγ given as "weak" by an author should be noted as such in a comment; also important to distinguish between cases where a missing Iγ is weak, and where such an emission is obscured by an impurity (and therefore could be strong).

> Note: One could distinguish between observed and unobserved transitions expressed as limits by the use of "≤" for the former, and "<" for the latter; however, the distinction between these two non-numeric uncertainties is not universally agreed upon, and is probably too subtle.

4. The TI field should be used only if TI, rather than Iγ, is the quantity measured or deduced. Two common cases where this occurs are when TI is deduced from intensity-balance arguments, or TI is given by summing I(ce). When TI is given and α is known, the corresponding Iγ should be calculated and entered into the Iγ field, unless the value is negligibly small. The uncertainty given for Iγ should include the uncertainties in both TI and α; a comment should be given stating that Iγ comes from TI and α.

Note 1: Iγ deduced from TI and α may be given in the RI field even when a direct measurement of Iγ is available, if the evaluator concludes that the deduced value is more reliable than the measured value.

Note 2: When TI rather than Iγ is the basic measured or deduced quantity, K/T(= αk/(l+α)) =... etc. , rather than αk-... etc. format on the continuation record should be used. For example, K/T operates directly on TI to generate the cek intensity (via MEDLIST) and the resulting x-ray intensities. This format avoids including some uncertainties twice, since Iγ (if calculated from TI and α) will already have an uncertainty combined from these two quantities.

5. Do not put TI values in the RI field, even if a comment is included to explain what is being done, and even if all the entries are TI values. RI and TI must not be mixed in the same field.

6. RI (or TI) field should be left blank for a transition which de-excites a daughter nucleus isomer whose T1/2 value is such that the intensity is time-dependent. A computer-retrievable comment should be included that defines % feeding of the isomer, and a comment is also required to explain why the intensity is missing.

7. I(x ray) and I(γ±) data of good quality should be given as comments in the form I(x ray)/Iγ(γi), where γi is the transition to which the γs are normalized. This procedure avoids the necessity of changing the comments if the Iγ are renormalized. The program MEDLIST should be run to compare the measured x ray and γ± intensities with those calculated on the basis of the adopted decay scheme. If I(x ray))/Iγ or I(γ±)/Iγ measurements are needed to obtain decay scheme normalization, MEDLIST can be used in an iterative fashion to deduce NR.

8. Internal conversion intensities are not needed, and they should not be given except in the following cases.

a) I(ce) ratios measured to a precision of better than about 3% should be included. At this level of precision, such values can be usefully compared with the theoretical data.

b) Where no Iγ is given, or where I(ce) are more precise, the I(ce) values should be quoted.

c) I(ce) are needed for E0 transitions, and should also be given for anomalously converted transitions.

9. A limit on a transition intensity (I < A) should be converted to I = 1/2A ± 1/2A for the purpose of calculating quantities that require the intensity of this transition, such as normalization factors, β^- and $\varepsilon + \beta^+$ feedings, or branchings (for branchings, see Note 4 under G. in GUIDELINES FOR ADOPTED LEVELS).

Note 1: Where $I\beta^-$(gs) is determined to be < 6% and the evaluator has no further information to suggest that this value should be closer to 0 than to 6, the intensity should be expressed as 3% 3 for the purpose of obtaining the gamma intensity normalization; one should set sum TI(gs) = 97 3 and explain what is being done. This procedure is preferable to any of the alternatives, namely setting ΣTI(gs) = l00, or ΣTI(gs) > 97. There is no justification for adopting the first alternative, and adopting the second alternative leads to lower limits being given for all the intensities. The usefulness of the procedure depends on the value of the limit - if I(β^-) is known only to be < 50%, perhaps normalizing the decay scheme is not worthwhile, although setting sum TI(gs) - 75% 25 is still better than doing nothing (if no normalization is adopted, a comment could be given stating what the

normalization factor would be for the extreme cases, namely for $I\beta^- = 0$, and $I\beta^- = 50$). The intensity of the gs β^- group should still be given as a limit in the β^- listing.

Note 2: $I\gamma$ values given as limits should be converted to $1/2I\gamma \pm 1/2I\gamma$ for the purpose of obtaining β^- and/or ε feedings from intensity imbalances. This procedure may lead to some feedings with rather large uncertainties, but this approach reflects correctly the state of knowledge of the decay scheme. The procedure is analogous to setting mult = [Ml+E2] for a highly converted transition in order to estimate the total intensity. Again, there is no implied suggestion that the intensities themselves should be changed from their limit form in the $I\gamma$ field. The GTOL program has been modified to treat limits automatically in this manner.

If the evaluator feels that the limit in a given case should not be treated in this fashion, a comment should be given justifying whatever approach is taken.

10. For the purpose of obtaining β and/or ε feedings, gamma transitions whose placements are uncertain (that is, transitions that have a "?" in column 80) should be handled in the same manner as for transitions given as limits discussed in Note 2 under 9, above. One should take $I\gamma = \Delta I\gamma = 1/2(A + \Delta A)$, where $I\gamma = A \pm \Delta A$ is the measured value. GTOL has been modified to treat uncertain transitions in this manner, but the evaluator will also be responsible for ensuring that the input to GTOL is modified as discussed.

J. Mult, δ, α

1. As stated in the introductory section, the multipolarity and δ entries (and thus α) for decay data sets should be adopted values. The inclusion of such data is mandatory, while for reaction gamma data sets such information should be included as needed or if measured.

Note: TI values are not needed in many reaction data sets, nor δ and α. However, the multipolarity should be defined. If TI values are required, adopted values for multipolarity and δ should also be used.

2. When multipolarity and/or δ values are determined, the basis for such determinations should be stated. Sources for the multipolarity data used by the evaluator (such as $\gamma(\theta)$, αk), along with the normalization required in αk data determined from relative $I\gamma$ and I(cek), should be given whether or not the experimental data (e.g., A2 and A4, αk, etc.) are explicitly given. Multipolarity assignments from ce data should originate from the evaluator based on the output from BrIcc (or HSICC). Multipolarities deduced by the authors (or by the evaluator) on the basis of "stretched" $\gamma(\theta)$ should be noted as a comment in the style of "$\Delta J = 1$, or $\Delta J = 2$".

Note 1: $\gamma(\theta)$ data determine only the L component of the gamma character (i.e., mult = D, D + Q, etc). Further assumptions are needed to establish the change in π, and should be stated when D is converted to M1, or D + Q to M1 + E2, etc. In particular, Q = E2 should not be considered an "obvious" conclusion. If T1/2 is known, RUL can sometimes be invoked to eliminate specific possibilities, particularly Q = M2, and D + Q = E1 + M2 when δ is known. If known values of $J\pi$ are used to establish any part of the character of a gamma, that part should be placed in parentheses. Remember that one of the implied uses of a non-parenthesized multipolarity is as a strong argument to assign $J\pi$ values, so one must avoid circularity.

Note 2: If any multipolarity = D, D + Q, etc. can be assigned as M1, M1 + E2, etc., only by the use of level scheme arguments, the designation mult = D should be retained in the source data set unless the complete designation (mult = (MI)) is needed to determine α.

The mult = (M1) assignment can be adopted when choosing the multipolarity for the adopted γs section. The main advantage in following this procedure (other than such assumptions should be made onlv when necessary) is that a transition known to have mult = D (strong assignment) may be more useful in defining a Jπ value than having only the parenthesized mult = (M1) (weak assignment). When such an argument is used, the reference for the multipolarity should be to the source data set, and not to adopted γs if the adopted value is mult = (M1).

3. Entries in the multipolarity, δ and α fields should be mutually consistent, and the following guidelines should be followed.

(a) If a single multipolarity is adopted, the δ field should be blank.

(b) If only a limit on δ is available and this limit is significant and worth giving, there are two options.

(i) Give the dominant multipolarity with corresponding α, and give the δ limit in a comment.

(ii) Give both multipolarities and the δ limit in the δ field. The value of α should correspond to 1/2δ(max), with an uncertainty chosen to overlap the 0 to δ(max) range.

Note: Option (i) is recommended when (in the evaluator's judgement) the admixed component is likely to be smaller than the experimental limit; thus, E2 + M3 with δ < 0.5 should probably be entered as E2, while M1 + E2 with δ < 0.5 should probably be retained as a mixed multipolarity entry.

(c) If two multipolarities are given but no δ is known, the corresponding α value should be the value calculated as described in 7(a), below.

(d) If the multipolarity field contains more than two multipolarities (e.g. E0 + M1 + E2), the E2/M1 or E2/E0 etc., mixing ratios should be given if known on a continuation record rather than in the δ field.

(e) If δ overlaps zero or infinity, the corresponding multipolarity component should be in parentheses. For δ values with experimental limits that do not overlap zero or infinity, the evaluator may still choose to adopt the corresponding component in parentheses if the difference from zero or infinity is not felt to be significant (equivalent to interpreting the author's uncertainty as being somewhat larger than quoted).

4. The mixing ratio notation (M1 + x%E2) used occasionally by authors should be converted to δ.

5. Mult = M1, E2 is not equivalent to mult = M1 + E2. The first designation refers to the case where the experimental data overlap the theoretical values for both multipolarities. The second designation refers to the situation where the experimental data lie between the theoretical values for the two multipolarities. The designation M1(+E2) is an intermediate case where the experimental data overlap M1, but not E2 values.

6. If αk, etc. data or conclusions from such data are included, the bases for the adopted values should be given. Thus, the basis for the normalization of the relative scales should be stated for relative I(ce) and Iγ, and the multipolarity for any transition used in this scale normalization should be independently established.

7. When internal conversion is significant but the multipolarity is unknown (apart from level scheme considerations) and TI is otherwise unobtainable and required, the following procedures can be followed.

(a) If ΔJ, $\Delta\pi$ are known, one can enter mult = [M1], [E1 + M2], etc., in the multipolarity field and choose α accordingly. For example if mult = [M1 + E2], one should enter $\alpha = 1/2[\alpha(M1) + \alpha(E2)]$ and $\Delta\alpha = |\alpha-\alpha(M1)| - |\alpha - \alpha(E2)|$.

(b) If ΔJ and/or $\Delta\pi$ are not known, one can still follow the procedure described in (a) and set mult = [D, E2] (or mult = [E1, M1, E2]). Mult = M2 or higher are assumed to be less probable, but can be included.

The usefulness of either (a) or (b) depends on the range of α values for the possible multipolarities.

> Note 1: If $\Delta J = 1$, $\Delta\pi$ = no, mult = [M1 + E2] should be adopted rather than mult = [M1] or mult = [E2] , unless there are good arguments for believing that one of the two possible multipole components dominates. Thus, α from M1 + E2 is always "correct" even with a large uncertainty, whereas α(M1) may lead to misleading conclusions. The possible large uncertainty in α for M1 + E2 when δ is not known reflects the correct state of knowledge concerning the total intensities.
>
> Note 2: The use of the mult = [ ] convention should be restricted to cases in which the internal conversion is significant. Do not assign mult = [ ] simply because the mult can be deduced from the level scheme; see also F. 5. in GUIDELINES FOR ADOPTED LEVELS, below.

8. Experimental αk, etc., and ce ratios that are used to determine multipolarities can be given at the evaluator's discretion; however, values measured with a precision of better than approximately 3% should be given, as well as values for transitions within 2 keV of the binding energy (and thus outside the range of values given by Band and Raman or Hager and Seltzer). Except in these cases, the evaluator should state that "Mult and δ are from αk(exp) calculated from relative Iγ, and I(ce) normalized so that ..."; also important to point out when conversion electron intensity ratios rather than just αk have been used, since αk data alone do not always uniquely define a single multipolarity or combination of multipolarities. The references used as sources for the I(ce) data must be given, either in the footnote explaining the source for the multipolarity and δ, or in the general comments.

9. Note the distinction between ( ) and [ ] for multipolarities. These are discussed in the introductory section. Parentheses are used when there are some experimental data, but the data are not conclusive. The square brackets are used to denote a value deduced solely from level scheme considerations. Note that for the case where $\gamma(\theta)$ determines mult = D + Q and the level scheme is used to assign M1 + E2 rather than E1 + M2, the multipolarity should be in parentheses, mult = (M1 + E2), with a comment stating that "mult: D + Q from $\gamma(\theta)$ in ... $\Delta\pi$ = no from the level scheme". Square brackets are not appropriate for this case, since the level scheme argument forms only part of the assignment.

