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INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

Summary Report of the
2nd Research Coordination Meeting on

"Compilation and Evaluation of Photonuclear Data for Applications"

Los Alamos National Laboratory
Los Alamos, U.S.A.
23 - 26 June 1998

Prepared by
P. Obložinský
IAEA Nuclear Data Section
Vienna, Austria

September 1998

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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Abstract

The report contains the summary of the 2nd Research Coordination Meeting on "Compilation and Evaluation of Photonuclear Data for Applications" hosted by the Los Alamos National Laboratory. The project aims to produce an IAEA Photonuclear Data Library and a TECDOC "Handbook on Photonuclear Data". Summarized is the status of the project, along with future tasks towards its completion in 1999.

September 1998

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1. Summary of the Meeting

1.1 Objectives and Participation

The 2nd Research Co-ordination Meeting (RCM) on "Compilation and Evaluation of Photonuclear Data for Applications" was held in the Los Alamos National Laboratory. The local host of the RCM was M.B. Chadwick.

The purpose of the meeting was to review results achieved in compilation and evaluation of photonuclear data, to compare available photonuclear files, to select data for the international file with emphasis on medical applications, and to review the first draft of the Handbook on Photonuclear Data. Mr. M.B. Chadwick of the Los Alamos National Laboratory, Los Alamos, U.S.A., acted as chairman of the Meeting. The detailed Agenda is attached (Appendix 1).

The meeting was attended by the chief scientific investigators or their representatives of all six laboratories participating in the project, by two external experts (Y. Lee, KAERI, South Korea and S. Mughabghab, BNL, USA), and by several local observers. The participating laboratories were represented by M.N. Martins (Instituto de Física da Universidade de São Paulo, São Paulo, Brazil), Yu Baosheng (China Institute of Atomic Energy, Beijing, China), T. Fukahori (Japan Atomic Energy Research Institute, Tokai-mura, Japan), A.I. Blokhin (Institute of Physics and Power Engineering, Obninsk, Russia), V.V. Varlamov (Institute of Nuclear Physics of Moscow State University, Moscow, Russia), and M.B. Chadwick (Los Alamos National Laboratory, Los Alamos, NM, U.S.A.). For details see Appendix 2.

1.2 Main Conclusions

The CRP is well underway and expected output (IAEA Photonuclear Data Library and related TECDOC) can be realistically completed by the end of 1999 as originally planned, followed by the release of the library and publication of the TECDOC in 2000.

The participation of KAERI, Republic of Korea in the CRP was recommended in view of its recently established photonuclear data program. The final RCM should be held in JAERI, Japan, 25 - 29 October 1999.

2. Progress Reports

Good progress since the 1st RCM in Obninsk, December 1996, was reported by all six laboratories participating in the CRP. Extended abstracts of presented papers can be found in Appendix 3. In addition, the first intercomparison of various evaluations was performed and the first draft of the TECDOC was prepared.

Several other participants presented their papers (see Agenda, Appendix 1 for more details). It was felt that the contributions of two external experts (for extended abstracts see Appendix 3) and several local observers represented a useful contribution to the meeting.

3. Intercomparison of Various Evaluations

3.1 Criteria for selecting an evaluation

One of the CRP's goals is to arrive at a single recommended IAEA photonuclear library in ENDF format for radiation transport simulations. In addition to this, all evaluations from all laboratories will be included as separately available databases.

Fukahori presented his results showing intercomparisons between various evaluations from different laboratories, compared with experimental data. Such intercomparisons are essential for assessing the quality of the evaluations, and for enabling a choice to be made as to which evaluation should be recommended by the IAEA.

The participants of the CRP agreed that the following criteria should be used to determine which evaluation should be recommended in cases where more than one evaluation exists.

The two most important criteria are:

1) Quality of the evaluation, particularly the extent to which it agrees with measured data. Evaluators should also compare their results against evaluated experimental data as incorporated in the EPNDL.

2) Completeness of the evaluation. The evaluations are intended for use in radiation transport codes, and therefore it is important that they include descriptions of, for instance, the energy spectra of the photoneutrons.

Additional criteria that will be considered are:

3) The upper energy limit should be as high as possible - e.g. 140 - 150 MeV maximum energy is preferable to 20 - 30 MeV, all other things being equal.

4) The evaluations should be processable by NJOY, for use by a code such as MCNPX/MCNP. This implies that evaluators from Los Alamos, JAERI, CNDC, and Obninsk, should interact with LANL researchers (particularly R.E. MacFarlane, R.C. Little, and M.B. Chadwick) to ensure that the latest version of NJOY is able to process their evaluations. Chadwick will provide feedback to other evaluators on progress in processing their data.

5) Consistency. How accurate are most of the evaluations produced by certain evaluators?

6) Other issues include a desire that the final recommended library have contributions from all the participants in the CRP who are developing transport photonuclear ENDF files.

3.2 Future intercomparisons and tasks for evaluators

The extensive collections of figures provided by Fukahori represent a valuable first step. However, the following additional developments are needed:

a) Evaluators should provide Fukahori with new evaluations as they are produced.

b) The graphs should include legends describing which experimental data are used.

c) Participants should send Fukahori experimental data that they made use of in their evaluations. This is particularly important to ensure that it is clear why an evaluator chose a certain cross section - and it is easy for Fukahori to miss a data set by mistake. Furthermore, at the final selection activity at the final CRP meeting, it will be important to have all such information available so that each evaluator can explain the basis for his results.

d) Care should be taken to ensure that the evaluated curves and the experimental data are for the same physical quantity, e.g. both for (γ,1n) and not, say, evaluation of (γ,1n) and measurement of (γ,1n) + (γ,1n+1p). Where possible, comparisons for the (γ,Xn) cross sections, that is, for neutron production, should be made since this is of key importance in applications.

e) Important priority elements should be included in the comparison figures, namely Be, C, O, Al, Fe, Ni, Cu, Zr, W, Pb, Bi and U as agreed at the 1st RCM, Obninsk, December 1996.

3.3 Specific remarks on preliminary intercomparisons

We list below some specific comments relating to the preliminary Figures 5.3.1 - 5.3.39 prepared for the first draft of the TECDOC by Fukahori:

5.3.1 Si-28(γ,n): JENDL needs improving.
5.3.2 V-51(γ,n): Both JENDL and CNDC appear equally good.
5.3.3 V-51(γ,2n): Both JENDL and CNDC appear to be in reasonable agreement with data.
5.3.4 Cr-52(γ,n): BOFOD, which is based upon EPNDL, looks good.
5.3.5 Fe-54(γ,n): CNDC appears low, JENDL is in better agreement.
5.3.6 Fe-56(γ,abs): All appear reasonable, though there is a lack of experimental data.
5.3.7 Fe-56(γ,n): Both JENDL and CNDC are reasonable. The experimental data here is probably for (γ,n0) and therefore should not be shown.
5.3.8 Cu-63(γ,n): Both JENDL and CNDC are reasonable.
5.3.9-10 Cu-63(γ,p), (γ,np): CNDC needs improving.
5.3.11 Cu-65(γ,n): CNDC should consider adopting Varlamov's view of the correct magnitude of the photoabsorption here, as shown by the EPNDL curve, instead of using the Livermore data.
5.3.12-13 Cu-65(γ,p), (γ,np): CNDC needs improving.

5.3.14-19 Mo-94(γ,n), (γ,2n): JENDL needs improving, BOFOD ok.
Mo-96(γ,n), (γ,2n) -"-
Mo-98(γ,n), (γ,2n) -"-
5.3.20, 22 W-182(γ,abs), W-184(γ,abs): Both JENDL and CNDC look reasonable.
5.3.21 W-182(γ,n): JENDL needs improving.
5.3.23 W-184(γ,n): BOFOD appears to drop too sharply.
5.3.24 W-186(γ,abs): All reasonable.
5.3.25 missing
5.3.26-27 W-186(γ,2n), (γ,3n): All reasonable.
5.3.28 Pb-nat(γ,abs): EPNDL data should be multiplied by 207.2 here! JENDL needs improving.
5.3.29-31 Bi-209(γ,abs), (γ,n), (γ,2n): JENDL needs improving.
5.3.32-33 U-235(γ,abs), (γ-fis): All reasonable.
5.3.34-35 U-235(γ,n), (γ,2n): Discontinuities in JENDL near 18 MeV should be removed.
5.3.36-39 U-238(γ,abs), (γ,fis), (γ,n), (γ,2n): All reasonable.

4. Review of TECDOC

The first draft of the TECDOC was reviewed. It is understood that the TECDOC is prepared for data users rather than data producers. The discussion focused on major aspects of individual chapters rather than on numerous details. It was agreed that each chapter will have its coordinator with an overall responsibility for communication with contributors and for editing of the chapter. Comments on each chapter are summarized below.

4.1 Chapter 1. Introduction

Coordinator: P. Obložinský
- Keep the length to approximately 5 - 6 pages.
- Remove the separation between 1.1 and 1.2, and merge together.
- Remove item 7.

4.2 Chapter 2. Definitions and Notations

Coordinator: M.N. Martins
- Take the last part of this chapter and move into the EXFOR section.
- Rewrite the relationships as equations, including sigmas to denote cross sections.
- Remove the errors in the (gamma,abs) equation, i.e. remove (gamma,dn) and (gamma,F).
- Add a list of symbols used, along with 1-line explanations (a first draft to be provided by Chadwick).

4.3 Chapter 3. Available Experimental Data

Coordinator: M.N. Martins
- In section 3.1.1. remove most of the equations and instead provide brief summaries of the methods, with citations. Consider the possibility of omitting figure 3.
- In Section 3.2 the last paragraph should be modified according to Varlamov's comments.

- Section 3.3 needs to be drastically shortened, and the detailed information on EXFOR formats, from page 15-24 removed. Instead, a few paragraphs should be written outlining what is available in the EXFOR system, and explaining to a non-specialist the kind of data that is available. It could include the fact that all data in the Dietrich-Berman atlas are included, but also a large amount of data from Russia and other countries has been added.
- A few illustrative tables may be useful, but the whole section should be comprised of about 4 pages if possible. Varlamov will work on this with Martins.
- Sao Paulo's work should be mentioned in addition to that of CDFE.
- Access to EXFOR data via the internet should be discussed.
- Section 3.4 should have the example removed.
- Sections 3.2-3.5 should be merged into one single section with the new structure: 3.2 Compiled data, with 3.2.1 Bibliographic information, 3.2.2 EXFOR library, 3.2.3 Atlas of cross sections and GDR parameters, 3.2.4 Additional data in other formats, and 3.2.5 Access to data.

4.4 Chapter 4. Nuclear Models

Coordinator: M.B. Chadwick

- In 4.1 (Photoabsorption) add more equations, and provide more details. Include some of the text provided by Blokhin. Include some illustrative figures. This section should reflect the approaches used by all laboratories. Possibly include the frequently used figure on photoabsorption.
- In 4.2 the title of the section should be replaced with 4.2.1. Add a subsection on angular distributions (4.2.3).
- Photofission should be moved into subsection 4.2.4, and remove entirely the subsections on 4.3.3 - and 4.3.4 (with parts of 4.3.2 being moved into 4.1). The photofission section should be largely reduced, with only a minimum of equations. The text should concentrate on main ideas used in the fission model, including the role of damping. But details should be omitted and a citation provided.
- 4.4 (now becomes 4.3) should have subsections on MCPHOTO, ALICE-F, GNASH, Obninsk code, GUNF. Each of these should be about two pages long, since details of the models are provided above in 4.1 and 4.2.

4.5 Chapter 5. Evaluations

Coordinator: M.B. Chadwick

- 5.1. Evaluations based on experimental data. Varlamov will reduce his current section. Two figures will remain (figs 6,7 in the first draft). Eq. 1 will be moved into chapter 3, and only equations 20 - 28 will remain. A citation to a detailed discussion in the Brookhaven conference book will be provided.
- 5.2. Evaluations based on theory. Chadwick will include a 2 - 3 page discussion on how evaluations are performed, and how both theory and experimental data are used. General information on fission evaluations will also be included.
- 5.3. Summary of national evaluated libraries. Listed in alphabetical order will be Beijing (CNDC-photo), JAERI (JENDL-PDF), Los Alamos (LA150), Moscow (EPNDL), and Obninsk (BOFOD). Each will include a few-page (less than 5 pages long) summary, including tables describing the contents of the libraries. Some key physical input

parameters can be included, e.g. fission barriers, but further additional details should be left out and provided in other papers that can be cited. Evaluators are encouraged to provide details in the file-1 parts of the ENDF files.

- 5.4. Intercomparison of evaluations. Fukahori will provide figures for all cases where more than one evaluation exists, compared with EXFOR data. For the most important elements: C, O, Be, Al, Fe, Ni, Cu, Zr, W, Pb, Bi, U, comparison pictures with EXFOR data will be provided even if there is just one evaluation available. If possible (γ,Xn) figures will be shown.
- Varlamov will assist Fukahori to ensure correct use and descriptions of EXFOR data. Of the above list of priority elements, C, O, Be, and Al have not yet been evaluated. Beijing plans to evaluate Be, and LANL and JAERI plan to evaluate C, O and Al. LANL also plans to evaluate D and Ca.

4.6 Chapter 6. IAEA photonuclear library

Coordinator: P. Obložinský

- 6.3 will be deleted.

4.7 Chapter 7. Recommendations

Coordinator: M.B. Chadwick

New chapter. This will include:

- Priority future experiments needed, e.g. photonuclear reactions on iron, and the general need for emission spectra data from monochromatic photons.
- A statement that with the development of evaluated photonuclear data, the importance of photoneutron production in a variety of application, such as medical accelerators, shielding, accelerator driven systems, can be studied.
- Future priority evaluations could be listed, e.g. mercury, for spallation sources.

4.8 Revised outline of the TECDOC

The title of the TECOC will be "Handbook on Photonuclear Data for Applications" with the subtitle "Final report of a co-ordinated research project". The revised outline of the TECDOC is summarized below.

Foreword

Chapter 1: Introduction (Coordinator: P. Obložinský)

1.1 Data needs for applications
1.2 Overview of the present TECDOC
References

Chapter 2: Definitions and notations (Coordinator: M.N. Martins)

Chapter 3: Available experimental data (Coordinator: M.N. Martins)

3.1 Experiments
3.1.1 Bremsstrahlung
3.1.2 Positron annihilation in flight
3.1.3 Bremsstrahlung tagging
3.1.4 Electron-induced reactions

5 ENDF-6 formats for photonuclear evaluations

A discussion took place between R.E. MacFarlane, R.C. Little, M. White, T. Fukahori, A. Blokhin, Yu Boasheng, and Y. Lee, regarding ENDF-6 formats, and some notes on this subject were provided by R.E. MacFarlane see Appendix 3. Conclusions are summarized below in the Table 1 and Table 2:

Table 1: Recommended ENDF-6 format

MF	MT	Explanation
1	451	Descriptive information and dictionary
3	1	Total photoabsorption cross section
3	4	Total (γ,1n) cross section
3	5	Photoabsorption cross section (from which production cross sections for particles and isotopes are determined using yields in MF6 MT5)
3	16	Total (γ,2n) cross section
3	18	Photofission cross section
3	103,4,..7	Total (γ,1z) cross sections
4	2	Elastic cross sections
4	18	Photofission
5	18	Prompt photoneutrons
5	455	Delayed photoneutrons
6	5	Yields (also known as branching ratios or multiplicities) and also possibly double-differential cross sections for light particles (n,p,d..γ) and residual isotopes.
6	16	DDXS for (γ,2n) reaction
6	18	DDXS for photofission
6	103-7, 600-850	Discrete and continuum levels

Table 2: Sum rules for cross sections (MF=3)

MT 1	=	MT 5 + MT 18 + MT 4 + MT 16 + MT 103 + ...
MT 4	=	sum (MT 50-91)
MT 103	=	sum (MT 600-649)

In the case that partial cross sections such as MT 4,16,103 etc. are given, they must be omitted from MT 5. MF 3/MT 4 must be only the sum of cross sections for MT 50-91. Therefore MF 6/MT 4 is not allowed. If evaluators wish to include DDX for (γ,1n), it must be in MF 6/MT 91 etc. MT 103-7 should be used in the same manner as MT 4.

In the case of the photofission cross section, MF 12,14,15 must be used for photofission gamma-ray spectra if MT 5 is used for the photofission neutron spectrum. If MF 6 is use for neutrons, MF 6 must also be used for gamma-rays.

MT 201-207 are not allowed for particle production, and such production should instead be placed in MT 5. Where spectra of residual nuclides are not given, a combination of LAW=0 and 7 for residuals and particles, respectively, is allowed. For the particle reactions, DDX must be stored in MF 6; MF 4 and MF 5 are not allowed. MF 13 is not allowed.

6. Future tasks

6.1 Individual tasks

A.I. Blokhin (IPPE, Obninsk)
1. Evaluate $^{234,236}U$ and $^{238,239,241}Pu$.
2. Submit BOFOD-98 to IAEA (November 1998).
3. Prepare revised contributions for TECDOC.

M.B. Chadwick (LANL, Los Alamos)
1. Evaluate major isotopes Pb, Fe, Cu, Al, C, O, D and possibly also Si up to 150 MeV.
2. Act as coordinator of chapters 4, 5 and 7.
3. Act as an editor of TECDOC.

T. Fukahori (JAERI, Tokai-mura)
1. Complete evaluation/formatting of C, N, O, ^{40}Ca, Na, Mn, Mg, Al, Ti, Cr, Co, Cu, Zr, remaining Mo, remaining W, Pb, and also D.
2. Prepare intercomparison for the IAEA Photonuclear Library.
3. Prepare revised contributions for TECDOC.

M.N. Martins (University Sao Paulo)
1. Compile data for EXFOR on (e^-,xp), (e^-,xα) and derived (γ,xp), γ(x,α) on $^{90,92}Zr$, possibly also on ^{56}Fe, ^{59}Co, ^{55}Mn and several isotopes of Ni.
2. Prepare revised contributions for TECDOC.
3. Act as coordinator of chapters 2 and 3.

V. Varlamov (CDFE Moscow)
1. Evaluate ^{14}N, ^{20}Ne, $^{54,56}Fe$ and $^{58,60}Ni$ and include them into EPNDL (task pending from the 1st RCM in Obninsk).
2. Produce a new addition to the EXFOR library (about 20 ENTRYs with accent on photoabsorption data, including Fe, Al and possibly also Cu).

3. Prepare publication "Atlas of photonuclear cross sections and systematics of main GDR parameters".
4. Prepare revised contributions for TECDOC.

Yu Baosheng (CNDC Beijing)
1. Evaluate Cr, Al and Be up to 30 MeV.
2. Prepare revised contributions for TECDOC.

Young Ouk Lee (KAERI, new participant)
1. Evaluate photoproduction of ^{99}Mo.
2. Evaluate Mo, Sn, possibly also S, Cl and Zn.

6.2 TECDOC timetable

- 15 August 1998: Chadwick will distribute the chapters to coordinators as *.tex files.
- 30 October 1998: Individual contributors will send their revised pages to coordinators.
- 30 January 1999: Coordinators will send their chapters to Chadwick.
- 28 February 1999: Chadwick will produce the second draft of the whole TECDOC.
- 15 March 1999: Nuclear Data Section will distribute the draft to all participants for comments.

6.3 Library timetable

The IAEA Photonuclear Library will be prepared in the preliminary version before the final meeting (October 1999). Final selection of evaluations will be made at that meeting.