10. Do not define α with a lower limit; Iγ(1 + α) could then appear incorrectly as a lower limit whereas there must be an upper bound. The situation arises almost exclusively in connection with transitions that have an E0 component in their multipolarity. Basic data are usually measured I(cek) and an upper limit on Iγ which leads to TI = I(ce) + < Iγ, where I(ce) = Σ_i(cei), i.e., TI has an upper bound. This situation is best addressed by giving I(cek) in a comment, along with the Iγ limit in the RI field. TI should be also be defined, and αk can be given in a comment. Only TI = I(ce) will be given for a transition adopted as pure E0.

Note: Recommended procedure for obtaining TI will depend on the relative magnitude of I(ce) and the limit of Iγ . The most useful quantity to quote for I(ce) >> Iγ is TI = I(ce) ± 1/2Iγ, with an uncertainty calculated in the usual way from ΔI(ce) and ΔIγ = 1/2Iγ; TI < [Iγ + I(ce)] is an appropriate choice for I1 >> I(ce); the first alternative is recommended for the intermediate case.

K. g Factors, μ, Q

Values of μ should be taken from 78LeZA/2001StZZ where possible and entered directly into adopted levels. The μ values, or the corresponding values of the g factor, do not need to be repeated in the source data set. However, when the value of T1/2 used in 78LeZA is different from your adopted value, the value of μ should be corrected for this difference if possible. A comment should be included if not readily corrected, giving the T1/2 value to which μ in 78LeZA corresponds.

More recent g-factor data should be given in the appropriate source data sets with the corresponding value of μ given in adopted levels (based on the adopted g factor). These values should be corrected for the adopted T1/2 where necessary. When corrected, adopt a comment such as "g: For T1/2=... The authors report g=... for T1/2=... ". A comment is also required stating whether or not the diamagnetic and Knight-shift corrections have been applied (if the data are accurate enough to be affected by these corrections); this comment should be given in both the source data sets and adopted levels.

Similarly, Q values should be taken from 78LeZA/200StZZ where possible, and quoted in adopted levels. More recent values should be given in the appropriate source data sets, with the adopted value also given in adopted levels. A comment should be given stating whether or not the Sternheimer correction (or some other polarization correction) has been applied, if the accuracy of the measured value warrants such a correction.

GUIDELINES FOR ADOPTED LEVELS, GAMMAS DATA SETS

A. General

1. All distinct levels that are observed in any of the individual data sets and the evaluator feels are firmly established should be included in adopted levels. Uncertain levels (shown with "?" in one or more of the individual data sets) can be included or not included at the evaluator's discretion. Isobaric analog states (resonances) should be included; neutron and proton separation energies should not be included.

Note 1: The calibration and general trend of energies compared with adopted values should be checked for each data set to avoid the introduction of "extraneous" levels. Corrections should be made for systematic shifts of energies in one or more data sets when the energies from such data sets are used to obtain the adopted value:

(a) to avoid the assignment of level "a" in one reaction as corresponding to level "b" in another reaction based only on the energy difference, and

(b) to ensure that the energy adopted for level "a", if seen in only one reaction, is as correct as possible.

Note 2: When levels from two (or more) reactions lie close in energy (values agree within the uncertainties) and the evaluator chooses to adopt both (or all) levels, the justification

for assuming that the levels are distinct should be given, unless obvious from XREF or other adopted level properties.

Consider the following cases:

E = 5000 10, Jπ = 3/2+ and E = 5010 10, Jπ = 5/2+ are known from reactions, and E = 5005.3 2 is known from a gamma reaction; however, there is considerable uncertainty as to which of the two reaction levels this level corresponds, and there is no evidence to suggest that the gamma-reaction level is a separate and distinct level. The reaction levels should be adopted, with a comment on each stating that probably the more accurate value of 5005.3 corresponds to one of the two adopted levels. There is no unambiguous way to include the accurate energy as an adopted energy. The evaluator should not adopt three levels, unless there is definite evidence that the gamma-deduced level is distinct from the others.

E-596.7 5 with Jπ = 0+, 1, 2 and E-597.1 3 with Jπ = l+, 2, 3 are known to be different levels, and l(p, d) = 2, leading to Jπ = l-, 2-, 3- with E = 598 2 is also known. Unless there is evidence to suggest that the (p, d) level is distinct, just two levels should be adopted, with a comment on each stating that l(p, d) = 2, Jπ = l-, 2-, 3- for one or both of the levels.

2. Do not unnecessarily adopt values different from those that appear in the literature when the differences are small relative to the quoted uncertainty, and if the literature value has been widely quoted in other sources.

Note: Consider a situation in which an author recommends T1/2 = 6.54 s 22 as an average from several determinations, and this value has subsequently been used by other researchers. The evaluator determines that the value should be 6.56 s 20. Such a small difference does not merit the introduction of a different recommended value into the literature. The slight error in the recommended value should be noted - this warning would be useful in case someone recomputes a recommended value on the basis of some new values, and relies on the earlier quoted recommendation as a single input value representing the old data.

3. Make use of the XREF entries so that unnecessary comments can be avoided. For example, a comment such as "seen only in (d, p)" is not needed since XREF should already convey that information. However, an exception could arise if the evaluator wishes to emphasize some doubt about the level. XREF can also convey "one level corresponds to many levels", so that comments that convey only this information are not needed. However, comments are still needed such as "L(d, p) = l for E = 3450" for two or more adopted levels to which the (d, p) level could correspond.

4. Important comments on level properties which appear in source data sets should be repeated in the adopted levels data sets - "doublet", "possible contaminant", "not resolved from X" are usually just as important in adopted levels.

5. If the evaluator adopts a Q value (Q^-) that is different from the value given in the most recent mass adjustment, the mass adjustment value should be given in a comment for comparison. Furthermore, when the mass links are not too complicated, the other entries on the Q record could be adjusted to reflect the change in Q^- value. Under such circumstances, and if the change in Q^- is significant (considerably outside the limits given by the mass adjustment), listings of the adjusted S(n), S(p), and Q(α) values would represent a valuable contribution. However, the inclusion of these data is left to the discretion of the evaluator.

Note: When a re-adjustment is not feasible, a comparison between the mass adjustment value and the adopted value allows the reader to judge qualitatively what the effect on the other Q values might be.

6. All available first-card data should be included for gamma records; however, continuation-record data generated from the HSICC program are not required.

7. Since the data in adopted levels, gammas are the evaluator's recommended values, discrepant data should not be adopted.

Note 1: If a gamma multipolarity disagrees with the adopted Jπ, and Jπ are considered to be well established, the discrepant multipolarity should not be adopted. The discrepancy should be noted in a comment, and a flagged comment should be used so that a footnote symbol appears in the multipolarity field.

Note 2: Since BE2 and T1/2 are equivalent data (if all quantities needed to convert from one to the other are known) and T1/2 is more basic, adopted values for both quantities should not be shown for the same level. The adopted T1/2 will normally be based on all of the available data, including any reliable BE2 measurements. By definition, the best BE2 value will be that deduced from this adopted T1/2 value and the adopted branchings, Q etc. If T1/2 comes from BE2, quoting both values is a redundant exercise; if T1/2 does not come solely from BE2, quoting both T1/2 and BE2 is essentially adopting two different values for the same quantity. A BE2 or BE3, etc. value is best adopted if T1/2 is not known and cannot be calculated from these same BE2 or BE3 etc. values.

B. E(level)

The introductory section to Nuclear Data Sheets includes the statement "The excitation energies for levels connected by gamma transitions are taken from a least-squares fit to the adopted gamma energies. Other excitation energies are based on best values from all available reactions". No further comment is needed for any adopted levels section for which this statement is appropriate. When this statement may not be appropriate, the evaluator should add a comment explaining the source for the excitation energies.

Uncertainties should be included where available, and should be estimated if the authors do not provide them (see D. 1. under GUIDELINES FOR DECAY AND REACTION DATA SETS).

C. Jπ

1. Assignments should be based on the fewest and best arguments. There are two main advantages to this "fewest and best" approach:

(a) Jπ arguments are easier to read and follow when redundancy is eliminated,

(b) alternate arguments can be used to build up systematics.

For example, consider the assignment of 1+ to a level based on the arguments "Ml γ to 0+. Logft = 4.4 from 0+". Either argument alone is sufficient: if the multipolarity argument is used, the logft value can be combined with the values from which the logft arguments are derived, thus helping to build up confidence in the application of such systematics to cases where other strong arguments are not available.

Note: The above approach refers to strong arguments. When only weak arguments are available, the more arguments that can be marshalled, the more valid the assignment. However, no combination of weak arguments constitutes a strong argument.

2. "Direct" measurements of J (e.g., atomic beam) should be referenced as 76Fu06. More recent values should be referenced directly. The method should be stated in either case, thus "atomic beam", "NMR". These methods give J only; a separate argument is required for π.

3. Arguments should be detailed enough to convince the reader that the assignments are reliable, and allow judgement to be made as what the consequences would be if new data were to become available.

(a) The argument "From (α, xnγ)" is not much use, especially if the (α, xnγ) data set contains no details. Statements such as "Excit. in ((α, xnγ)", "γ(θ) in (α, xnγ)" are needed. If such arguments appear frequently, they can be included in a flagged comment on Jπ such as "From (α, xnγ) based on...", or "Member of band X based on energy fit and inertial parameter". An alternative method is to write a Jπ footnote which states "Assignments from (α, xnγ) are based on excit. and 1(0). Assignments from (d, p) are based on L values and analyzing powers. etc". The Jπ argument can then be simply "From (α, xnγ)", "From (d, p)", etc. for the relevant levels. This approach is particularly useful when the arguments are somewhat lengthy.

(b) Gamma-decay arguments should be specific: thus "Ml γ to 2+", "γs to 3/2+, 5/2+", while the gamma energy is optional: thus "326γ to 2+ is Ml". A vague statement such as "JP is based on 'γ-decay modes" is not much use to the reader.

An argument for Jπ = 2-, 3- could be expressed as "L(d, p) = l gives 0- to 3-. γ to 4-". If the γ transition were to be subsequently determined as Ml, the reader can quickly determine that Jπ would be 3-. If the argument had only been given as a general statement such as "From L values in (d, p) and γ feedings", the consequences of the new piece of evidence would not be so transparent.

Note that Jπ values and γ-ray multipolarities referred to in these comments should be adopted values: "Ml γ to (3/2+)", "(E2) γ to (4)-".

Give Jπ(parent, target) in the specific Jπ arguments when the target is not even-even; for example, "logft = 5.4 from 1/2+", or "L(p, t) = 2 from 9/2+".

4. Jπ arguments for two or more levels can be linked if they are interconnected in such a way that giving separate arguments for each level can be awkward, or can give the appearance of circularity. As an example, consider the sequence 7-(β-)A(Ml)B(El)C(E2)2+: the argument "Logft = 5.1 from 7- and the Ml-El-E2 cascade to 2+ uniquely establishes Jπ(A) = 6-, Jπ(B) = 5- and Jπ(C) = 4+" can be given for one of the relevant levels (say C), and then one can say "Jπ: See C level" for the others.

5. Consider an L = 0 component in a particle-transfer reaction in which S = 0 can be assumed: leads to ΔJ-0, Δπ = no, even if other L components are present, and the same is true of an E0 component in a gamma transition. A level connected via an Ml + E2 γ to a level with J = l/2 must have J = 3/2.

6. Jπ arguments for the ground state of an even-even nucleus are not needed. For example, L(p, t) = 0 gives only ΔJ = 0 and relies on the assumption of J = 0 for the even-even target nucleus. The absence of hyperfine structure is also not conclusive, since a small μ or Q value can lead to the same result.

7. Maintain consistency between the source data and the conclusions. For example, L(p, t) = 2 (S = 0 assumed) from an even-even target gives Jπ = 2+, not (2)+ or 2(+); if the L value is considered to be a strong argument for J, this same argument applies to π. Similarly, if the argument is not considered to be strong for J, such an argument should not be considered strong for π; thus, L(p, t) = (2) gives Jπ = (2+).

> Note: A reaction such as (Q, d) with a measured L value can be used as a strong argument for π, namely, $\pi = (-)^L$, even though J is determined only as J = L-l, L, or L+l.

8. Expressions such as "preferred" or "consistent with" are not strong arguments. Avoid these expressions since they leave open the question of whether other alternative Jπ values have been ruled out; however, such expressions are valid for weak arguments.

9. Configurations

"Conf = 3/2[521]" is not a valid argument for Jπ; this argument only shifts the burden of proof from establishing Jπ = 3/2- to establishing conf = 3/2[521]. The configuration is normally deduced from Jπ, not vice-versa, although sometimes the reverse is true and the same argument for Jπ can be used to assign the configuration (sometimes a measured μ will also determine a specific configuration).