Appendix 1

Second Research Co-ordination Meeting on
Compilation and Evaluation of Photonuclear Data for Applications
Los Alamos National Laboratory
Los Alamos, New Mexico, USA
23 - 26 June 1998

AGENDA

Tuesday, 23 June, 9:30 - 18:00

- Opening
  * Welcome (Dr. R.E. MacFarlane, LANL Group T-2 Leader)
  * Welcome (Dr. L.S. Waters, LANL APT Project Leader)
  * Remarks (P. Obložinský, IAEA)
- Approval of Agenda
- Announcements

- Status of the CRP (P. Obložinský)
- Progress reports/presentations by the CRP participants
  * M.B. Chadwick: Photonuclear evaluations using the GNASH code at Los Alamos
  * T. Fukahori: Progress report
  * M.N. Martins: Progress report
  * V.V. Varlamov: 1) MSU INP CDFE photonuclear data compilation and evaluation activities
    2) Atlas of photonuclear cross sections and systematics of main GDR parameters
  * Yu Baosheng: Evaluation and calculation of photonuclear data for 11 isotopes of W, Zr and V
  * A.I. Blokhin: Progress report

- Presentations by other participants
  * Y.-O. Lee: Photonuclear data project in KAERI
  * S.F. Mughabghab: 1) Novel approach to nuclear level densities
    2) Comment on photonuclear data evaluation

- Evening: Dinner at the Chadwick's house

Wednesday, 24 June, 9:00-18:00

- LANL presentations
  * 9:00 T. Brown/M.B. Chadwick: Photoneutrons using MCNP for radiation protection considerations in an electronic linac
  * 9:25 M. White/R.C. Little: Upgrading MCNP to use new photonuclear libraries in transport calculations
  * 9:40 R.E. MacFarlane: Processing photonuclear data with NJOY
  * 10:00 W.B. Wilson: Temporal neutron-source magnitudes and spectra in LWRs following shutdown
  * 10:20 A. Mashnik: Cascade-exciton model of photonuclear reactions

- Review of the draft TECDOC "Compilation and Evaluation of Photonuclear Data for Applications" (M.B. Chadwick)
- Review of intercomparison of evaluated photonuclear data (T. Fukahori)
- Discussion
  * General
  * TECDOC
  * IAEA Photonuclear Library

<u>Thursday, 25 June, 9:00-18:00</u>

- Discussion
  * Plans for completion of the CRP
  * Coordination and procedures
- Drafting of the Meeting Report

- Afternoon: Excursion
- Evening: Meeting dinner at a local New Mexican restaurant

<u>Friday, 26 June, 9:00-17:00</u>

- Drafting of the Meeting Report continued
- Adoption of the Meeting Report
- Adjournment

Appendix 2

Second Research Co-ordination Meeting on
Compilation and Evaluation of Photonuclear Data for Applications
Los Alamos National Laboratory
Los Alamos, New Mexico, USA
23 - 26 June 1998

LIST OF PARTICIPANTS

BRAZIL
Marcos Nogueira Martins
Departamento de Fisica Experimental
Laboratorio do Acelerador Linear
Instituto de Fisica
Universidade de Sao Paulo
Caixa Postal 66318
05389-970 Sao Paulo
Tel.: +55-11-818-7045
Fax: +55-11-818-6832
E-mail: martins@if.usp.br

CHINA
Baosheng Yu
Chinese Nuclear Data Centre
China Institute of Atomic Energy
P.O. Box 275 (41)
Beijing, 102413
Fax: +86-10-69357008
E-mail: bsyu@mipsa.ciae.ac.cn

JAPAN
Tokio Fukahori
Nuclear Data Center
Department of Reactor Engineering
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun
Ibaraki-ken, 319-11
Tel.: +81-29-282-5907
Fax: +81-29-282-5766
E-mail: fukahori@cracker.tokai.jaeri.go.jp

RUSSIA
Anatoly I. Blokhin
Centr Jadernykh Dannykh
Fiziko-Energeticheskij Institut
Ploshchad Bondarenko
249 020 Obninsk, Kaluga Region
Tel.: +7-084-399-8986
Fax: +7-095-230-2326
E-mail: blokhin@ippe.rssi.ru

RUSSIA
Vladimir V. Varlamov
Centr Dannykh Fotojad. Eksp
Institut Yadernoj Fiziki
Moskovskij Gosudarstvennyi Universitet
Vorob'evy Gory
119899 Moscow
Tel.: +7-095-939-3483
Fax: +7-095-939-0896
E-mail: varlamov@depni.npi.msu.su

UNITED STATES OF AMERICA
Mark B. Chadwick
Group T-2, MS B243
Theoretical Division
Los Alamos National Laboratory
Los Alamos, NM 87545
Tel: +1-505-667-9877
Fax: +1-505-667-9671
E-mail: chadwick@t2e.lanl.gov

CONSULTANT

S. KOREA
Young-Ouk Lee
Nuclear Data Evaluation Laboratory
Korea Atomic Energy Research Institute
P.O. Box 105
Yusung, Taejon 305-600
Tel.: +82-42-868-2964
Fax: +82-42-868-8356
E-mail: yolee@lui.kaeri.re.kr

OBSERVER

UNITED STATES OF AMERICA
S.F. Mughabghab
Building 701
Dept. of Advanced Technology
Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
Tel.: +1-516-344-5085
Fax: +1-516-344-3021
E-mail: **?**

LOCAL OBSERVERS

Los Alamos National Laboratory

T. Brown
Y. Lee
R.C. Little
A. Mashnik
R.E. MacFarlane
M. White
W.B. Wilson

IAEA

Pavel Obložinský
Nuclear Data Section
Wagramer Strasse 5
A-1400 Vienna
Tel.: +43 1 2060 21712
Fax: +43 1 20607
E-mail: oblozinsky@iaeand.iaea.or.at

Appendix 3

Extended Abstracts of Presented Papers

BOFOD-98: Present Status of the Evaluated Photonuclear Data File

A.I.Blokhin
State Scientific Centre of Russian Federation
Institute of Physics and Power Engineering
249020 Obninsk, Kaluga region, Russia

The BOFOD-98 library is one of various kinds of BROND special purpose files. The present status of the BOFOD-98 library is described briefly. The main efforts in 1997-98 were aimed to prepare the complete sets of evaluated data for the elements and their isotopes for what we performed the evaluation of photo-absorption cross-sections in previous years. In the first step we constructed the preliminary version of the evaluated photonuclear data for chromium, iron, nickel, zirconium isotopes and for Th-232, U-233, U-235, U-238. In Table we give a present content of the BOFOD-98 library. Data obtained in 1997-1998 are mentioned as "Yes" in a last colomn.

The BOFOD-98 library is in "ENDF-6" format and has N-LIB=42 for identifying the library. According to Recommendations of 1-st Research Co-ordination Meeting on "Compilation and Evaluation of Photonuclear Data for Applications" we used MT's numbers for a presentation of the photo-nuclear reactions:

MT= 3 for $\sigma(\gamma,abs)$ - photo-absorption cross-section;

MT= 4 for $\sigma(\gamma,n+np)$ - single neutron emission cross-section;

MT= 5 for $\sigma(\gamma, Sn) = \sigma(\gamma,n+np) + 2*\sigma(\gamma, 2n+2np) + \nu*\sigma(\gamma, fis)$;

MT=16 for $\sigma(\gamma,2n+2np)$ - double neutron emission cross-section;

MT=18 for $\sigma(\gamma,fis)$ - photo-fission cross-section;

References.

1. Summary report of the 1-st Research Co-ordination Meeting on "Compilation and Evaluation of Photonuclear Data for Applications" by P.Oblozinsky. Report INDC(NDS)-364, IAEA, Vienna, 1997.

Table. Status of Evaluated Photonuclear Data Files from BOFOD-98 Library.

Element or Isotope	MAT	Reaction	Quantity	Data prepared in 1997-98
Be-009	409	(γ, n)	σ	
Na-023	1123	(γ, n)	σ	
Cr-050	2450	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Cr-052	2452	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Cr-053	2453	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Cr-054	2454	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Mn-055	2555	(γ, n)		
Fe-054	2654	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Fe-056	2656	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Fe-057	2657	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Fe-058	2658	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Ni-nat	2800	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Ni-058	2858	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Ni-060	2860	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Ni-061	2861	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Ni-062	2862	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Ni-064	2864	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Sr-088	3888	(γ, abs), (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Zr-nat	4000	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes
Zr-090	4090	(γ, abs), (γ, Sn) (γ, n), $(\gamma, 2n)$	σ, $d\sigma/dE$, $d\sigma/d\Omega$	Yes

Table. Status of Evaluated Photonuclear Data Files from BOFOD-98 Library (cont'd).

Element or Isotope	MAT	Reaction	Quantity	Data prepared in 1997-98
Zr-091	4091	(γ, abs), (γ, Sn) (γ, n), (γ, 2n)	σ, dσ/dE, dσ/dΩ	Yes
Zr-092	4092	(γ, abs), (γ, Sn) (γ, n), (γ, 2n)	σ, dσ/dE, dσ/dΩ	Yes
Zr-094	4094	(γ, abs), (γ, Sn) (γ, n), (γ, 2n)	σ, dσ/dE, dσ/dΩ	Yes
Zr-096	4096	(γ, abs), (γ, Sn) (γ, n), (γ, 2n)	σ, dσ/dE, dσ/dΩ	Yes
Mo-092	4292	(γ, abs)	σ	
Mo-094	4294	(γ, abs)	σ	
Mo-096	4296	(γ, abs)	σ	
Mo-098	4298	(γ, abs)	σ	
Mo-100	4299	(γ, abs)	σ	
Sn-114	5014	(γ, abs)	σ	
Sn-116	5016	(γ, abs)	σ	
Sn-117	5017	(γ, abs)	σ	
Sn-118	5018	(γ, abs)	σ	
Sn-119	5019	(γ, abs)	σ	
Sn-120	5020	(γ, abs)	σ	
Sn-122	5022	(γ, abs)	σ	
Sn-124	5024	(γ, abs)	σ	
Te-120	5220	(γ, abs)	σ	
Te-122	5222	(γ, abs)	σ	
Te-124	5224	(γ, abs)	σ	
Te-126	5226	(γ, abs)	σ	
Te-128	5228	(γ, abs)	σ	
Te-130	5230	(γ, abs)	σ	
W-182	7482	(γ, abs)	σ	
W-184	7484	(γ, abs)	σ	
W-186	7486	(γ, abs)	σ	
Pb-nat	8200	(γ, abs), (γ, Sn) (γ, n), (γ, 2n)	σ	Yes
Bi-209	8309	(γ, abs), (γ, Sn) (γ, n), (γ, 2n)	σ	Yes

Table. Status of Evaluated Photonuclear Data Files from BOFOD-98 Library (ended).

Element or Isotope	MAT	Reaction	Quantity	Data prepared in 1997-98
Th-232	9032	(γ, abs), (γ, Sn) (γ, n), (γ, 2n), (γ, fis)	σ, ν(E) dσ/dE, dσ/dΩ, dν/dE	Yes
U-233	9233	(γ, abs), (γ, Sn) (γ, n), (γ, 2n), (γ, fis)	σ, ν(E) dσ/dE, dσ/dΩ, dν/dE	Yes
U-234	9234	(γ, n), (γ, 2n), (γ, fis)	σ	
U-235	9235	(γ, abs), (γ, Sn) (γ, n), (γ, 2n), (γ, fis)	σ, ν(E) dσ/dE, dσ/dΩ, dν/dE	Yes
U-236	9236	(γ, n), (γ, 2n), (γ, fis)	σ	
U-238	9238	(γ, abs), (γ, Sn) (γ, n), (γ, 2n), (γ, fis)	σ, ν(E) dσ/dE, dσ/dΩ, dν/dE	Yes
Np-237	9237	(γ, n), (γ, 2n), (γ, fis)	σ	
Pu-239	9439	(γ, n), (γ, 2n)	σ	
Pu-241	9441	(γ, n)	σ	
Am-241	9541	(γ, fis)	σ	
Am-243	9543	(γ, fis)	σ	

APPLICATION OF THEORETICAL METHODS FOR EVALUATION PHOTO-NUCLEAR DATA FOR ACTINIDES UP TO 20 MeV

A.I. Blokhin

Institute of Physics and Power Engineering

Obninsk, Kaluga Region, Russia

Abstract. The present work is intended to continue the evaluation of the photonuclear cross-section for the main materials what should be proposed by the 1-st CRP-Meeting on "Compilation and Evaluation of Photonuclear Data for Applications" (03-06 Dec 1996, Obninsk, Russia).

The general purpose of this research is to improve the theoretical methods for the calculations and the evaluations of the differential and integral photonuclear cross-sections in the wide excitation energy up to 20 MeV. On the base of that for the Th-232, U-233, U-235, U-238 elements the evaluated data files were prepared.

The quasiparticle-phonon model created for deformed nuclei was adopted for the analysis and description a photoabsoption cross-section in the excitation energy range up to 20 MeV. The statistical model was used for the analysis the experimental data about the (γ,n), (γ,2n), and (γ,fiss) reactions.

On the base of the EXFOR library and information published in different journals it was compiled and analysed the experimental data concerning the Th-232, U-233, U-235 and U-238 nuclei.

From analysis of experimental data the modern set of the parameters needed for the theoretical description the photonuclear cross-sections in a wide gamma-ray energy range was obtained and used to produce the complete evaluated data files for fissile nuclei: Th-232, U-233, U-235 and U-238. On the fig. 1-24 the intercomparision of the evaluated and experimental data are presented.

The preliminary version of evaluated photonuclear data files for the Th-232, U-233, U-235 and U-238 elements was created in ENDF-6 format and presented in the IAEA Nuclear Data Section (May 1998) for the intercomparision with another similar data in the frame of the CRP-Meeting on "Compilation and Evaluation of Photonuclear Data for Applications" (LANL, June 1998). It included the data sets for the (γ,abs), (γ,n), (γ,2n), (γ,Sn) and (γ,fiss) - cross-sections and the angular-energy distributions concerning the scientific background and scope of the research project.

The evaluated photonuclear data library developed can be used as a part for the future development of complete international library. Some of the photonuclear cross-section data can be applied for the practical calculations.

It was modified and constructed a lot of the codes for the description of photoabsoption, (γ,n), (γ,2n), (γ,Sn) and (γ,fiss) - cross-sections for fissile nuclei. These codes were adopted on PC-computer.

The photonuclear data processing by the Njoy-system was performed for the Th-232, U-233, U-235 and U-238 elements. The original data were processed to "gendf" and "acer"-format presentation for future data testing. For that process some additional information was inserted to original evaluated data files.

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Photonuclear evaluations using the GNASH code at Los Alamos

M.B. Chadwick and P.G. Young
University of California, Los Alamos National Laboratory,
Theoretical Division, Los Alamos, NM 87545, USA

Since the 1st Research Coordination Meeting on Compilation and Evaluation of Photonuclear Data for Applications, held in Obninsk in 1996, we have made progress in developing a capability to produce ENDF-format photonuclear data evaluations up to 150 MeV, based on GNASH model calculations. Our progress can be summarized as follows:

- Developed GNASH modeling capability, based on GDR and quasideuteron absorption mechanisms, and preequilibrium and Hauser-Feshbach decay mechanisms
- Developed the GSCAN code to handle photon projectiles, for transforming the GNASH calculated results into ENDF-6 format, and included a capability to calculate photonuclear recoil spectra
- Discussed with LANL researchers modifications needed for the NJOY code (to process photonuclear data), and the MCNP/MCNPX transport codes (to utilize the new data in transport calculations).
- Produced a first LANL photonuclear evaluation for ^{184}W in ENDF-6 format; initiated work on developing similar evaluations for other important elements including D, C, O, Al, Fe, Cu, Pb
- Drafted documentation on this work for an IAEA TECDOC on photonuclear reactions, and collected together contributions from other participants for the TECDOC

SUMMARY OF LANL PHOTONUCLEAR EVALUATION PROCEDURE

The evaluations provide a complete representation of the nuclear data needed for transport, damage, heating, radioactivity, and shielding applications over the incident photon energy range from 1 to 150 MeV. The evaluations utilizes ENDF-6 formats MF=6, MT=5 to represent all reaction data. Production cross sections and emission spectra are given for neutrons, protons, deuterons, tritons, alpha particles, gamma rays, and all residual nuclides produced (A≥5) in the reaction chains. To summarize, the ENDF sections with non-zero data above are:

```
MF=3 MT= 5   Photoabsorption (total nonelastic) cross section
             = Sum of binary (g,n') and (g,x) reactions

MF=6 MT=  5  Production cross sections and energy-angle
             distributions for emission neutrons, protons,
             deuterons, and alphas; and angle-integrated
             spectra for gamma rays and residual nuclei that
             are stable against particle emission
```

The evaluations are based on nuclear model calculations that have been benchmarked to experimental data. We use the GNASH code system (Yo92), which utilizes Hauser-Feshbach statistical, preequilibrium and direct-reaction theories. Optical model calculations are used to obtain particle transmission coefficients for the Hauser-Feshbach calculations. An exciton model (modified to account for photon projectiles - see below) of Kalbach is used, including cluster preequilibrium emission (Ka85,Ka77).

Input parameters for the optical model calculations, level densities, and discrete levels, and gamma-ray strength functions, were identical to those used for our corresponding neutron-induced 150 MeV GNASH calculations, as documented in the corresponding LA150 ENDF file 1.

The GNASH code was extended to calculate photonuclear reactions in the following way, described in detail in Ref.(Ch95b). Photoabsorption is modeled through the giant resonance at the lower energies, and the quasideuteron (QD) mechanism (Ch91) at higher energies. After the initial interaction, primary and multiple preequilibrium emission of fast particles can occur, followed by sequential Hauser-Feshbach decay. Preequilibrium decay is calculated with an exciton model, based on a $2p1h$ initial state to approximate correlation effects in the QD mechanism, as proposed by Blann. The equi-probability of neutron and proton excitons following photoabsorption (in contrast to nucleon-induced reactions) is accounted for in the primary and multiple preequilibrium calculations. Full angular momentum and parity conservation is included in a Hauser-Feshbach treatment of equilibrium emission, accounting for the fact that an E1-photon brings in one unit of angular momentum

A model was developed to calculate the energy distributions of all recoil nuclei in the GNASH calculations - a modification of our theory in (Ch96) to include the fact that an incident photon brings in a smaller momentum than a nucleon projectile of the same energy. The recoil energy distributions are represented in the laboratory system in MT=5, MF=6, and are given as isotropic in the lab system. All other data in MT=5,MF=6 are given in the center-of-mass system. This method of representation utilizes the LCT=3 option approved at the November, 1996, CSEWG meeting.

While angle-integrated spectra are provided for the secondary ejectiles, we intend angular distributions of the light ($A \leq 4$) particles to be determined by a data processing code such as NJOY. To do this, we provide preequilibrium fractions for the light particles, to facilitate the calculation of angle-energy correlated double-differential spectra. For preequilibrium emission, such a calculation could make use of the theory of Chadwick et al. (Ch95a), which modifies Kalbach's angular distribution systematics for incident photons. For the ejectiles emitted through other mechanisms (equilibrium decay, or direct emission), the NJOY code could assume isotropy, or account for the fact that experimental data often shows emission in the GDR energy region to have a dipole shape, peaked at 90 degrees.

The GNASH code's ability to model photonuclear reactions has been tested in a number of works (Ch91,Ch94,Ch95a,95b), where comparisons against experimental data were shown (Al64,Be87,Br66,Bl73,Di88,Fu85,Le81,Le82,Ve70,Yo72). This involved tests of calculated photoneutron reaction channels (g,1n), (g,2n), (g,3n), etc., as well as the photoneutron production (g,xn), emission spectra, and photoneutron multiplicities (yields) up to 140 MeV which are useful for indirectly validating our preequilibrium modeling, since preequilibrium reactions strongly influence the multiplicity. While experimental data often exist for total neutron production, they rarely exists for the emission spectra, and thus a model code such as GNASH is essential for providing emission spectra data information, after it has been validated against measured cross section data.

In the evaluation of g+184W, the calculated photoabsorption cross section using GDR Lorentzian and QD parameters was modified slighly to better agree with the elemental tungsten photoabsorption cross section from Saclay (Ve75), as shown in Dietrich and Berman's compilation (Di88).(No isotopic 184W photoabsorption data exists). At the higher energies, use was made of the total Ta absorption cross section data of Lepretre et al (Le81) to guide the quasideuteron model calculation of the absorption cross section, giving a Levinger parameter of L=6.7. (No such data exists for W, but we expect W and Ta experimental data to be similar). Good agreement was obtained with (g,1n) and (g,2n) elemental W experimental data from Saclay (Ve75,Di88), as well as neutron multiplicity data on Ta (Le81). The GNASH input parameter describing the preequilibrium exciton level density was modified to optimize agreement with the measured data.