Knowledge of L and the analyzing power in a transfer reaction may give Jπ = 1/2- (and assign this level as a pl/2 orbital), but the Jπ argument should be "From L and analyzing power in (d, p)", not "From conf = pl/2". The configuration should be treated as a separate data type from Jπ, and be placed on a continuation record. Comments on "Conf" should normally be treated as distinct from comments on Jπ.

> Usually in the deformed regions, the cross sections and cross section ratios (e.g., (d, p) and (d, t) reactions) determine directly the combination JπK[ ], rather than Jπ (such as 5/2- 3/2[521]) or just Jπ = 5/2- alone. Under such circumstances, the configuration must be included in the Jπ argument.

10. Do not use multiply-placed transitions in Jπ arguments unless the connection with the level in question is definite.

> Note: A multipolarity determined for a multiplet will not necessarily be the correct multipolarity for each member of the multiplet (see B. 6. (d)) under GUIDELINES FOR DECAY AND REACTION DATA SETS). If part of the multiplet is definitely established as being connected with the level in question, Jπ of the connected level can be used as a Jπ argument in the usual way, (e.g., "γ to 3/2+").

11. When choices of Jπ are limited to three or fewer, they should be clearly specified rather than given as a range; thus Jπ = 5/2-, 7/2-, 9/2- rather than Jπ = 5/2- to 7/2-. There is less chance of values being misinterpreted when they are written out completely, and the extra space required is not significant (which is the only good argument for quoting Jπ values as a range).

12. RUL is an argument for multipolarity, not for Jπ.

13. Note the difference between "Jπ = 5/2+ and 7/2-" (or 5/2+&7/2-) and "Jπ = 5/2+, 7/2-". The first notation indicates the presence of two unresolved levels with Jπ = 5/2+ and 7/2-, respectively; while the second notation indicates two alternate Jπ values for a single level.

D. Other Level Properties

1. Cross referencing of data should give the data set, and not just the keynumber, because the data sources are much easier to locate with this information. The method and keynumber are optional except in the following cases where this information is needed.

(a) μ, Q etc., values for stable or long-lived states should be taken from 78LeZA where possible. The method should be given since these data will normally not appear anywhere else in the mass chain. More recent data can be quoted directly, along with the method and keynumber. For values of μ not taken from 78LeZA and when warranted by the accuracy, a comment stating whether or not the diamagnetic and Knight-shift corrections have been applied should be included. Similarly for Q values, a comment should be given stating whether or not the Sternheimer correction (or other polarization correction) has been applied.

b) If T1/2 is obtained from BE2, this fact should be stated: "T1/2: From BE2 in Coul. ex.".

2. "g factor" quoted in a source data set should be converted to "μ" in adopted levels if J is known.

3. When branching modes are given (e.g., "%IT="), the bases for the values can be given here or in the source data sets. There is no need to repeat the arguments, but they must appear in one place or the other. Also, all possible modes of decay should be accounted for, unless the reason for omitting a mode is obvious.

> Note: Where "%ε+%β+ = 99.0 1; %IT = l.0 l" exists but β^- is also energetically allowed, there should be a comment explaining why the β^- branch is considered negligible; for example, "%β^- is negligible since the only available decay branch has $\Delta J = 2$, $\Delta\pi$ = yes, for which, from logflut>8.5, one derives %β-<lxl0^{-4}". An experimentally determined limit of this magnitude should be included explicitly in the branching statement. One can state simply "$\Delta J = 4$ for possible β^- branch so %β^- is negligible" for more obviously negligible branches such as where the only available branch has $\Delta J = 4$.

4. BEλ values should be included in adopted levels where T1/2 is not independently known and cannot be calculated from BEλ.

E. Eγ, Iγ, TI

1. Sources of data should be stated unless obvious (i.e., if there is only one or possibly two sources (small mass chain)). General comments are usually sufficient; thus, "From X unless noted otherwise" or "Weighted average of values from A, B, and C".

2. The introductory section to Nuclear Data Sheets includes the explanation that I_γ are "photon branchings (normalized to 100 for the most intense transition from each level)". An uncertainty should be included in the value "l00" if there is an uncertainty given for the original intensity; however, when there is only one transition de-exciting the level, the uncertainty has no meaning and should not be given. Any major deviation from this policy should be stated, such as quoting branching ratios in %. There are some situations in which this policy should not be followed (i.e., where a transition other than the strongest should be chosen and for which no explanation is needed):

(a) strongest transition is an unresolved multiplet;

(b) strongest transition is given as an upper limit.

Note: Iγ for multiply-placed transitions where the intensity has not been divided should be given as limits (Iγ < A + ΔA if Iγ = A ± ΔA), with "&" in column 77.

3. Where possible, TI should be given for transitions that have no measured Iγ, or for which only a limit on Iγ is available. The most common cases would be for E0 transitions or low-energy transitions when I(ce) but no Iγ (or α) are available; see Note under J. 10. in GUIDELINES FOR DECAY AND REACTION DATA SETS .

Note: When TI is the "measured" quantity from an intensity balance and α is known so that Iγ can be determined, TI as well as Iγ should be given if known more accurately than TI calculated from Iγ(1+α). This approach allows the most accurate branching ratios to be obtained for the transitions from the level in question.

F. Mult, δ, α

1. Data sources should be stated unless obvious. The introductory section states that the α values are theoretically determined on the basis of the given multipolarity and δ. Origins of any α value which is not based on this procedure should be explained in a comment. Sources for multipolarity and δ can usually be quite general: "Mult are based on αk and subshell measurements in and γγ(θ) data in ...". When multipolarities are based on measurements that yield only L, such as γ(θ) or γγ(θ), and M1 + E2 is adopted rather than El + M2, the basis for this choice must be stated.

2. See J. 3. in GUIDELINES FOR DECAY AND REACTION DATA SETS for requirements on consistency among the multipolarity, δ and α entries. α is not needed for transitions with mixed multipolarity and unknown δ, even though such values may have been used in a data source.

3. The relationship between BE2 and T1/2 allows δ (and/or α) to be deduced in cases where BE2 and T1/2 are independently known, and the ground-state branch is known (ground-state branch could be deduced if all other quantities are known).

4. γ(θ) and γγ(θ) normally lead to two solutions for δ, and both should be noted. In particular, both should be placed in a comment if the correct one is not known; do not adopt one value in the δ field and the alternate value in a comment.

5. As well as using [ ] to indicate multipolarities deduced solely on the basis of the level scheme for transitions for which you want to list α, this convention may also be adopted in cases where α is negligible, but you wish to show the multipolarity because you are recommending a reduced transition probability. However, as noted earlier, do not assign mult=[ ] simply because the multipolarity can be deduced from the level scheme.

G. Reduced Transition Probabilities

Reduced transition probabilities are required whenever calculable, i.e., when T1/2, branching, multipolarity and δ are known. Values for both multipole components should be given for mixed transitions.

Note 1: When δ is consistent with zero or infinity, the reduced transition probability for only the dominant component is required. The limit for the other component is optional and can be given in certain cases: BE2(W.u.) < l000 is not of interest, but BE2(W.u.) < $l0^{-3}$ might be significant.

Note 2: Values should be given for transitions that have not been experimentally characterized, but can be determined from the level scheme as $\Delta J = l$, $\Delta\pi$ = yes; $\Delta J = 2$, $\Delta\pi$ = no, or $\Delta J \geq 3$ (i.e., cases where significant mixing is not expected).

Note 3: When one or more of the relevant pieces of information required to calculate reduced transition probabilities is/are missing, the calculation should be carried out if reasonable assumptions can be made that fill the gaps. For example, a branch with a small gamma fraction of known multipolarity should be estimated (if the multipolarity would lead to a relatively small total branch) so that reduced transition probabilities for the other branches can be calculated.

Note 4: When only limits are available for some of the relevant data, special care must be taken.
(a) Transition with mult = Ml + E2 and $\delta < 0.l$: while BE2(W.u.) can only be given as an upper limit, assigning BM1(W.u.) as a lower limit would be incorrect since an upper bound occurs for $\delta = 0$. BM1(W.u.) should be given as an average of the values corresponding to $\delta = 0$ and $\delta = 0.l$, with an uncertainty chosen to overlap the two values.
(b) Consider a transition with a total intensity known only as an upper limit: provided that this intensity limit is not the dominant branching mode, the branch for this transition should be treated as $1/2TI \pm 1/2TI$ for the purpose of calculating the reduced transition probabilities for the other transitions.
(c) When T1/2 is only available as an upper limit, the resulting lower limits on the reduced transition probabilities should be given. When T1/2 is a lower limit, the resulting upper limits on the reduced transition probabilities are not of much interest, except perhaps as stated in Note 1, above.

Note 5: Consider the reduced transition probability of a transition for which the corresponding Coulomb excitation probability has been determined (BE2 being the most common case): this parameter can be deduced directly from the measurement and appropriate single particle value. This procedure should be followed when the level T1/2 has been adopted from a measured BE2 (to avoid including the uncertainty in BE2 twice), or where BE2 is known but branches and/or mixing ratios are not known so that T1/2 for the corresponding level cannot be calculated.

Note 6: When $E\gamma$ is poorly known, the factor $E\gamma^{2L+l}x(l + \alpha)$ appearing in the formula for the reduced transition probabilities may exhibit a smaller range of values than the factors $E\gamma^{2L+l}$ and $(l + \alpha)$ taken separately. The correlation in $E\gamma$ and α should always be taken into account when calculating uncertainties for BEλ(W.u.) and BMλ(W.u.).

Note 7: BEλ(W.u.) and BMλ(W.u.) are not needed for mixed multipolarities when δ is not known. However, if an evaluator chooses, these parameters can be given as upper limits.

14.

DRAFT

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NUCLEAR STRUCTURE AND DECAY DATA: INTRODUCTION TO RELEVANT WEB PAGES

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Summary

A brief description is given of the nuclear data centres around the world able to provide access to those databases and programs of highest relevance to nuclear structure and decay data specialists. A number of Web-page addresses are also provided for the reader to inspect and investigate these data and codes for study, evaluation and calculation. These instructions are not meant to be comprehensive, but should provide the reader with a reasonable means of electronic access to the most important data sets and programs.

1. Introduction

A network of international/national nuclear data centres constitutes the infrastructure for the provision of a wide range of atomic and nuclear data services to scientists worldwide (Table 1). More than 100 data libraries are readily available cost-free from these centres through the Internet, CD-ROM and other media.

Two nuclear data centres of particular note are the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory and the Nuclear Data Section at the International Atomic Energy Agency (IAEA-NDS) in Vienna, Austria. Access to the most relevant databases and associated codes through their web addresses are described below (both main directional web pages are shown in the Annex):

National Nuclear Data Center, Brookhaven - *http://www.nndc.bnl.gov/*

IAEA Nuclear Data Section - *http://www-nds.iaea.org*/

and IAEA-NDS mirror sites at IPEN, Brazil, *http://www-nds.ipen.br/*
and BARC, Mumbai, India, *http://www-nds.indcentre.org.in/*
that are maintained by NDS staff.

All libraries and related documentation held by the Nuclear Data Section are available free of charge to scientists in IAEA Member States. Overviews are given by Schwerer and Obložinský (2001) and in the document *Index of Nuclear Data Libraries Available from the* IAEA *Nuclear Data Section* (Schwerer, 2007) – also available on:

http://www-nds.iaea.org/reports/nds-7.pdf to download as PDF file.

Brief descriptions of the contents and format of most libraries are published in the IAEA-NDS-report series (Schwerer and Lemmel, 2007), while an introduction to NDS database projects and services can be found at *http://www-naweb.iaea.org/napc/nd/index.asp*

2. Nuclear Structure and Decay Data Evaluators' Network

A network of centres has been established that specializes in nuclear structure and decay data (Pronyaev *et al.*, 2004); see also Table 2 for a list and access addresses through the Web and e-mail contacts. These laboratories and institutes are involved in all facets of compilation and production of recommended nuclear structure and decay data (*i.e.*, review, evaluation and processing), sharing the evaluation work by mass chain, and meeting biennially to discuss their common problems and interests under the auspices of the IAEA Nuclear Data Section.

3. World Wide Web (WWW)

The web page of the IAEA Nuclear Data Services can be found at the web addresses http://www-nds.iaea.org/ (IAEA, Vienna, Austria), http://www-nds.ipen.br/ (IPEN, Brazil), and http://www-nds.indcentre.org.in/ at BARC, India; the equivalent web page for NNDC is http://www.nndc.bnl.gov/. These pages contain interactive access to the major databases, as well as overviews of all nuclear data libraries and databases available from the IAEA *(IAEA Nuclear Data Guide)* and NNDC, and access to various reports, manuals, nuclear data utility programs, Nuclear Data Newsletters and other informative documentation.