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JAERI Progress Report of IAEA/CRP on Compilation and Evaluation of Photonuclear Data for Applications

Tokio FUKAHORI
Nuclear Data Center, Japan Atomic Energy Research Institute,
Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195 Japan
e-mail: fukahori@cracker.tokai.jaeri.go.jp

1. Evaluation and Compilation of JENDL Photonuclear Data File

For γ-ray induced reaction data up to 140 MeV, the JENDL Photonuclear Data File is provided for applications such as electron accelerator shielding and radiation therapy. The photon absorption cross section is evaluated with the giant dipole resonance model and quasi-deuteron model, and the decaying processes are estimated with the statistical model with preequilibrium correction by using MCPHOTO and ALICE-F codes. The isotopes shown in Table 1 are planning to be included in the file.

Table 1 The nuclei included in the JENDL Photonuclear Data File and its status

H-2, C-12, N-14, O-16, Na-23, Mg-24,25,26*, Al-27, Si-28*,29*,30*, Ca-40*,48, Ti-46,48, V-51*, Cr-52, Mn-55, Fe-54*,56*, Co-59, Ni-58*,60*,61*,62*,64*, Cu-63,65, Zn-64*, Zr-90, Nb-93*, Mo-92,94*,96*,98*,100, Cs-137*, Gd-160*, Ta-181*, W-182*,184,186*, Au-197, Pb-206,207,208, Bi-209*, U-235*,238*

* Compilation has been finished and files are now in the review stage.

The evaluation work was in a final stage. However, the hard disk of the host computer compiled JENDL Photonuclear Data File in was crashed, and many of evaluated results and files were lost, unfortunately. In 1998, the recovering work was carried out, but not yet completed. The nuclides listed in Table 1 with symbol "*" have been almost recovered and some of them was used in the intercomparison mentioned in Section 3.

2. Production of IAEA-TECDOC Documents

Draft manuscript of IAEA-TECDOC on Photonuclear Data Library has been written for the items of

- Chapter 4: Nuclear modeling technique
  - 4.4 Nuclear modeling codes
    - 4.4.1 ALICE-F, MCPHOTO
- Chapter 5: Evaluation technique
  - 5.1 Evaluation
    - 5.1.2 Evaluations based on theory calculations
  - 5.2 Models used for producing evaluated libraries
    - 5.2.1 JAERI libraries
  - 5.3 Intercomparison of results in libraries
- Chapter 6: Summary of the IAEA Photonuclear Data Library
  - 6.4 ENDF-6 format.

The draft has been sent to Mark Chadwick to convert TeX format. The draft for the part of

Chapter 6:

6.2 Contents of library

6.3 Illustration of evaluated photonuclear data compared with measurements for important elements

has not been prepared yet, because IAEA Photonuclear Data Library has not been compiled yet.

3. Intercomparison of Results in Libraries

The status of evaluated photonuclear data files of BOFOD, CNDC, EPNDL, JENDL and LANL were checked. BOFOD and EPNDL include limited physical quantities, for instance, photoabsorption, (g,1n) and photofission cross sections. The others are full evaluated files. Originally the intercomparison should be made for the elements of Be, C, O, Al, Fe, Ni, Cu, Zr, W, Pb, Bi and U. However, it was difficult to do so, because the target files were not completed. Intercomparison of above files was performed for the quantities of certain nuclides that have two or more available files and experimental data in EXFOR. The selected reactions are:

Si-28(g,n)Si-27,	V-51(g,n)V-50,	V-51(g,2n)V-49,
Cr-52(g,n)Cr-51,	Fe-54(g,n)Fe-53,	Fe-56(g,abs),
Fe-56(g,n)Fe-55,	Cu-63(g,n)Cu-62,	Cu-63(g,p)Ni-62,
Cu-63(g,np)Ni-61,	Cu-65(g,n)Cu-64,	Cu-65(g,p)Ni-64,
Cu-65(g,np)Ni-63,	Mo-94(g,n)Mo-93,	Mo-94(g,2n)Mo-92,
Mo-96(g,n)Mo-95,	Mo-96(g,2n)Mo-94,	Mo-98(g,n)Mo-97,
Mo-98(g,2n)Mo-96,	W-182(g,abs),	W-182(g,n)W-181,
W-184(g,abs),	W-184(g,n)W-183,	W-186(g,abs),
W-186(g,n)W-185,	W-186(g,2n)W-184,	W-186(g,3n)W-183,
Pb-nat(g,abs),	Bi-209(g,abs),	Bi-209(g,n)Bi-208,
Bi-209(g,2n)Bi-207,	U-235(g,abs),	U-235(g,fis),
U-235(g,n)U-234,	U-235(g,2n)U-233,	U-238(g,abs),
U-238(g,fis),	U-238(g,n)U-237 and	U-238(g,2n)U-236.

The results of intercomparison are illustrated in figures. Some of JENDL results are not completed. For photoabsorption and photofission cross sections, all the files can reproduce the experimental data. However, some files are not in good agreement with the experimental data for partial reaction cross sections such as (g,n) and (g,2n) reactions. It is concluded that some improvements are necessary. Above comments were made for IAEA-TECDOC manuscript as well as table of each file status and result figures.

Progress Report

2nd CRM on *Compilation and Evaluation of Photonuclear Data for Applications*

LANL, Los Alamos, NM, USA, 23-26 June, 1998

Marcos N. MARTINS
Laboratório do Acelerador Linear, Instituto de Física da Universidade de São Paulo
CP 66318, 05315-970 São Paulo, SP, Brazil

I - Introduction

This Progress Report will be divided in two parts. The first one presents some high accuracy data on the electrofission of ^{238}U in the energy range 90-250 MeV, a comparison with the available data in this energy region, and a preliminary analysis in terms of the several processes that may contribute to the cross section. The second part will describe the development of our effort in the compilation of photonuclear data from electrodisintegration experiments.

II - Electrofission of ^{238}U

The absolute cross section of the $^{238}U(e,f)$ reaction was measured with high accuracy using the 300 MeV Linac of the Kharkov Institute of Physics and Technology, Ukraine.

The target (233(3) $\mu g/cm^2$ thick) was prepared from depleted ^{238}U (isotopic purity 99,9%) evaporated over a 10 μm thick aluminum backing. The photofission contribution to the yield came only from bremsstrahlung in the target and was evaluated to be less than 2%. Fission fragments were detected by silicon surface barrier detectors. The solid angle was determined using an α-source with the same geometry of the beam spot and also calculated by Monte Carlo simulation [1], with good agreement. The measured energy spectra present the typical two-bump structure and were integrated from 10 MeV to obtain $d\sigma/d\Omega$. The total cross section, σ_e, was calculated assuming an isotropic angular distribution for the fission fragments. This assumption implies an uncertainty of less than 3 %, which increases the absolute uncertainty to 6 %.

The analysis of the total cross section was performed using virtual photon spectra calculated in DWBA [2]. The ground state charge distribution of the scattering nucleus was described by a three-parameter Fermi model [3]. The total electrofission cross section was calculated from photonuclear cross section data [4,5] considering the E1 and E2 giant resonances, and the quasi-deuteron and meson production processes as possible photoabsorption mechanisms. The E2 giant resonance strength was obtained from electron scattering data [6]. The quasi-elastic mechanism was not considered in this framework (virtual photon formalism) since it does not contribute at the photon point.

Figure 1 shows the measured data (and others from the literature, available in the energy range under study) and the calculated contribution from photonuclear processes. The approximately 30 % difference could be due to the contribution of the quasi-elastic mechanism.

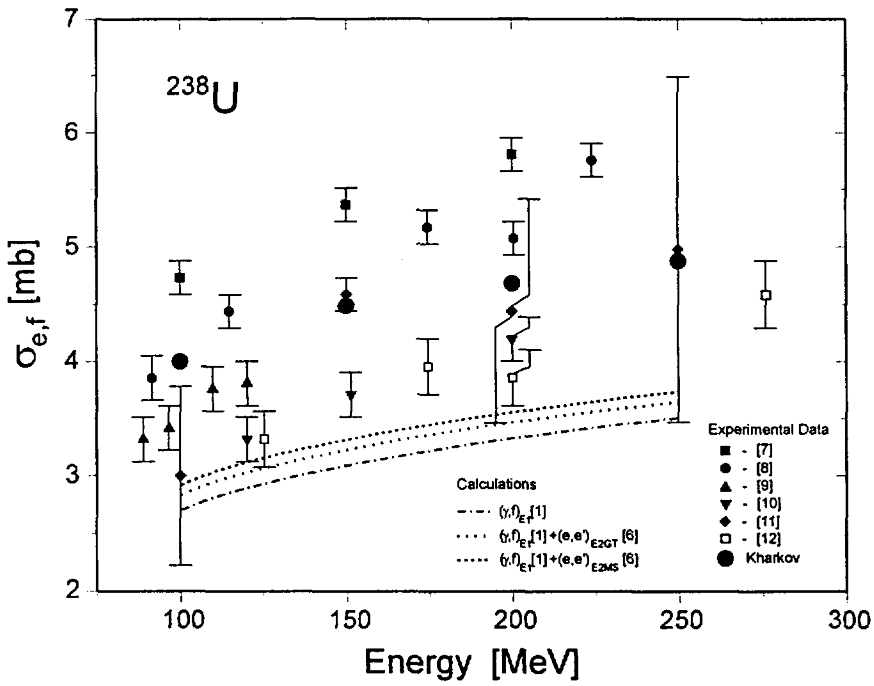

Figure 1 - Electrofission cross section

III - Compilation of Photonuclear Data

The compilation of photonuclear cross sections continues our proposal of increasing the amount of compiled data obtained from electrodisintegration experiments.

The importance of this kind of experiment stems from its sensitivity to separate E1 and E2 multipole strengths involved in photonuclear processes.

An electrodisintegration experiment, or (e,x), is one in which an outgoing nuclear fragment or radioactivity is detected. It is the experiment complementary to electron scattering, (e,e'), where the scattered electron is detected. In the (e,x) case, the scattered electron is not observed, so the experiment integrates over all its final states. The electrodisintegration cross section includes all the multipoles excited in electron scattering, but it emphasizes the transverse parts of the interaction because it is dominated by the very forward angles (which are rarely sampled in electron scattering experiments).