The web addresses specified above provide links with the following highly relevant databases (see also Section 4):

- ENSDF - evaluated nuclear structure and decay data (http://www.nndc.bnl.gov/ensdf/)
- MIRD - medical internal radiation dose tables (http://www.nndc.bnl.gov/mird/)
- Wallet cards - Ground and metastable state properties (http://www.nndc.bnl.gov/wallet/)
- NUDAT - selected evaluated nuclear data (http://www.nndc.bnl.gov/nudat2/)
- NSR - Nuclear Science References (http://www.nndc.bnl.gov/nsr/)
- Masses - Atomic Mass Evaluation Data File (http://www.nndc.bnl.gov/amdc/)

For example, NSR bibliographic information can be explored through:

- Known author name,
- Keynumber (*e.g.,* 1970Ya02 consists of the first two letters of the lead author (Ya (of Yamazaki)), year (1970), and number designation (02)); also to be found in *Recent References, Nuclear Data Sheets*, although curtailed since early 2004; *Recent References* are also available as PDF files – see http://www.nndc.bnl.gov/nsr/recref.html),
- Nuclide,

as well as through other criteria.

The reader is encouraged to access all of these databases, codes and information manuals through an explorative process, and assess their user-friendliness and usefulness. Your feedback is also welcome, and would help us to improve our web services.

4. Access to Relevant Databases and Programs

The data in some of the nuclear structure databases have been evaluated and assembled through the combined efforts of specialists within the international nuclear structure and decay-data evaluators' network (Section 2), while others are effectively more user-friendly derivatives and subsets of these same data files (*e.g.*, Nuclear Wallet Cards and NuDat).

4.1 Primary databases

NSR: Nuclear Science References is a bibliographic database for low and intermediate energy nuclear physics and available on-line
(see http://www-nds.iaea.org/nsr/ and http://www.nndc.bnl.gov/nsr/).

ENSDF: Evaluated Nuclear Structure Data File is the 'master' library for nuclear structure and decay data maintained through the evaluators' network co-ordinated by the IAEA (see Section 2), and containing evaluated experimental data for most known nuclides in the mass range from 1 to 294; published in *Nuclear Data Sheets* (Tuli, 2008) and *Nuclear Physics A* (Bakker, 2008) and available on-line (see http://www.nndc.bnl.gov/ensdf/).

4.2 Other specialised and derived databases

Atomic masses 2003 (Wapstra *et al.*, 2003): mass evaluations for over 2900 nuclides; available on-line (see both http://www-nds.iaea.org/masses/ and http://www.nndc.bnl.gov/masses/).

Nuclear Wallet Cards (Tuli, 2005): basic properties of ground and metastable states; available as pocket book and on-line (see http://www.nndc.bnl.gov/wallet/). The NNDC site also contains Nuclear Wallet Cards for Radioactive Nuclides (Tuli, 2004), available as a pocket book and online, and Palm Pilot versions of both books.

NuDat: Nuclear Data contains user-friendly extracts of applications data from ENSDF and the Nuclear Wallet Cards, plus thermal neutron data; available on-line (see http://www.nndc.bnl.gov/nudat/).

MIRD: Medical Internal Radiation Dose is based on ENSDF and data processed by RADLST to generate, for example, tables of energies and intensities for X-rays and Auger electrons (Burrows, 1988); available on-line (see http://www.nndc.bnl.gov/mird/).

Reduced Transitional Probabilities: Electric quadrupole transition probabilities for the ground to first 2+ state of even-even nuclides extracted from the evaluation of Raman *et al.* (2001) (see http://www.nndc.bnl.gov/be2/).

Double Beta Decay: Set of double beta (ββ) decay data based on experimentally observed double beta (ββ) decay transitions in ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128,130}Te, ^{130}Ba, ^{150}Nd and ^{238}U (see http://www.nndc.bnl.gov/bbdecay/)

XUNDL: eXperimental Unevaluated Nuclear Data Library is a compilation of experimental nuclear structure and decay data in ENSDF format – oriented primarily to high-spin data, but also contains some reaction and decay data (see http://www.nndc.bnl.gov/ensdf/).

4.3 Programs

Useful computer codes for the calculation of specific nuclear structure and decay data parameters include the following:

BrIcc: calculates internal conversion electron coefficients based on the "frozen orbitals" approximation (Band *et al.*, 2002 and Raman *et al.*, 2002), internal electron-positron pair formation coefficients based on Schlüter and Soff (1979), and Hoffman and Soff (1996), and E0 electronic factors based on Hager and Seltzer (1969), Bell *et al.* (1970), and Passoja and Salonen (1986);

GABS: calculates absolute γ-ray intensities;

GTOL: undertakes least-squares fits to γ-ray energies and calculates net feeding to nuclear levels;
LOGFT: calculates *log ft* values for β and electron-capture decay, average $\beta^{\pm}$ energies and capture fractions based on Gove and Martin (1971);
PANDORA: checks "correctness" of the physics in ENSDF;
and others are available through the NNDC web page:
http://www.nndc.bnl.gov/nndcscr/ensdf_pgm/.

4.4 Interactive calculational tools

Users can perform calculations interactively over the web by means of four processing tools:

Nuclear Structure Calculational Tools:

- BrIcc: calculates internal conversion electron coefficients based on the "Frozen orbitals" approximation (Band *et al.*, 2002 and Raman *et al.*, 2002), internal electron-positron pair formation coefficients based on Schlüter and Soff (1979), and Hoffman and Soff (1996), and E0 electronic factors based on Hager and Seltzer (1969), Bell *et al.* (1970), and Passoja and Salonen (1986) (see http://www.rsphysse.anu.edu.au/nuclear/bricc/);
- HSICC: calculates internal conversion coefficients based on the theoretical values of Hager and Seltzer (1968), and Dragoun *et al.* (1969 and 1971) (see http://www.nndc.bnl.gov/hsicc/);
- LOGFT: calculates *log ft* values for β and electron-capture decay, average $\beta^{\pm}$ energies and capture fractions based on Gove and Martin (1971) (see http://www.nndc.bnl.gov/logft/).

Atomic Masses, Q-values and Threshold Energies: calculates reaction Q-values, threshold energies and decay Q-values based on the 2003 Update to the Atomic Mass Evaluation (Audi *et al.*, 2003), and retrieves other quantities contained in this evaluation (see http://www.nndc.bnl.gov/qcalc2/).

4.5 Other network web sites

Web sites of other members of the Nuclear Structure and Decay-data Network (Table 2) contain much useful information, for example:

Energy Levels of Light Nuclei, A = 3 - 20: evaluations, preprints, lists of recent references, reprints for A = 3 - 20 nuclides, and Palm Pilot applications and databases (see http://www.tunl.duke.edu/NuclData/);

jvNubase: ground and metastable state properties, based primarily on ENSDF with some additions derived from more recent data (see http://www.nndc.bnl.gov/amdc/jvnubase/Nucleus.html);

RadWare: software package for interactive graphical analysis of gamma-ray coincidence data library of level scheme files in the RadWare ASCII-gls format that have been derived from ENSDF, XUNDL and contributed level schemes (see http://radware.phy.ornl.gov/).

4.6 Nuclear structure and decay-data evaluator's corner

http://www.nndc.bnl.gov/nndc/evalcorner/ is primarily designed for ENSDF evaluators and currently contains:

- an interface to ENSDF which allows evaluators to retrieve ENSDF mass chains and nuclides in a basic format (*i.e.*, ComTrans has not been run),
- simplified NSR retrieval system designed for ENSDF evaluators,
- new ENSDF analysis and utility codes in β testing, and
- links to relevant manuals and materials from previous ENSDF or NSDD workshops.

5. Concluding Remarks

The contents of this report represent a brief introduction to the means of accessing a powerful set of compiled and evaluated nuclear structure and decay-data libraries, as well as codes for the analysis and development of such data. Useful applications of these data and tools are wide ranging, and the reader is encouraged to explore their potential through the various routes outlined above, and so develop a much greater understanding of their capabilities.

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Burrows, T.W., 1988. The Program RADLST. Brookhaven National Laboratory Report BNL-NCS-52142, February 29, 1988;
see also *http://www.nndc.bnl.gov/nndcscr/ensdf_pgm/analysis/radlst/radlstdoc.pdf*.

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Hager, R.S., Seltzer, E.C., 1968. Internal conversion tables: Part I: K-, L-, M-shell conversion coefficients for Z = 30 to Z = 103. Nucl. Data Tables **A4**, 1-235.

Hager, R.S., Seltzer, E.C., 1969. Internal conversion tables: Part III: Coefficients for the analysis of penetration effects in internal conversion and E0 internal conversion. Nucl. Data Tables, **6**, 1-127.

Hofmann, C.R., Soff, G., 1996. Total and differential conversion coefficients for the internal pair creation in extended nuclei. At. Data Nucl. Data Tables **63**, 189-273.

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see also *http://www-nds.iaea.org/nds-0.html*.

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Tuli, J.K., 2004. Nuclear Wallet Cards for Radioactive Nuclides. March 2004, National Nuclear Data Center, Brookhaven, USA; see also *http://www.nndc.bnl.gov/wallet/*.

Tuli, J.K., 2005. Nuclear Wallet Cards. 7th Edition, April 2005, National Nuclear Data Center, Brookhaven, USA; see also *http://www.nndc.bnl.gov/wallet/*.

Tuli, J.K., Editor, 2008. Nuclear Data Sheets. Academic Press, Elsevier Science, Amsterdam, the Netherlands, ISSN 0090-3752.

Wapstra, A.H., Audi, G., Thibault, C., 2003. The AME2003 atomic mass evaluation (I). Evaluation of input data, adjustment procedures. Nucl. Phys. **A729**, 129–336; Audi, G., Wapstra, A.H., Thibault, C., 2003. The AME2003 atomic mass evaluation (II). Tables, graphs and references. Nucl. Phys. **A729**, 337-676.

Table 1. Network of International/National Nuclear Data Centres.

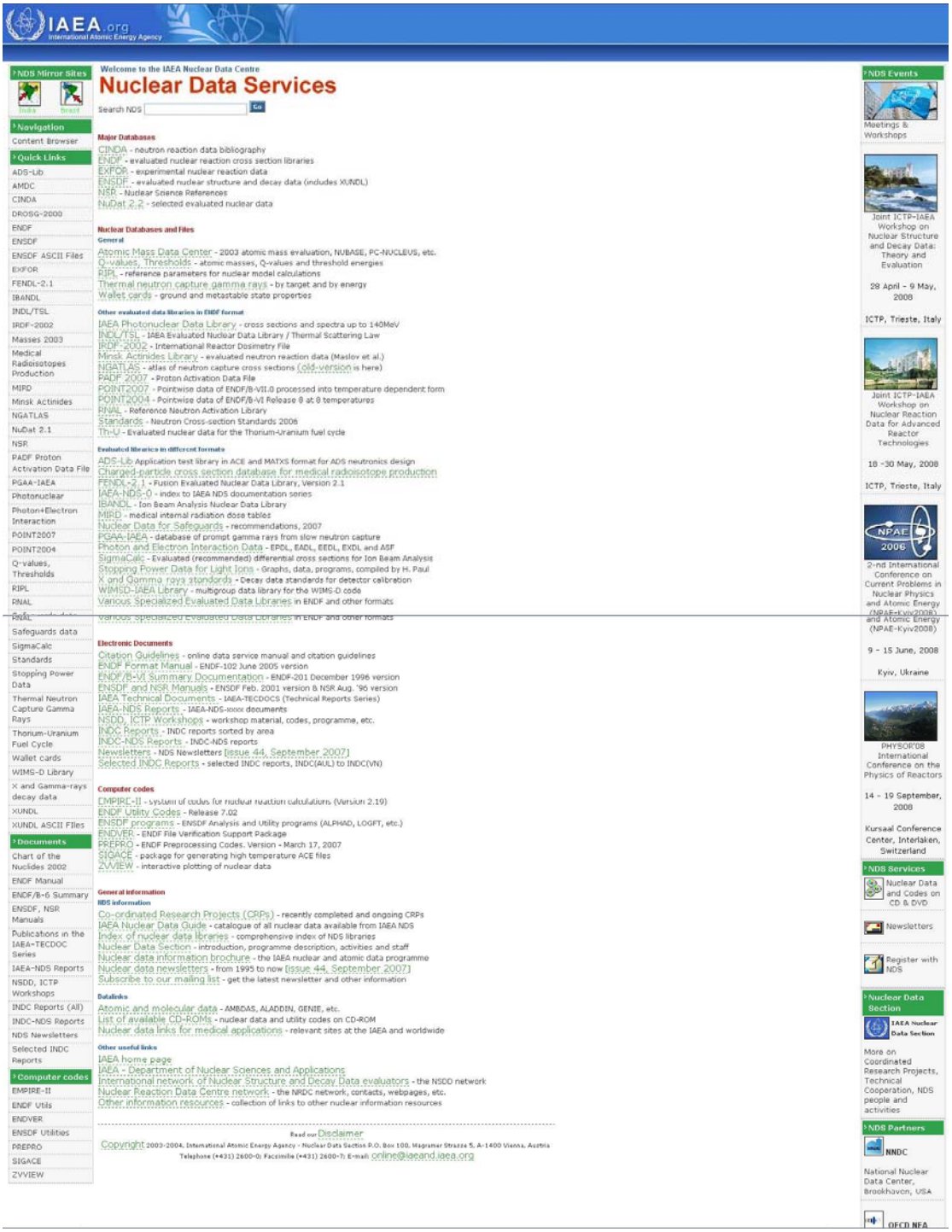
IAEA Nuclear Data Section, Vienna, Austria *http://www-nds.iaea.org/*
US National Nuclear Data Center, Brookhaven, USA *http://www.nndc.bnl.gov/*
OECD, NEA Data Bank, Paris, France *http://www.nea.fr/*
Russian Federation Nuclear Data Centre, Obninsk, Russian Federation *http://www.ippe.obninsk.ru/podr/cjd/*
9 co-operating specialised centres within: PR China, Hungary, Japan (2), Republic of Korea, Russian Federation (3) and Ukraine