Electrodisintegration experiments are usually analyzed using the virtual photon technique [13,14]. The basic premise of this technique is that we can express the electrodisintegration cross section, $\sigma_{e,x}(E_0)$, in terms of the photonuclear cross sections, $\sigma^{\lambda L}_{\gamma,x}(E)$, associated with the absorption of real photons of multipolarity λL, through an integral over the corresponding virtual photon spectra, $N^{\lambda L}(E_0,E,Z)$:

$\sigma_{e,x}(E_0) = \int_{Thresh.}^{E_0-m_0c^2} \sum_{\lambda L} \sigma^{\lambda L}_{\gamma,x}(E) N^{\lambda L}(E_0,E,Z) \frac{dE}{E}$. In this expression E_0 stands for the total electron energy, E for the virtual photon energy, Z for the atomic number of the target nucleus and m_0 for the rest mass of the electron. Several groups (mainly in Brazil, Scotland, Germany and United States) used this method in order to separate the multipole components of the photonuclear cross section, using the substantial difference between the virtual photon spectra of different multipolarities [14].

Even though this method is not very sensitive to the detailed shape of the cross section, it allows a very accurate separation of E1 and E2 multipole strengths, which can not be done in experiments using real photons. For this reason electrodisintegration experiments have been a powerful tool in the study of the multipole composition of photonuclear cross sections [15]. This kind of information, associated to the accurate shape and intensity determination from photonuclear cross section obtained with monochromatic photons, draw a quite complete picture of the interaction of photons and nuclei.

The following nuclides and reactions were selected for compilation: $^{238}U(e,n)$; $^{238}U(\gamma,n)$ [16]; $^{181}Ta(e,xn)$; $^{208}Pb(e,xn)$; and $^{209}Bi(e,xn)$ [17].

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The MSU INP CDFE

Photonuclear Data Compilation and Evaluation Activities.

I.N.Boboshin, A.V.Varlamov, V.V.Varlamov, M.E.Stepanov

Progress Report
to the 2-nd Research Co-ordination Meeting
(23 - 26 June 1998, Los-Alamos, New Mexico, USA)
of the IAEA Co-ordinated Research Programme on
"Compilation and Evaluation of Photonuclear Data for Applications"

In accordance to the scientific Scope and Programme Goals of the IAEA Research Coordination (RC) Programme on "Compilation and Evaluation of Photonuclear Data for Applications" /1/ the following works have been carried out by the CDFE in 1997 - 1998 period of time and the following results have been obtained.

1. The new (corrected and added) version of the systematics /2/ of the main "**PARAMETERS OF GIANT DIPOLE RESONANCE**" has been developed.

Included are parameters deduced from the photoabsorption, total neutron production, neutron yield, and also single, double and triple neutron production, charged particle emission and fission reaction cross sections. The table contains information on the GDR parameters for 215 isotopes and natural compositions with Z between 1 and 95. There is altogether about 1 050 entries. The data from the CDFE collection /2/ and from /3/ have been used as a base and data for almost all more than 400 various photoneutron cross section entries from /4/ have been included.

2. The relevant part of the table "**PARAMETERS OF GIANT DIPOLE RESONANCE**" for data deduced from the most interesting photoabsorption (G,ABS) cross sections and neutron production (G,SN) = (G,N) + (G,NP) + (G,2N) + (G,3N) + ... +(G,F) cross sections has been included into the IAEA NDS **REFERENCE INPUT PARAMETER LIBRARY (RIPL).** Altogether, this part contains 366 entries for 6 reaction types.

3. The main "**PARAMETERS OF GIANT DIPOLE RESONANCE**" added by the information on the relevant numbers of **EXFOR SUBENTs** in the form of the table with the following columns

EXFOR	NUCL	A	REACT	E-MAX MEV	SIG MB	FWHM MEV	E-INT MEV	SIG-INT MEV*MB	SIG-INT-I MB	REFERENCE	AUTHOR

has been put up on the CDFE Web-site

<u>`http://depni.npi.msu.su/cdfe/`</u>

The relevant plots of various photonuclear reaction cross sections have been put up on the Web-site also. The digital data in the form of the EXFOR DATA section are available to users as downloadable sources.

4. The new **CDFE EXFOR TRANSes M020** (ENTRYs M0370, M0386 - M0390, M0501 - M0515), and **M022** (ENTRYs M0516 - M0530) have been produced and transmitted to the IAEA NDS:

TRANS	ENTRYs	DATA TABLES
M020	21	109
M022	17	144

5. The single complete photonuclear data bibliography – the combination of /2, 5, 6/ Photonuclear Data Indexes for 1955 – 1996 has been produced and put up on the CDFE Web-site in the form of 2 compressed files with the data in the forms of DATA TABLE and BIBLIOGRAPHY /2/ as downloadable sources.

6. The complete version of the evaluated photonuclear data library **EPNDL** including altogether 40 reactions for 20 materials has been produced in the cooperation with the CJD (Dr. A.I.Blokhin) by merging of the data from previously prepared libraries **EPNDL1** and **EPNDL2**:

LIBRARY	MATERIALS	REACTIONS
EPNDL1	15	21
EPNDL2	7	21
EPNDL	20	40

7. The CDFE contributions to the **IAEA HANDBOOK ON PHOTONUCLEAR DATA** specified in /1/ have been prepared.

8. The program of the EPNDL3 library development has been started (the preliminary version of the EPNDL3 includes evaluated photonuclear reaction cross sections for Ne isotopes /7/).

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ATLAS OF VARIOUS PHOTONUCLEAR REACTION CROSS SECTIONS AND SYSTEMATICS OF THE MAIN GIANT DIPOLE RESONANCE PARAMETERS

V.V.Varlamov, B.S.Ishkhanov, M.E.Stepanov

Centre for Photonuclear Experiments Data (CDFE)
Institute of Nuclear Physics
Moscow State University, Moscow Russia

The main GDR parameters obtained from the various photoneutron reaction cross sections studied using the quasimonoenergetic positron annihilation photon beams have been presented in forms of both tables and plots in several publications, for example in /1, 2/. The most complete data were published in /3/. A number of not only various reaction cross sections but other quantities such as for example outgoing particle angular distributions and energy spectra also obtained using both bremsstrahlung and quasimonoenergetic photons has been presented in forms of tables and plots in /4/. The plots of experimental and evaluated photoneutron reaction cross section data for selected nuclides have been published /5/ using the international EXFOR library.

The presented systematics (the improved (corrected and added) version of the table "PARAMETERS OF GIANT DIPOLE RESONANCE" published in /6/) includes the various photonuclear reaction cross section parameters data obtained using both bremsstrahlung and quasimonoenergetic photons. Data sources are the International Nuclear Data EXFOR library, the USA National Institute of Standards and Technology (NIST) photonuclear data collection for 1955 – 1982 /7/, and the MSU INP CDFE data collection for 1976 - 1996 /6, 8/. The data for almost all more than 400 various photoneutron cross section entries from /3/ are included also.

The parameters deduced from various photonuclear reaction cross sections are included:

G,ABS	total photoabsorption cross section
G,XN	neutron yield cross section [(γ,n) + (γ,np) + 2(γ,2n) + 3(γ,3n) + ... + ν(γ,F)]
G,SN	total neutron production cross section: [(γ,n) + (γ,np) + (γ,2n) + (γ,3n) + ... + (γ,F)]
G,N	single neutron cross section [(γ,n) + (γ,np)]
G,1N	pure one-neutron cross section (γ,n)
G,2N	double neutron cross section [(γ,2n) + (γ,2np)]
G,3N	triple neutron cross section [(γ,3n) + (γ,3np)]
G,F	fission/neutron cross section for actinides [(γ,F) = (γ,f) + (γ,nf) + ...]

The Table contains information on the GDR parameters derived directly from the data for 82 elements (215 isotopes and natural compositions) with Z between 1 and 95. There is altogether about 1050 entries.

The Table consists of the following columns

EXFOR	NUCL	A	REACT	E-MAX MEV	SIG MB	FWHM MEV	E-INT MEV	SIG-INT MEV*MB	SIG-INT-1 MB	REFERENCE	AUTHOR

and contents of codes are the following:

Code	Contents
EXFOR	the relevant EXFOR SUBENT number
NUCL	nucleus investigated
A	nucleus investigated (mass number)
REACT	reaction
E-MAX	cross section maximum energy
SIG	maximum cross section value
FWHM	full width at half maximum
E-INT	integration energy limit
SIG-INT	integrated cross section
SIG-INT-1	first moment of the integrated cross section
REFERENCE	reference
AUTHOR	1-st author

Each entry as a rule is represented by one line containing the description of the reaction and numerical data of the GDR parameters from the paper of relevant reference. In the cases when there are more than one clear maxima with comparable amplitudes in the reaction cross section, their parameters are shown in additional lines. The addition lines are represented also for cases of several integrated cross section values for different integration energy limits.

The plots of various photonuclear reaction cross sections presented in the international EXFOR library are organized by element and isotope also. For each isotope the cross section data for the same reaction from various experiments are presented on the same plot by the different symbols.

The information on the each isotope abundance and the most important reactions threshold values is added.

The data from the presented systematics are put upon the MSU INP CDFE Web-site:

http://depni.npi.msu.su/cdfe

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Evaluation and Calculation of Photonuclear Data for 11 isotopes of W, Zr and V

Yu Baosheng Han Yinlu Zhang Jingshang

(China Nuclear Data Center, CIAE)

According to requirement of the Contract N0. 8833/R1/RB, we have performed the improvement of theoretical calculation method. Meanwhile, the evaluations and calculations were carried out for $^{180,182,183,184,186}W$, $^{90,91,92,94,96}Zr$ and ^{51}V in photon energy range up to 30 MeV in format ENDF/B-VI..

1) Improvement of the Photonuclear data calculation with GUNF code

The GUNF code implements the Unified Hauser-Feshbach and exciton model in an open-ended sequence of reaction chains including (γ, γ), (γ, n), (γ, p), (γ, α), (γ, ^{3}He), (γ, d), (γ, t), (γ, 2n), (γ, np), (γ, nα), (γ, pn), (γ, 2p), (γ, αn) and (γ, 3n).

This code has three main functions:

(1) Adjusting the parameters of gamma absorption cross section by fitting gamma absorption cross section or (γ,n) cross section.

(2) Calculating the cross sections and spectra of each reaction channel.

(3) Outputting the calculated data in ENDF/B6 format with incident gamma energies up to 30 MeV.

2) Evaluation and Analysis of Experimental Data

The various available measured data of photonuclear reaction for wolfram's (Zirconium and Vanadium) isotopes were collected and analyzed. The available experimental data for photonuclear reaction cross sections of $^{182,184,186}W$, $^{90,91,92,94}Zr$ and ^{51}V up to 1997 are included. Many data were retrieved from EXFOR master files, in addition the supplemented data with new information. These measured photonuclear reaction data, which cover from threshold to 30 MeV.

For photonuclear reactions (γ, ABS), (γ, n)+(γ, n+p), (γ, 2n)+ (γ, 2n+p) ..., the available experimental data were analyzed and evaluated so as to guide the theory calculation. At present work, the photonuclear reactions, for which the cross sections were evaluated, are as follows: (γ, ABS), (γ,n)+(γ,n+p), (γ,2n)+(γ,2n+p), (γ. 3n), (γ, n+p), (γ, n+α), (γ, 2n), (γ, 3n), (γ, p), (γ, d), (γ, t), (γ, ^{3}He), (γ, α) ....and also neutron spectra of (γ,2n), (γ, 3n), (γ, n+p), (γ, n+α) and (γ, $n'_{continue}$) are given.

3) Calculation Photonuclear Data for 11 isotopes of W, Zr and V

Using the code APOM, the best neutron optical potential parameters can be searched automatically by fitting experimental total, nonelastic scattering cross sections and elastic scattering angular distributions of n + ^{182,184,186,Nat}W (^{90,91,92,94,Nat}Zr, ^{51}V) reactions, a set of optimum neutron optical potential parameters for W(Zr, ^{51}V) were obtained, respectively. The optical potential parameters for particles p, α, ^{3}He, d and t were taken from concerned references.

The absorption cross sections of γ with ^{182,184,186}W (^{90,91,92,94}Zr , ^{51}V), a set of giant resonance parameters of gamma for W (Zr , ^{51}V) were obtained. Then photonuclear reaction data for ^{180,182,183,184,186}W (^{90,91,92,94,96}Zr , ^{51}V) can be calculated by the code GUNF. Since the calculated results for many channels are in pretty agreement with existed experimental data, therefore the cross sections there without experimental data were predicted.

4) Recommended Photonuclear Reaction Data in ENDF/B-VI format

The photonuclear data for ^{180,182,183,184,186}W, ^{90,91,92,94,96}Zr , ^{51}V were recommended in ENDF/B-VI format based on evaluated and calculated data. The file descriptions for recommended data are as following :

MF = 1 General information

MT = 451 is the general description for recommended data based on evaluated and calculated data and including the directions of MF and MT.

MF = 3 Photonuclear reaction cross section

MT = 3 Photoabsorption cross section
MT = 4 Photoneutron cross section for (γ, n) reaction
MT = 50, 51 ..66... and 91 are Photoneutron cross section of partial excitation state from ground, first to the latest state and continuum state.
MT = 16, 17 (γ, 2n) and (γ, 3n) reaction cross sections
MT = 102, 103, 104, 105, 106, 107, 111 (γ, γ), (γ, p), (γ, d), (γ, t), (γ, ^{3}He), (γ,α) and (γ, 2p) reaction cross sections.

MF = 6 The double differential cross sections

MT = 16, 17, 22, 28, 91 (γ, 2n),(γ, 3n), (γ, n+α) , (γ, n+p) and (γ, $n_{continuum}$) reactions

The check and test of the recommended data of photonuclear reaction in ENDF/B-VI format were carried out with computer programs in CNDC, including format, the consistence between the total and sum of partial cross sections, the physics characterization and the energy balance between incident gamma and emission particles.

Photonuclear Data Project in KAERI

LEE, Young-Ouk and CHANG, Jonghwa
Nuclear Data Evaluation Lab.
Korea Atomic Energy Research Institute
P.O. Box 105, Yusung, Taejon, 305-600, Korea
Phone: +82-42-868-2964 e-mail: yolee@lui.kaeri.re.kr

I. Introduction

Although nuclear data activities in Korea are still in the early stage, considerable demands for more accurate and wide-range nuclear data from nuclear R&D fields activated a new nuclear data project titled as "Development of Nuclear Data System". It was launched in 1997 as one of nation-wide long-term nuclear R&D programs in Korea for the next decade. Its main goals are establishing highly reliable nuclear data system and building up the infra-structure for utilization of nuclear data. As for the R&D's on the nuclear reactor, reactor safety and nuclear fuel, high quality of nuclear data ensures the nuclear design accuracy which is the key factor for the safety and efficiency of nuclear system. In order to respond to nuclear data needs from various R&D projects as well as to establish the infra-structure of the nuclear data production, KAERI wants to build an intense pulsed neutron source by utilizing accelerator facilities, technologies and manpower at Pohang Accelerator Laboratory (PAL). Therefore, the evaluation of photonuclear data become an urgent task for the design of head/target system, radiation protection and shielding analysis. We first describe the design and status of the pulsed neutron source based on a 100 MeV eletron linac. We then introduce our plan for the photonuclear data evaluation, together with some preliminary results.

II. Pulsed Neutron Source Based on a 100 MeV Electron Linac

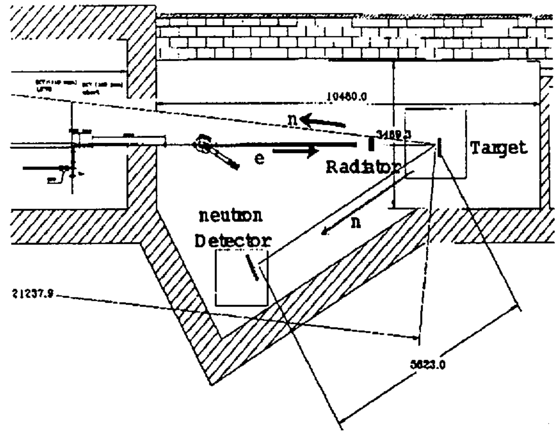
KAERI and PAL proposed to construct the Pohang Neutron Facility (PNF), which consists of a 100-MeV electron linac, a water-cooled Ta target, and at least three different TOF paths[1]. The nominal beam energy of the designed electron linac is 100 MeV, and the operating frequency is 2,856 MHz. The repetition rate of the linac is varied between 30 Hz and 300 Hz depending on the pulse width. Two SLAC 5045 klystrons may be used to increase the pulse repetition and the beam power. The 100-MeV electron linac consists of a triode type e-gun (EIMAC Y824), and S-band prebuncher and buncher, two accelerating sections, and various components. On Dec. 1997, it was completed the construction of a test-linac for various R&D activities, i.e. tests for the target system, for the data acquisition system, and for the detection system.

Table 1. Electron beam modes and parameters

Mode	Pulse Width [ns]	Beam Current [A]	Beam Energy [MeV]	Beam Power, kW (RF pulse rep. rate)	
				180 pps	300 pps
short pulse	2	5	97	0.17	0.3
	10	5	88	0.8	1.3
	100	1	79	1.4	2.4
Long Pulse	1000	0.3	77	4.1	6.9

* The Klystron is operated with the pulse repetition rate of 300 pps and with the RF pulse width of 2 μs

As a photoneutron target, we are considering Ta-181 because the technology for the handling and the characteristics of the targets are well known. The design of the target assembly is undergoing by use of the Monte Carlo simulation codes, EGS4 and MCNP4. Since the present building arrangement at PAL makes it difficult to place the target assembly in rectilinear downstream of the linac, the electron beam has to be bent in the direction of 45



degree. The electron beam is transported to a photoneutron target in the target room (10x15 m^2) which is 6 m below the ground level and beside the present linac building. The flight tubes and detector stations will be placed underground and flight path lengths range between 10 m and 100 m as described in Fig. 1. Two or three data aquisition rooms (10x15 m^2) for experments will be placed in the ground level beside the linac building.

Fig. 1 Diagram of photonuclear experiment

III. Photonuclear Data Evaluation

Our evaluation plan for the photonuclear data covers all important elements not only for the target system but also for structural and shielding materials of PNF for licensing from safety authority. We are also evaluating some important elements which, in photoneutron or photoproton reactions, produce residual nuclei used for the medical purpose. For example, we evaluated photonuclear cross sections of Ta-181, a target material of PNF, up to an incident photon energy of 140 MeV which is the threshold for pion production energy[2]. Re-analyses were performed on the (γ,n) and (γ,2n) data measured at Saclay and Livermore, and reference data were reconstructed. The absorption cross sections were evaluated with the giant dipole resonance (GDR) model below 40 MeV. The calculated results with statistical model with preequilibrium correction reproduced the reference data of all the photoneutron cross sections consistently. From 40 to 140 MeV, the quasideuteron model (QDM) was adopted to evaluate photoabsorption cross sections and the results are compared with the measurements. The decaying processes including n, p, d, t, He-3, and α particle emission up to 140 MeV were theoretically evaluated by the ALICE-F code.