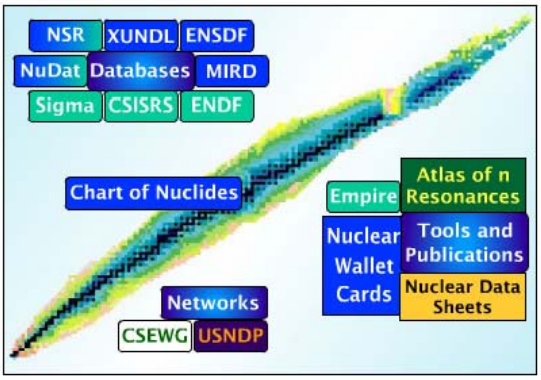
Table 2. Nuclear Structure and Decay-data Network.

US National Nuclear Data Center, Brookhaven, USA (maintenance of master ENSDF database) *http://www.nndc.bnl.gov/* Contact: J. K. Tuli (network co-ordinator) e-mail: Tuli@bnl.gov
Nuclear Data Project, Oak Ridge National Laboratory, USA *http://www.phy.ornl.gov/ndp/* Contact: M. S. Smith e-mail: MSmith@mail.phy.ORNL.gov
Isotope Project, Lawrence Berkeley National Laboratory, Berkeley, USA *http://ie.lbl.gov/* Contact: C. M. Baglin e-mail: baglin@lbl.gov
[Idaho National Laboratory, Idaho Falls, USA] Contact: C. W. Reich e-mail: cwreich@clearwire.net
Triangle University Nuclear Laboratory, Department of Physics, Duke University, USA *http://www.tunl.duke.edu/NuclData/* Contact: J. H. Kelley e-mail: kelley@tunl.duke.edu
Argonne National Laboratory, Nuclear Engineering Division, Argonne, USA http://www.td.anl.gov/NDP/ Contact: F.G. Kondev e-mail: kondev@anl.gov
Nuclear Data Centre, Petersburg Nuclear Physics Institute, Russian Federation Contact: I. A. Mitropolsky e-mail: mitrplsk@pnpi.spb.ru
Institute of Atomic Energy, Beijing, PR China Contact: Ge Zhigang e-mail: gezg@iris.ciae.ac.cn
Jilin University, Physics Department, Changchun, PR China Contact: Huo Junde e-mail: jdhuo@mail.jlu.edu.cn
Commissariat d'Énergie Atomique, Bruyères-le-Châtel, France Contact: J. Blachot e-mail: jblachot@orange.fr
JAEA Nuclear Data Centre, Tokai-Mura, Japan Contact: J. Katakura e-mail: katakura.junichi@jaea.go.jp
Nuclear Data Centre, Physics Department, Kuwait University, Kuwait Contact: A. Farhan e-mail: Ameenah@kuc01.kuniv.edu.kw
Department of Physics and Astronomy, McMaster University, Hamilton, Canada *http://physwww.physics.mcmaster.ca/~balraj/* Contact: B. Singh e-mail: ndgroup@mcmaster.ca
Department of Nuclear Physics, Australian National University, Canberra, Australia *http://wwwrsphysse.anu.edu.au/nuclear/* Contact: T. Kibédi e-mail: Tibor.Kibedi@anu.edu.au
Department of Physics , Indian Institute of Technology, Roorkee, India *http://www.iitr.ac.in/departments/PH/* Contact: A. K. Jain e-mail: ajainfph@iitr.ernet.in
IAEA Nuclear Data Section, Vienna, Austria (co-ordination of network meetings) *http://www-nds.iaea.org/* Contact: A. L. Nichols e-mail: *a.nichols@iaea.org*

ANNEX

Directional Web pages for NDS and NNDC

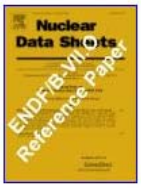

IAEA.org
International Atomic Energy Agency
NDS Mirror Sites
Index
Brazil
Navigation
Content Browser
Quick Links
ADS-Lib
AMDC
CINDA
DROSG-2000
ENDF
ENSDF
ENSDF ASCII Files
EXFOR
FENDL-2.1
IBANDL
INDL/TSL
IRDF-2002
Masses 2003
Medical Radioisotopes Production
MIRD
Minsk Actinides
NGATLAS
NuDat 2.1
NSR
PADF Proton Activation Data File
PGAA-IAEA
Photonuclear
Photon+Electron Interaction
POINT2007
POINT2004
Q-values, Thresholds
RIPL
RNAL
Safeguards data
SigmaCalc
Standards
Stopping Power Data
Thermal Neutron Capture Gamma Rays
Thorium-Uranium Fuel Cycle
Wallet cards
WIMS-D Library
X and Gamma-rays decay data
XUNDL
XUNDL ASCII Files
Documents
Chart of the Nuclides 2002
ENDF Manual
ENDF/B-6 Summary
ENSDF, NSR Manuals
Publications in the IAEA-TECDOC Series
IAEA-NDS Reports
NSDD, ICTP Workshops
INDC Reports (All)
INDC-NDS Reports
NDS Newsletters
Selected INDC Reports
Computer codes
EMPIRE-II
ENDF Utils
ENDVER
ENSDF Utilities
PREPRO
SIGACE
ZVVIEW
Welcome to the IAEA Nuclear Data Centre
Nuclear Data Services
Search NDS
Go
Major Databases
CINDA - neutron reaction data bibliography
ENDF - evaluated nuclear reaction cross section libraries
EXFOR - experimental nuclear reaction data
ENSDF - evaluated nuclear structure and decay data (includes XUNDL)
NSR - Nuclear Science References
NuDat 2.2 - selected evaluated nuclear data
Nuclear Databases and Files
General
Atomic Mass Data Center - 2003 atomic mass evaluation, NUBASE, PC-NUCLEUS, etc.
Q-values, Thresholds - atomic masses, Q-values and threshold energies
RIPL - reference parameters for nuclear model calculations
Thermal neutron capture gamma rays - by target and by energy
Wallet cards - ground and metastable state properties
Other evaluated data libraries in ENDF format
IAEA Photonuclear Data Library - cross sections and spectra up to 140MeV
INDL/TSL - IAEA Evaluated Nuclear Data Library / Thermal Scattering Law
IRDF-2002 - International Reactor Dosimetry File
Minsk Actinides Library - evaluated neutron reaction data (Maslov et al.)
NGATLAS - atlas of neutron capture cross sections (old-version is here)
PADF 2007 - Proton Activation Data File
POINT2007 - Pointwise data of ENDF/B-VII.0 processed into temperature dependent form
POINT2004 - Pointwise data of ENDF/B-VI Release 8 at 8 temperatures
RNAL - Reference Neutron Activation Library
Standards - Neutron Cross-section Standards 2006
Th-U - Evaluated nuclear data for the Thorium-Uranium fuel cycle
Evaluated libraries in different formats
ADS-Lib Application test library in ACE and MATXS format for ADS neutronics design
Charged-particle cross section database for medical radioisotope production
FENDL-2.1 - Fusion Evaluated Nuclear Data Library, Version 2.1
IAEA-NDS-0 - index to IAEA NDS documentation series
IBANDL - Ion Beam Analysis Nuclear Data Library
MIRD - medical internal radiation dose tables
Nuclear Data for Safeguards - recommendations, 2007
PGAA-IAEA - database of prompt gamma rays from slow neutron capture
Photon and Electron Interaction Data - EPDL, EADL, EEDL, EXDL and ASF
SigmaCalc - Evaluated (recommended) differential cross sections for Ion Beam Analysis
Stopping Power Data for Light Ions - Graphs, data, programs, compiled by H. Paul
X and Gamma rays standards - Decay data standards for detector calibration
WIMSD-IAEA Library - multigroup data library for the WIMS-D code
Various Specialized Evaluated Data Libraries in ENDF and other formats
Various Specialized Evaluated Data Libraries in ENDF and other formats
Electronic Documents
Citation Guidelines - online data service manual and citation guidelines
ENDF Format Manual - ENDF-102 June 2005 version
ENDF/B-VI Summary Documentation - ENDF-201 December 1996 version
ENSDF and NSR Manuals - ENSDF Feb. 2001 version & NSR Aug. '96 version
IAEA Technical Documents - IAEA-TECDOCS (Technical Reports Series)
IAEA-NDS Reports - IAEA-NDS-xxxx documents
NSDD, ICTP Workshops - workshop material, codes, programme, etc.
INDC Reports - INDC reports sorted by area
INDC-NDS Reports - INDC-NDS reports
Newsletters - NDS Newsletters [Issue 44, September 2007]
Selected INDC Reports - selected INDC reports, INDC(AUL) to INDC(VN)
Computer codes
EMPIRE-II - system of codes for nuclear reaction calculations (Version 2.19)
ENDF Utility Codes - Release 7.02
ENSDF programs - ENSDF Analysis and Utility programs (ALPHAD, LOGFT, etc.)
ENDVER - ENDF File Verification Support Package
PREPRO - ENDF Preprocessing Codes. Version - March 17, 2007
SIGACE - package for generating high temperature ACE files
ZVVIEW - interactive plotting of nuclear data
General Information
NDS information
Co-ordinated Research Projects (CRPs) - recently completed and ongoing CRPs
IAEA Nuclear Data Guide - catalogue of all nuclear data available from IAEA NDS
Index of nuclear data libraries - comprehensive index of NDS libraries
Nuclear Data Section - introduction, programme description, activities and staff
Nuclear data information brochure - the IAEA nuclear and atomic data programme
Nuclear data newsletters - from 1995 to now [Issue 44, September 2007]
Subscribe to our mailing list - get the latest newsletter and other information
Datalinks
Atomic and molecular data - AMDDAS, ALADDIN, GENIE, etc.
List of available CD-ROMs - nuclear data and utility codes on CD-ROM
Nuclear data links for medical applications - relevant sites at the IAEA and worldwide
Other useful links
IAEA home page
IAEA - Department of Nuclear Sciences and Applications
International network of Nuclear Structure and Decay Data evaluators - the NSDD network
Nuclear Reaction Data Centre network - the NRDC network, contacts, webpages, etc.
Other information resources - collection of links to other nuclear information resources
Read our Disclaimer
Copyright 2003-2004, International Atomic Energy Agency - Nuclear Data Section P.O. Box 100, Wagramer Strasse 5, A-1400 Vienna, Austria
Telephone (+431) 2600-0; Facsimile (+431) 2600-7; E-mail: online@iaeand.iaea.org
NDS Events
Meetings & Workshops
Joint ICTP-IAEA Workshop on Nuclear Structure and Decay Data: Theory and Evaluation
28 April - 9 May, 2008
ICTP, Trieste, Italy
Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies
18 -30 May, 2008
ICTP, Trieste, Italy
NPAE 2008
2-nd International Conference on Current Problems in Nuclear Physics and Atomic Energy (NPAE-Kyiv2008)
and Atomic Energy (NPAE-Kyiv2008)
9 - 15 June, 2008
Kyiv, Ukraine
PHYSOR'08 International Conference on the Physics of Reactors
14 - 19 September, 2008
Kursaal Conference Center, Interlaken, Switzerland
NDS Services
Nuclear Data and Codes on CD & DVD
Newsletters
Register with NDS
Nuclear Data Section
IAEA Nuclear Data Section
More on Coordinated Research Projects, Technical Cooperation, NDS people and activities
NDS Partners
NNDC
National Nuclear Data Center, Brookhaven, USA
OECD NEA