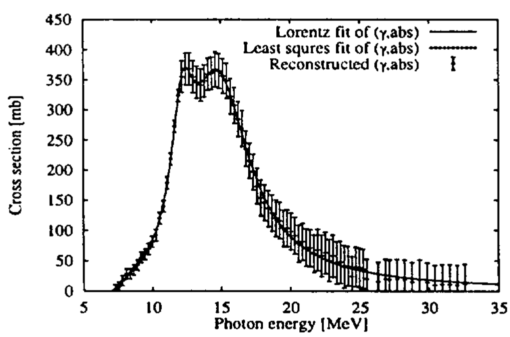


Fig. 2. Evaluated Ta-181(γ,abs) cross sections

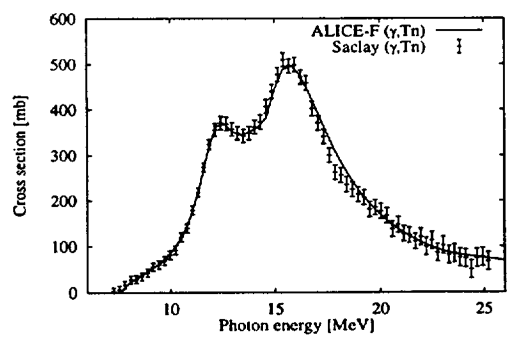


Fig. 3 Evaluated Ta-181 (γ,Tn) cross sections

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Novel Approach for the Determination of the Nuclear Level Density

S. F. Mughabghab
Brookhaven National Laboratory
Upton, New York, 11973

INTRODUCTION

The nuclear level density parameters play a central role in statistical calculations in reactor physics, nuclear model computations, neutron physics, astrophysics, intermediate heavy-ion collisions investigations, and spallation neutron design studies. Nonetheless, up until very recently, little attention was paid into a critical examination of the derivation of these parameters from the average s-wave level spacings of the nuclides. A large fraction of previous determinations of the level density parameter, a, is carried out on the basis of either the Gilbert-Cameron [1] relation for the spin dispersion parameter, σ, or the Bohr-Mottelson [2] expression in terms of the rigid body value of the nuclear moment of inertia. In addition, nucleon pairing correlations were not taken into consideration.

DATA ANALYSIS AND RESULTS

The approach followed here is the extraction of the spin dispersion parameter from the recommended average values of the level spacings for s-wave neutron resonances [3], for the two spin states, I + ½ and I - ½, where I is the spin of the target nucleus, and on the basis of the Bethe level density relation. Where possible, the data base was supplemented by new measurements of spin assignments.

To obtain reliable estimates of the average level spacings, and correct for unobserved resonances or weak resonances with no spin assignments, the Porter-Thomas and Dyson-Mehta statistics were invoked in the analysis.. The spin dispersion parameters spanning the mass region from ^{45}Sc to ^{209}Bi were readily deduced. A least-squares fitting procedure was first applied to the derived σ values in terms of the Gilbert-Cameron relation and without taking into consideration shell effects or nucleon pairing correlations. The following result is obtained

$$\sigma^2 = 0.0494 aTA^{2/3} \tag{1}$$

where T is the nuclear temperature = $(U/a)^{1/2}$.

Note that the numerical coefficient in the above relation is about half of the theoretical estimate. A closer examination of the derived σ values revealed that shell effects, particularly around the Pb region, as well as odd-even effects , are evident. The latter can be ascribed to nucleon pairing correlations. The above relation was then generalized to include these effects ; the final result is

$$\sigma^2 = 0.0888 P(U,\Delta,a)[1 + \frac{E_{shell}}{U}(1 - e^{-\gamma U})] a T A^{2/3} \qquad (2)$$

where P(U, Δ, a) is the pairing correlation function [4], U is the effective excitation energy, E_{shell} is the shell energy correction, and γ is the shell damping parameter.

With the aid of Eq. 2 and the Bethe level density relation, the level density parameters are then determined through an iterative procedure. The resulting level density parameters are in general smaller than what is available in the literature by 5 - 20 %, depending on the mass region.

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Some Comments On Photoneutron Evaluation

S. F. Mughabghab
Brookhaven National Laboratory
Upton, New York, 11973

INTRODUCTION

The evaluation of photoneutron data is becoming increasingly more important with time in other fields, such as neutron physics and spallation neutron studies. As an example, recent neutron capture spectra measurements revealed that the electric Giant Dipole Resonance (GDR) plays a major role in the gamma ray decay of excited states to low lying states near the ground state of the nucleus, i.e. electric dipole gamma-ray transitions strengths. In these studies, the GDR Lorentzian parameters are required. In addition, a wealth of information can be derived from photoneutron data, which can be applied in other fields. As an example, study of the giant dipole resonance width as a function of excitation energy revealed that the G.D.R. damping width increases with the temperature of the nucleus. Therefore, evaluation of photoneutron data is quite important.

Basically, there are two evaluation methods:

1. Available experimental data supplemented with model calculations.

2. Macroscopic or microscopic model calculations when measurements are not available.

In both methods the parameters of the giant dipole resonance based on systematics are of great value [1]. To illustrate the points two interesting examples are presented

1. The position of the giant dipole resonance as predicted by Danos' [2] hydrodynamical model. For details refer to the review article [3].

2. The nuclear level density parameters as derived from photoneutron data.

From the ratio of the double to the total photoneutron cross section and with the aid of Weisskopf statistical theory, the nuclear level density can be derived [2].

Values of the level density parameters for nuclides ranging from ^{74}As to ^{186}W were reported [3]. A comparison between those value and the ones derived recently on the basis of an empirically derived spin dispersion parameter shows that the former results are quite low. It is possible that preequilibrium processes which were not considered [3] may be the cause for the discrepancy. It will be of great interest to repeat these calculations taking into consideration the preequilibrium effects.

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Some Notes on Formatting Issues for Photonuclear Data

R.E.MacFarlane
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1. The ENDF-6 manual lumps photonuclear and charged-particle data together in Section 0.4.5. This would imply that the rule of only using MF6 would apply to photonuclear data.

   This would imply that 6/2 should be used for elastic angular distributions. However, I don't see any reason why 4/2 couldn't be used, and we could possibly make an official exemption for elastic. It has been stated that this is not an important reaction.

   I would like to see File 6 used for MT=50-91, 600-649, etc., with the gamma rays given explicitly in the corresponding section for each reaction.

2. The easiest representation to process is the one that Mark used containing only MT=5 and including all particle, photon, and residual production explicitly. The code doesn't have to make any guesses to get heating and nuclide production correct.

   Coding already available in MCNP can handle the limited angular distribution formats used.

   One problem here is that it might be difficult to handle more complex energy-angle distributions. Using current MCNP technology, we could handle data given using law 7 (angle-energy). We could convert data given in the lab as energy-angle tabulations or Legendre coefficients to law 7. Or we could extend the formats allowed in MCNP to handle other File 6 laws. What representations will really be needed for the evaluations?

   Another problem is what to do if the recoil data are missing. A heating code will have to recognize this and try to estimate a reasonable recoil spectrum. If you have good gammas in File 6, the code can calculate the heating by energy balance, but it still has to make approximations to get damage. Do you want to put a requirement on the evaluator to solve this problem, or leave it up to the processing code?

3. The next most complicated arrangement is to allow individual reaction MT numbers instead of or in addition to MT=5.

   There shouldn't be any problem using a reaction like MT=16 with Files 3 and 6. I think that current ENDF-6 rules forbid using Files 4 and 5 with MT=16, and I hope that you can agree to that. Photons for MT=16 should be given in that section of File 6. Is it possible to forbid use of MF13 for photonuclear photon emission from these kinds of reactions? I certainly hope we can forbid things like MF13/MT3.

The same possible problems with angular representations apply to MF6/MT16 and MF6/MT5. See above.

The same possible problems with heating and damage apply for invidual reactions in File 6. If you use MT28, how does the code handle missing residuals?

The evaluator can change from individual reactions to MT=5 at any energy.

4. What do we do about fission? Some people would probably like to use File 5 with an analytic law. Is it necessary to give that with File 4 as isotropic in the lab? Or should we insist that a tabulated distribution be provided in File 6? What about the gammas? They are normally given in 12/18 for resonance selfshielding reasons. Should that be allowed, or should File 6 be used?

5. Gammas from MT102 are normally given using File 12. This is probably OK for photonuclear capture also (when these gammas are not in MT=5). MCNP can currently handle anisotropy for MT102 photons using File 14. I wouldn't want to use MF12 and 14 for any other reactions.

6. MT103 is just a summation reaction if MT600-649 are present, and 6/600-649 should be present. A corresponding 6/103 should not be given.

7. MT201-207 are just summation reactions for photon, neutron, and gas production. File 6 data should not be given using these MT values. Use MT=5 instead. It is not necessary to give MT201-207 in the evaluation. If the data are properly complete, they can be constructed by GASPR. In fact, GASPR will throw away whatever is given in these MT values in the evaluation.

8. What do we do about MT=1 (total)? It should probably be required. For Mark's evaluations, MT1=MT5. But if there is a combination of individual reactions, or reactions and MT5, we will need to either read or reconstruct a total photonuclear cross section.

Possible Rules:

MF=1 is required.
  MT=451
  MT=452, 455, 456, 458 if fissionable

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MF=2 may be omitted entirely.

MF=3 is required.
  MT=1 is required.
  reaction MT's and/or MT=5 are OK.
  omit MT=201-207
  MT=4 is required if 50-91 are present.
  MT103 can appear without MT=600-649,
   and it is required if MT=600-649 present.
  etc.

MF=4 may or may not be present.
  MT=2 is allowed.
  MT=18 is allowed with isotropy in the lab only.
  no other MTs can be given in MF=4.

MF=5 may or may not be present.
  MT=18 is allowed.
  MT=455 is allowed.
  no other MTs can be given in MF=5.

MF=6 will usually be present.
  reaction MT's and/or MT=5 are OK.
  MT=201-207 are not allowed.
  MT=103 is allowed if MT=600-649 are not given.
  all File 6 laws are allowed.

MF=8 should be given for radioactive products.

MF=12 may be present
  MT=18 is allowed if 5/18 is used, but not if 6/18 is used
  MT=102 is allowed 6/102 is not used
  no other MTs allowed

MF=13 is not allowed

MF=14 may be present
  MT=18 is allowed if 5/18 is used, but not if 6/18 is used
  MT=102 is allowed if 6/102 is not used.
  no other MTs allowed.

MF=15 may be present
  MT=18 is allowed if 5/18 is used, but not if 6/18 is used
  MT=102 is allowed if 6/102 is not used.
  no other MTs allowed.

MF=30-40 are allowed.
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Nuclear Data Section
International Atomic Energy Agency
P.O. Box 100
A-1400 Vienna
Austria

e-mail: services@iaeand.iaea.or.at
fax: (43-1)26007
cable: INATOM VIENNA
telex: 1-12645 atom a
telephone: (43-1)2600-21710

online: TELNET or FTP: iaeand.iaea.or.at
username: IAEANDS for interactive Nuclear Data Information System
username: ANONYMOUS for FTP file transfer
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