National Nuclear Data Center

BROOKHAVEN NATIONAL LABORATORY

- Nuclear Structure and Decay Databases
- Nuclear Structure and Decay Tools
- Nuclear Reaction Databases
- Nuclear Reaction Tools
- Bibliography Databases
- Networks and Links
- About the Center
- Publications
- Meetings



Astrophysical Reaction Rates New Covariance Workshop, June 24-27

Site Index - Search the NNDC: go

AMDC Atomic Mass Data Center, **Q-value Calculator**

Atlas of Neutron Resonances Parameters & thermal values

CapGam Thermal Neutron Capture γ-rays

Chart of Nuclides Basic properties of atomic nuclei

CINDA Computer Index of Nuclear (reaction) Data

CSEWG Cross Section Evaluation Working Group

CSISRS alias EXFOR Nuclear reaction experimental data

Empire Nuclear reaction model code

ENDF Evaluated Nuclear (reaction) Data File, **Sigma**

ENSDF Evaluated Nuclear Structure Data File

IRDF International Reactor Dosimetry File

MIRD Medical Internal Radiation Dose

NMMSS & DoE NMIRDC Safeguards & inventory decay data standards

NSR Nuclear Science References

Nuclear Data Sheets Nuclear structure & decay data journal

Nuclear Wallet Cards Ground & isomeric states properties

Nuclear Wallet Cards for Homeland Security

NuDat Nuclear structure & decay Data

USNDP U.S. Nuclear Data Program

XUNDL Experimental Un-evaluated Nuclear Data List

Links ordered alphabetically Order by category

Sponsored by the Office of Nuclear Physics - Office of Science - U.S. Department of Energy

Acknowledgments - **Comments/Questions** - Disclaimer

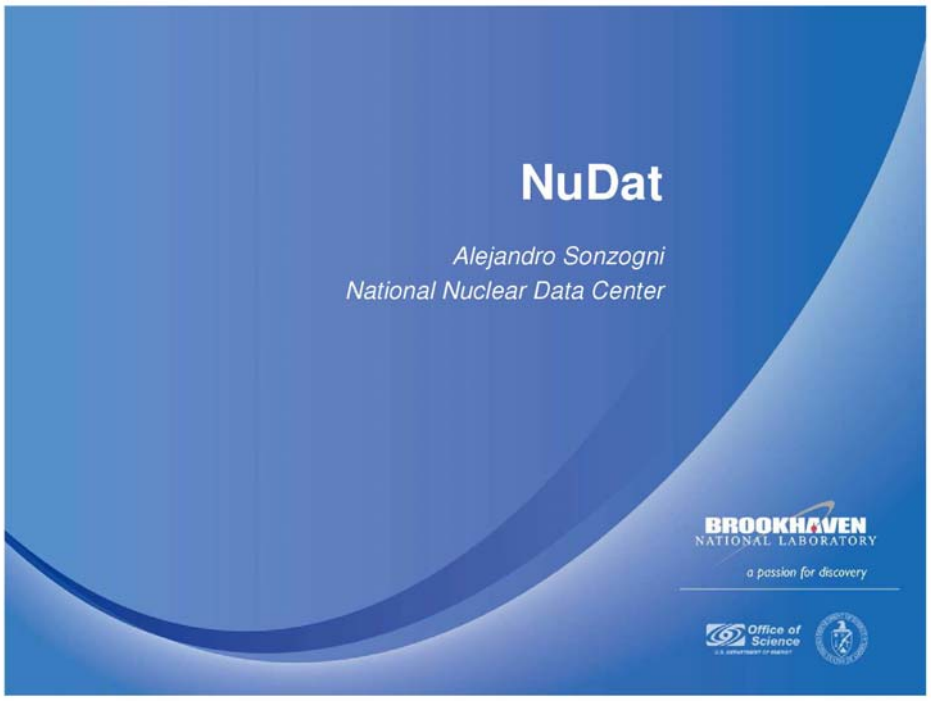
15.

NuDat
and
Q-calc

A. Sonzogni

NNDC, BNL

E-mail: sonzogni@bnl.gov

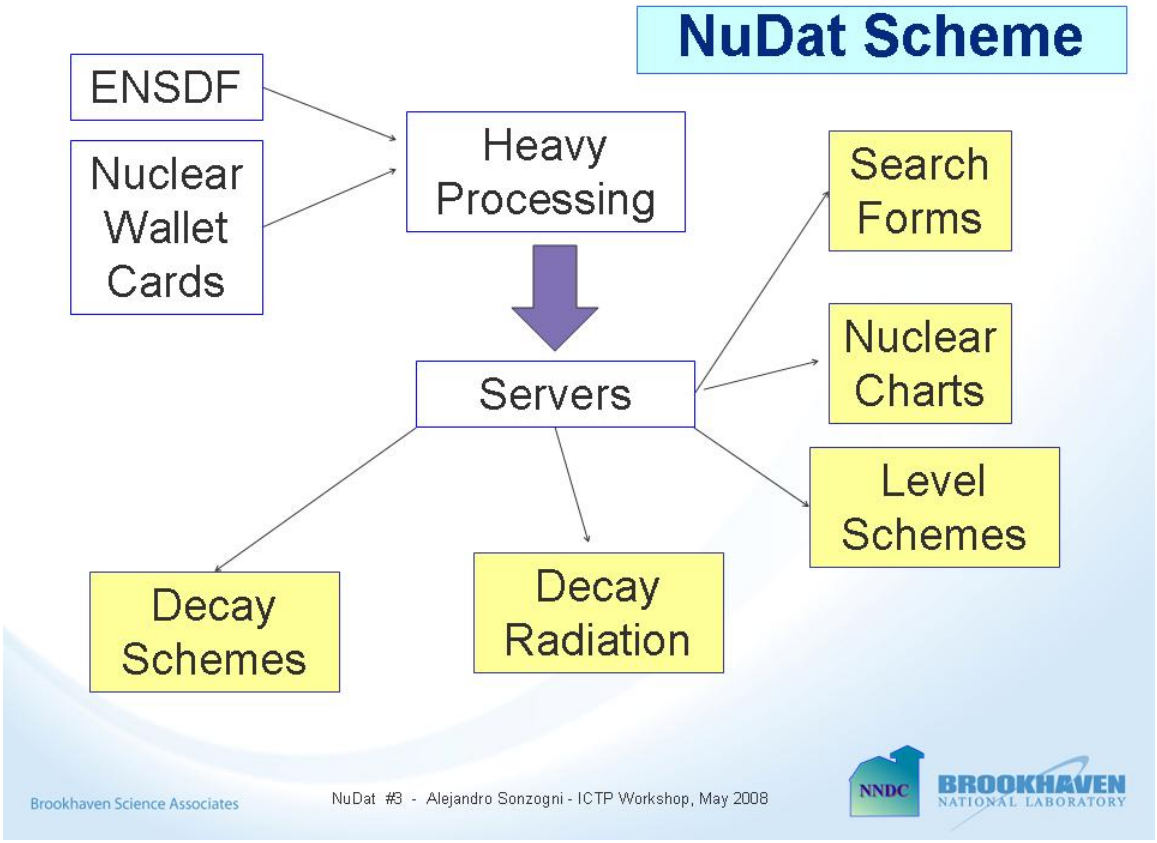


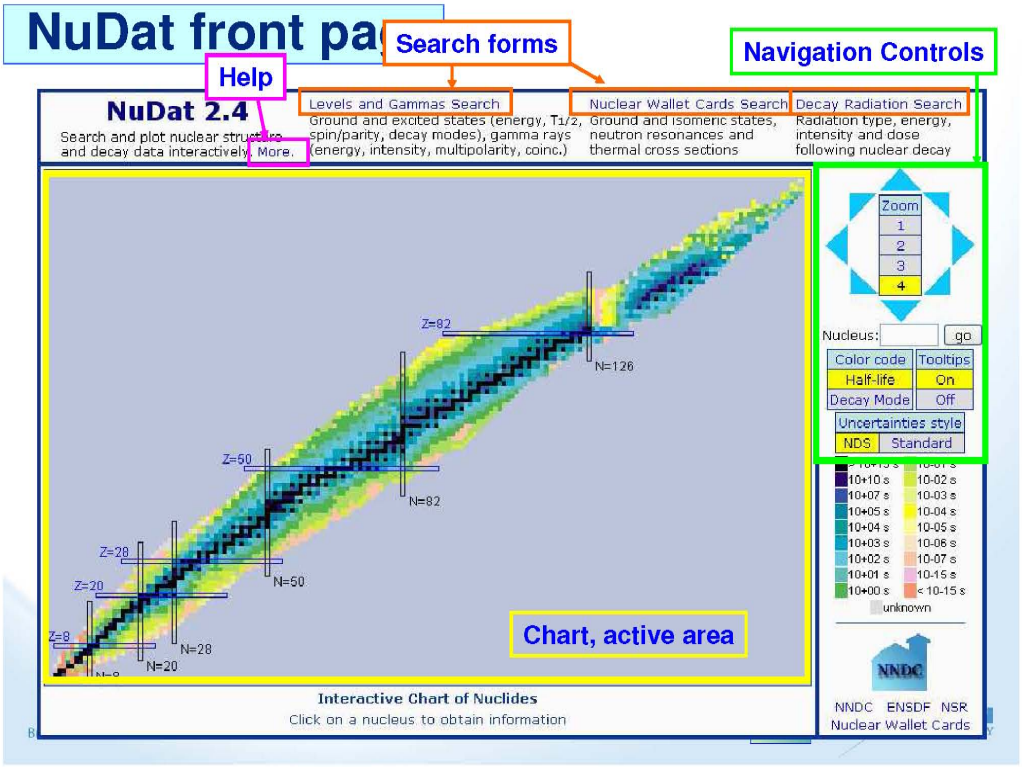
NuDat
www.nndc.bnl.gov/nudat2

NuDat is a web application with two main goals, (a) to present nuclear structure and decay information from ENSDF in a user-friendly way, and (b) to allow users to execute complex search operations in the wealth of data contained in ENSDF. NuDat provides an interactive chart of nuclides for navigation and an output in Table of Isotopes style. NuDat contents are updated regularly as new evaluations are entered into ENSDF.

NuDat 2 was developed by the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory Using NuDat 2, searches can be made for nuclear level properties (energy, half-life, spin-parity), gamma-ray information (energy, intensity, multipolarity, coincidences), and radiation information following nuclear decay (energy, intensity, dose).

See www.nndc.bnl.gov/nudat2/help

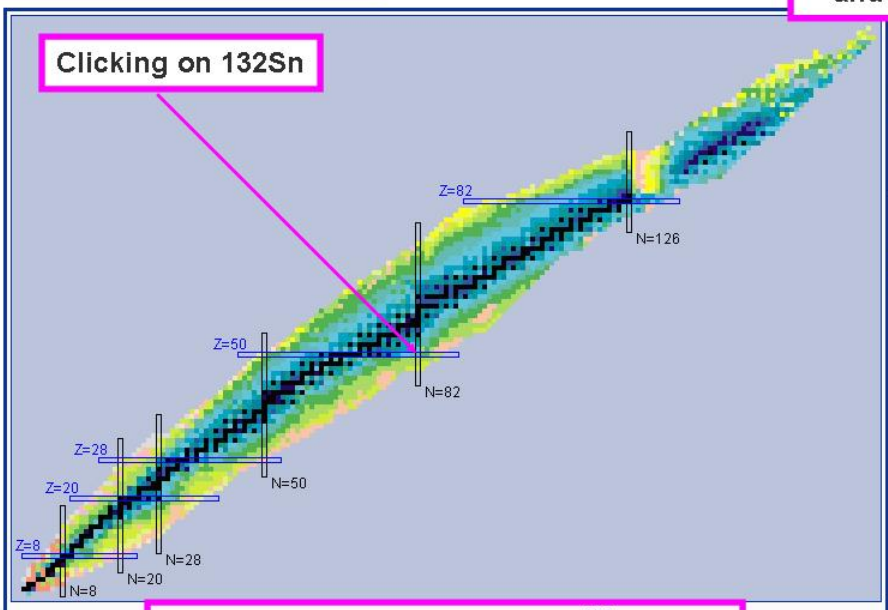

NuDat Scheme
ENSDF
Nuclear Wallet Cards
Heavy Processing
Servers
Search Forms
Nuclear Charts
Level Schemes
Decay Radiation
Decay Schemes
Brookhaven Science Associates
NuDat #3 - Alejandro Sonzogni - ICTP Workshop, May 2008
NNDC
BROOKHAVEN NATIONAL LABORATORY


NuDat front pa
Search forms
Navigation Controls
Help
NuDat 2.4
Search and plot nuclear structure and decay data interactively. More.
Levels and Gammas Search
Ground and excited states (energy, T1/2, spin/parity, decay modes), gamma rays (energy, intensity, multipolarity, coinc.)
Nuclear Wallet Cards Search
Ground and isomeric states, neutron resonances and thermal cross sections
Decay Radiation Search
Radiation type, energy, intensity and dose following nuclear decay
Zoom
1
2
3
4
Nucleus:
go
Color code
Tooltips
Half-life
On
Decay Mode
Off
Uncertainties style
NDS
Standard
Z=82
N=126
Z=50
N=82
Z=28
N=50
Z=20
N=28
Z=8
N=20
Chart, active area
Interactive Chart of Nuclides
Click on a nucleus to obtain information
NNDC ENSDF NSR
Nuclear Wallet Cards

NuDat chart

Same if typing 132sn and clicking "go"

Clicking on 132Sn



Zoom 1 2 3 4

Nucleus: go

Color code | Tooltips
Half-life | On
Decay Mode | Off

Uncertainties style: NDS | Standard

> 10+15 s, 10+10 s, 10+07 s, 10+05 s, 10+04 s, 10+03 s, 10+02 s, 10+01 s, 10+00 s
10-01 s, 10-02 s, 10-03 s, 10-04 s, 10-05 s, 10-06 s, 10-07 s, 10-15 s, < 10-15 s
unknown

NNDC

NNDC ENSDF NSR
Nuclear Wallet Cards

Ground and isomeric state information for $^{132}_{50}Sn$

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	0+	-76.5542	39.7 s *8*	β⁻ : 100.00 %
4.8485	(8+)	-71.7057	2.03 μs *4*	IT : 100.00 %

A list of levels, a level scheme and decay radiation information are available

Basic info + links to more details

NuDat chart

Changing the zoom value

Zoom 1 2 3 4

Nucleus: go

Color code | Tooltips
Half-life | On
Decay Mode | Off

Uncertainties style: NDS | Standard

> 10+15 s, 10+10 s, 10+07 s, 10+05 s, 10+04 s, 10+03 s, 10+02 s, 10+01 s, 10+00 s
10-01 s, 10-02 s, 10-03 s, 10-04 s, 10-05 s, 10-06 s, 10-07 s, 10-15 s, < 10-15 s
unknown

NNDC

NNDC ENSDF NSR
Nuclear Wallet Cards

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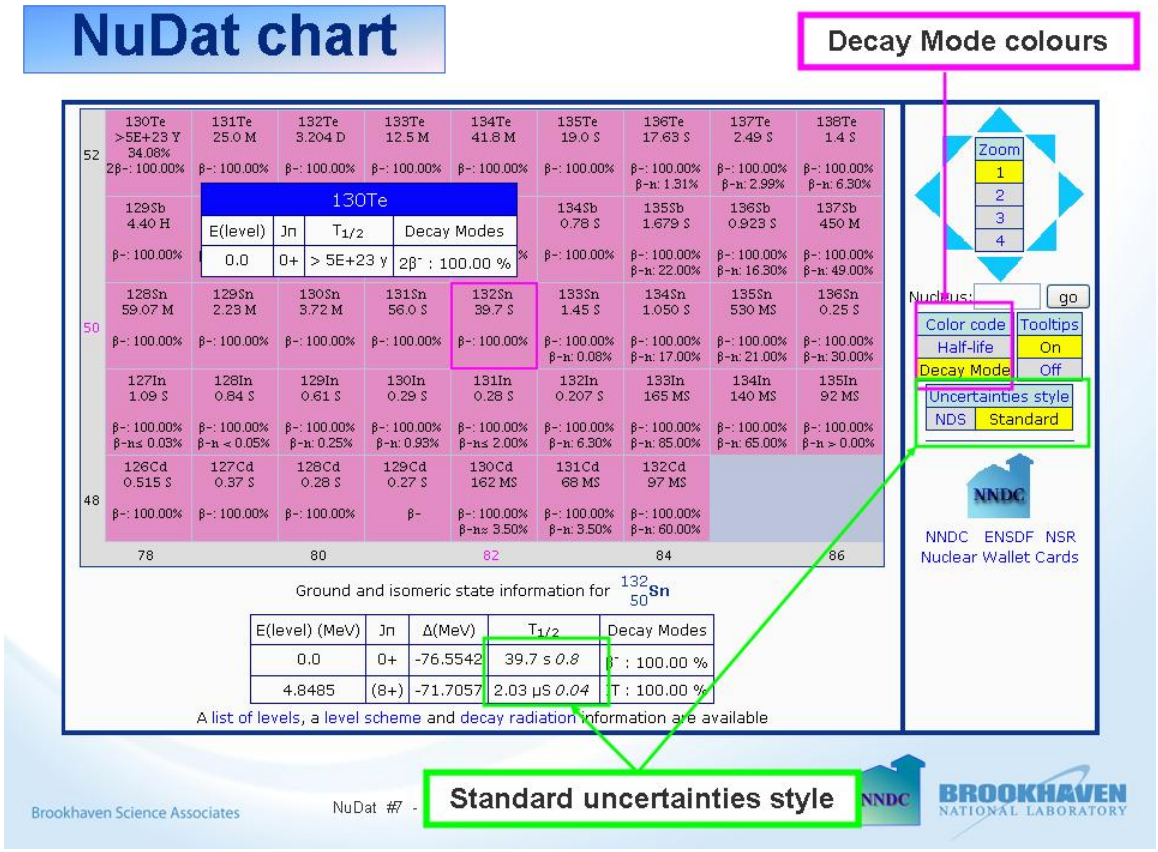


Nuclear Decay

A process where the protons and neutrons in a given nucleus are rearranged into a lower energy state. The transition may involve states of the same nucleus (gamma emission, electron conversion) or levels of different nucleus. Each different process is known as a 'decay mode':

* Gamma emission, electron conversion
* β- decay
* β+ decay
* Electron capture (EC)
* β-delayed particle emission
* Double β decay
* Proton decay
* Alpha decay
* Cluster decay
* Spontaneous fission (SF)

The probability of undergoing a given nuclear decay is often indicated using the percent sign followed by the decay mode name and the probability per 100 decays.

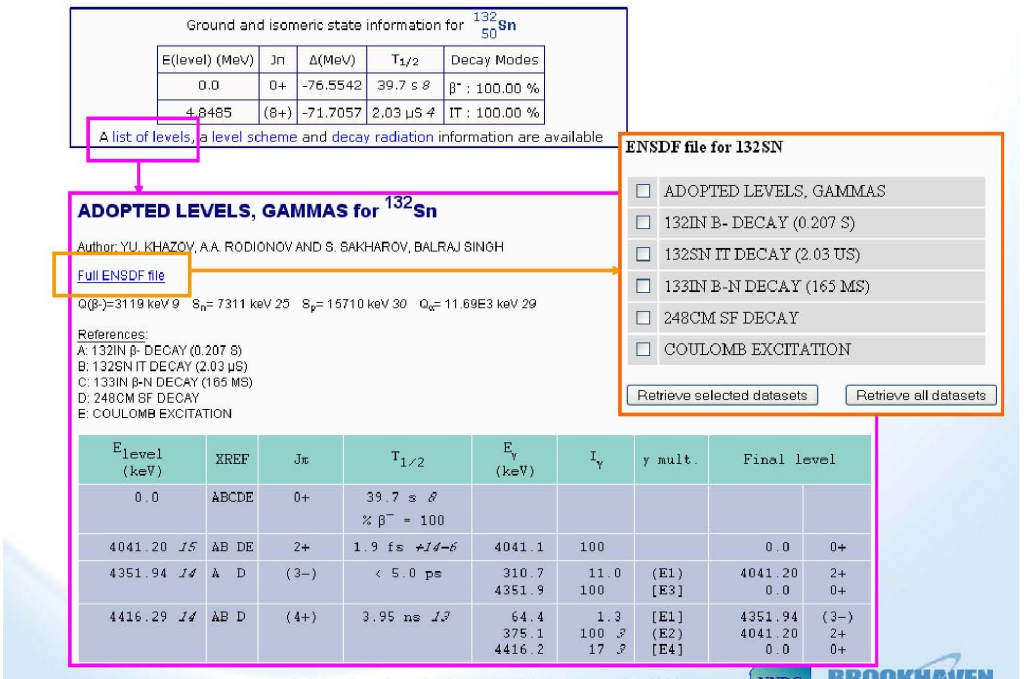
For instance, %β-=100 means 100% probability of β- decay.

The energy released during the decay is called 'Q-value'. For a given decay mode to have a probability larger than 0, the Q-value has to be positive.

Uncertainties

The uncertainty associated with a given quantity can be expressed in Nuclear Data Sheets style, or in a standard style. The Nuclear Data Sheets style has been used for a long time since this approach facilitates data storage, which was crucial in the early days. A table with a brief explanation of the Nuclear Data Sheet style is given below:

NDS Style	Standard style and meaning
4.623 3	4.623 +- 0.003
4.6 h 12	4.6 +- 1.2 hours
5.4×10^{3} *2*	5400 + - 200
4.2 *+8-10*	4.2 + 0.8 - 1.0
9.22 *SY*	9.22 is the result of a systematic study
9.22 CA	9.22 value is not an experimental measurement, but the result of a theoretical calculation

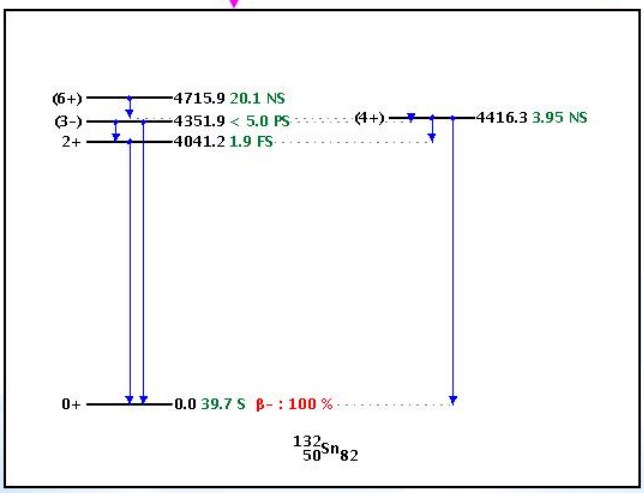


Ground and isomeric state information for $^{132}_{50}Sn$

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	0+	-76.5542	39.7 s *8*	β^- : 100.00 %
4.6483	(8+)	-71.7057	2.03 μS *4*	IT : 100.00 %

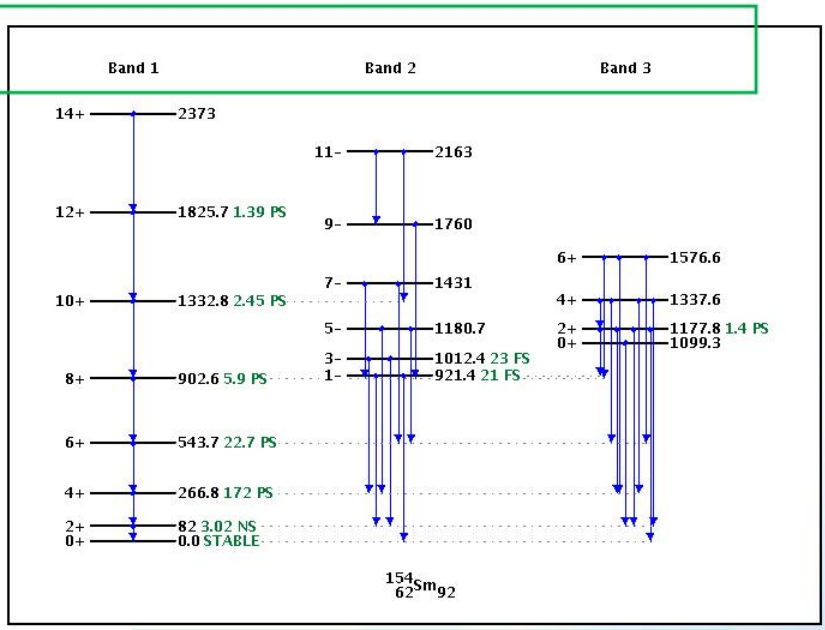
A list of levels, a level scheme and decay radiation information are available

Interactive Level Scheme

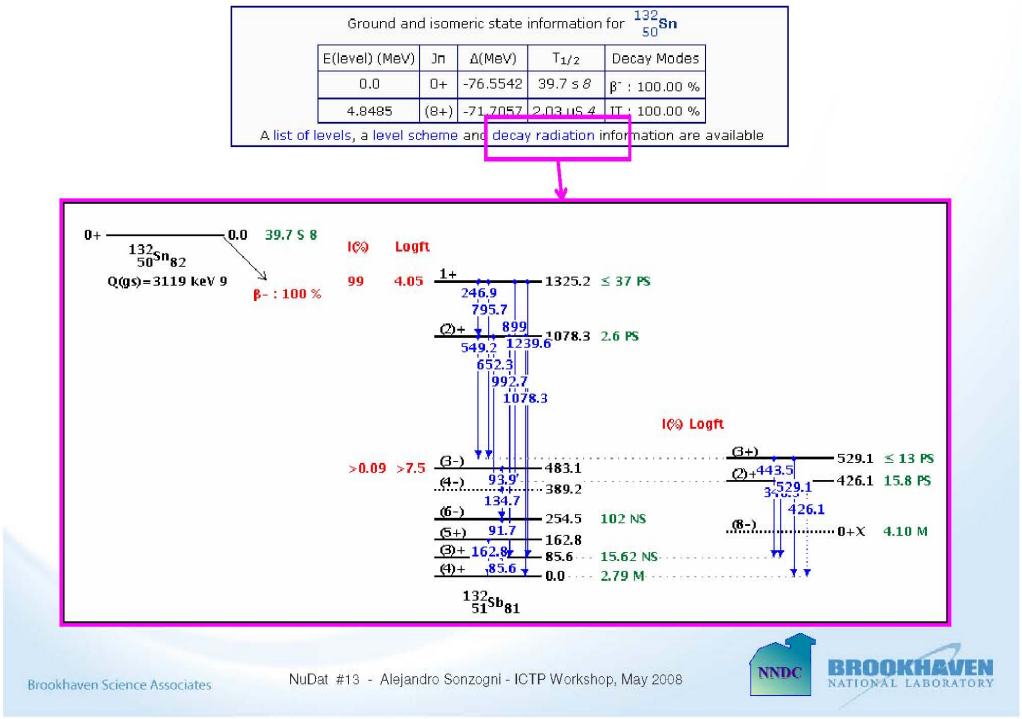


^{132}Sn is doubly magic - how does this impact a level scheme of a nucleus at mid-shell?

Rotational bands



Partial view of ^{154}Sm level scheme



Levels Search

Search for first 2+ states in N = 86 nuclides

Nuclear Levels and Gammas Search

(Help)

Specify Nuclei : Nucleus: Ex: 232TH or th232 or 232-Th or th-232 or Z / Element: A: N: 86 ≤ Z ≤ ≤ A ≤ ≤ N ≤ Even Z Any A Any N

E(level) condition: enabled disabled 0 ≤ E_{level}(keV) ≤ 40000

Decay Mode condition: enabled disabled Decay Mode ANY

Jπ(level) condition: enabled disabled J = 2 Order : 1st Parity : +

$T_{1/2}$(level) condition: enabled disabled 0 fs ≤ $T_{1/2}$ ≤ 1E10 Gy

No Upper/Lower limit values

γ condition #1: enabled disabled 0 ≤ E_γ(keV) ≤ 40000 Multipolarity: ANY Not mixed

γ condition #2: enabled disabled 0 ≤ E_γ(keV) ≤ 40000 Multipolarity: ANY Not mixed

γ condition #3: enabled disabled 0 ≤ E_γ(keV) ≤ 40000 Multipolarity: ANY Not mixed

γ coincidence condition : any coincident Coincidence gate ≤ 1 us

γ reduced transition probability: enabled disabled 0 ≤ B(M_λ,E_λ)(Weisskopf units) ≤ 40000 NEW

Ordering: Z, A, E(level),E(gamma) Output: Web Page Formatted File

Uncertainties: Nuclear Data Sheets style Standard style

Search Reset

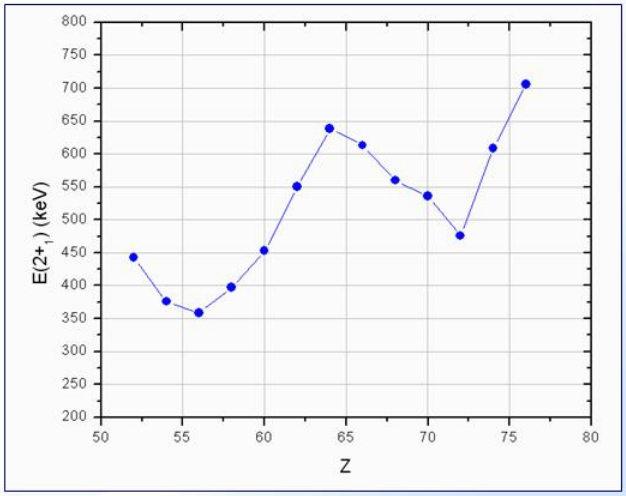
Levels and Gammas database version of 4/11/2008

Results

Nucleus	E_{level}(keV)	J^{π}	$T_{1/2}$
138TE	443.1 *10*	(2+)	
140XE	376.658 *15*	2+	70.5 ps *22*
142BA	359.597 *14*	2+	65 ps *2*
144CE	397.441 *9*	2+	35.4 ps *20*
146ND	453.77 *5*	2+	21.6 ps *13*
148SM	550.255 *8*	2+	7.72 ps *32*
150GD	638.045 *14*	2+	
152DY	613.82 *7*	2+	10 ps *5*
154ER	560.8 *1*	2+	
156YB	536.4 *1*	2+	
158HF	476.36 *11*	2+	
160W	609.9 *2*	2+	
162OS	706.7 *3*	(2+)	

See Help file for more search examples

Tool for systematic studies



Decay Search

Decay Radiation Search

Help

Specify Parent Nuclei : **Nucleus:** 232th Ex: 232TH or th232 or 232-Th or th-232 or
Z / Element: **A:** **N:**
≤ **Z** ≤ ≤ **A** ≤ ≤ **N** ≤
Any Z Any A Any N

Parent $T_{1/2}$ condition: enabled disabled 0 fs ≤ $T_{1/2}$ ≤ 1E10 Gy
No Upper/Lower limit values

Decay Mode condition: enabled disabled **Decay Mode** ANY

Radiation Type condition: enabled disabled **Radiation Type** ANY

Radiation Energy condition: enabled disabled 0 ≤ **Energy (keV)** ≤ 10000

Radiation Intensity condition: enabled disabled 0 ≤ **Intensity (%)** ≤ 100

Ordering: Z, A, T1/2, E Output: Web Page Formatted File

Uncertainties: Nuclear Data Sheets style Standard style

Search Reset

Decay Radiation database version of 4/11/2008

Author: AGDA ARTNA-COHEN Citation: Nuclear Data Sheets 80, 723 (1997)

Parent Nucleus	Parent E(level)	Parent Jπ	Parent $T_{1/2}$	Decay Mode	GS-GS Q-value (keV)	Daughter Nucleus	Decay Scheme
$^{232}_{90}$Th	0	0+	14.05E+9 y 6	α: 100 %	4082.8 14	$^{228}_{88}$Ra	

Results

Alphas:

Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
3811.1 14	0.069 % 13	0.0026 5
3947.2 20	21.7 % 13	0.86 5
4012.3 14	78.2 % 13	3.14 5

Electrons:

	Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
Auger L	9.09	8.7 % 5	7.9E-4 4
CE K	36.958 13	0.0060 % 11	2.2E-6 4
CE L	44.573 10	15.8 % 8	0.0070 3
CE M	58.988 10	4.27 % 21	0.00252 13
CE NP	62.602 10	1.53 % 8	9.6E-4 5
Auger K	65.9	1.9E-4 % 4	1.3E-7 3
CE L	121.643 10	0.031 % 6	3.8E-5 7
CE M	136.058 10	0.0084 % 16	1.14E-5 22
CE NP	139.672 10	0.0030 % 6	4.3E-6 8

Gamma and X-ray radiation:

	Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
XR l	12.3	7.1 % 5	8.8E-4 6
	63.81 1	0.263 % 13	1.68E-4 8
XR kα2	85.431	0.0017 % 3	1.4E-6 3
XR kα1	88.471	0.0028 % 5	2.4E-6 5
XR kβ3	99.432	3.4E-4 % 6	3.3E-7 6
XR kβ1	100.13	6.4E-4 % 12	6.5E-7 12
XR kβ2	102.498	2.4E-4 % 5	2.5E-7 5
	140.88 1	0.021 % 4	3.0E-5 6

Where are the electrons coming from?

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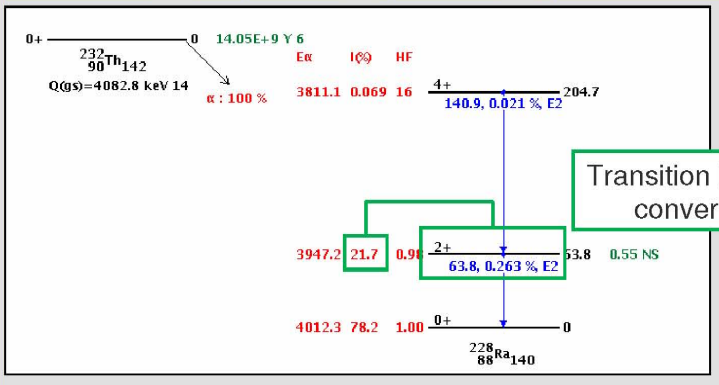
Interactive Decay Scheme

^{232}Th α decay

0.0 < E(level) < 225.0 | Level Energy | Level T1/2 | Level Spin-parity | Final Level

Highlight: Level | Gamma Energy | Gamma Intensity | Gamma Multipolarity | Decay Information

Image Height: 350 | Level Width: 100 | Band Spacing: 20 | Plot | Clear



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Q-calc
www.nndc.bnl.gov/qcalc

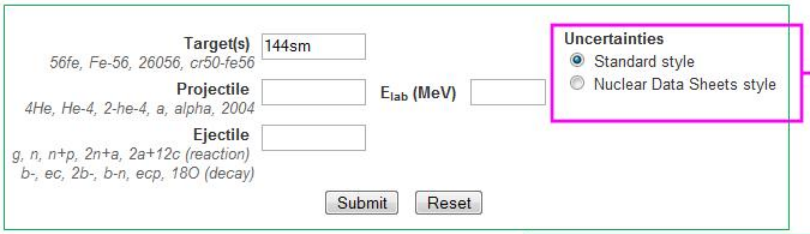
Nuclear reaction and decay Q-values can be calculated using the Q-Calc tool, which uses the 2003 atomic mass evaluation of Audi et al., G.Audi, A.H. Wapstra, C. Thibault, Nucl. Phys. A729, 337 (2003).

For a nucleus with Z protons, N neutrons and mass M(Z,N), the most common decay Q-values are:

β-	Q(β-) = M(Z,N) - M(Z+1,N-1)
Electron capture	Q(EC) = M(Z,N) - M(Z-1,N+1)
β+	Q(β+) = M(Z,N) - M(Z-1,N+1) – 2Me
Alpha emission	Q(α) = M(Z,N) - M(Z-2,N-2) - M(2,2)
Proton emission	Q(p) = M(Z,N) - M(Z-1,N-1) - M(1,1)
Double β-	Q(2β-) = M(Z,N) - M(Z+2,N-2)
Double EC	Q(2EC) = M(Z,N) - M(Z-2,N+2)

The neutron and proton separation energies are defined as:

S(p) = -Q(p)
S(n) = -Q(n)



ENSDF evaluation: most of the time we are interested in decay Q-values, which can be obtained by simply defining the nucleus of interest

Mass and decay Q-values for ^{144}Sm

Quantity	(keV)
Mass Excess	−81971.96 *2.81*
Binding Energy/A	8303.723 *0.019*
Atomic Mass (AMU)	143.912 *0.00301* *
Atomic Mass/neutron Atomic Mass	142.67574 *0.00299* **
$Q_{\beta-}$	−6350.3 *10.9*
Q_{EC}	−550.85 *2.55*
$Q_{\beta+}$	−1573.05 *2.55*
Q_{n}	−10520.08 *2.36*
Q_{p}	−6295.19 *2.73*
Q_{2n}	−19121.7 *5.63*
Q_{2p}	−10594.7 *1.79*
Q_{α}	−145.1 *28.1*
$Q_{2\beta-}$	−10212.5 *28.1*

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