INTERNATIONAL ATOMIC ENERGY AGENCY

INDC(NDS)-444
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I N D C INTERNATIONAL NUCLEAR DATA COMMITTEE

Nuclear Data for the Production of Therapeutic Radionuclides

Summary Report of First Research Coordination Meeting

IAEA Headquarters
Vienna, Austria
25 – 27 June 2003

Prepared by
J.-Ch. Sublet* and R. Paviotti-Corcuera

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*CEA Cadarache, Saint Paul lez Durance, France

June 2003

Produced by the IAEA in Austria
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Abstract

Presentations, discussions and conclusions from the First Co-ordination Meeting on Nuclear Data for the Production of Therapeutic Radionuclides are summarised in this report. The main purpose of the meeting was to discuss scientific and technical matters related to the subject and to co-ordinate related tasks. Programmes of work were agreed and assigned, and deadlines were set. Participants emphasized the importance of the completeness and accuracy of the resulting nuclear data for the production of these radionuclides to appropriate specific activities and purity along with the relevant decay data. The recommended data from this Co-ordinated Research Project should meet the requirements for the safe and efficacious application of therapeutic treatments in nuclear medicine.

June 2003

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1. OBJECTIVES AND AGENDA

The First Research Co-ordination Meeting (RCM) on Nuclear Data for the Production of Therapeutic Radionuclides was held at the IAEA Headquarters in Vienna, Austria, from 25 to 27 June 2003. Primary aims of this meeting were to present the main achievements reached during the first months of the CRP, discuss scientific and technical matters related to the subject, coordinate related tasks, and to assess assigned responsibilities.

Prof. Dr. S. M. Qaim of the Institut für Nuklearchemie, Forschungszentrum, Jülich, Germany was elected Chairman of the meeting; Dr. J.-Ch. Sublet from CEA Cadarache, France agreed to act as rapporteur. Other participating laboratories were represented by E. Běták (SAS, Slovakia), B.V. Carlson (ITA, Brazil), H.-D. Choi (SNU, Republic of Korea), F.M. Nortier (LANL, USA), Y.N. Shubin (IPPE, Russia) and T.F. Tarkanyi (HAS, Hungary); E. Menapace (ENEA, Italy) and B. Scholten (FZJ, Germany), participated as observers. The approved Agenda is attached as Appendix 1, while a full list of participants and their affiliations is given in Appendix 2.

Alan Nichols (Head of the IAEA Nuclear Data Section) welcomed the participants, and emphasized the significance of their role in the development and production of this important database for therapeutic applications. He also explained the overall aims and technical drivers behind the formation of IAEA CRPs (Appendix 3). R. Paviotti-Corcuera (IAEA-NDS Project Officer for the CRP) summarized the research objectives and expected outputs of the CRP (Appendix 3).

Contributions to the meeting by CRP participants are included in Appendix 4.

This is the second CRP dedicated to the generation of recommended nuclear for adoption in the medical field; an earlier CRP concentrated on diagnostic radionuclides, while this second CRP will focus on therapeutic radionuclides and is expected to require 3 to 4 years to achieve the desired objectives.

Whether nuclear data for the production of diagnostic and therapeutic radionuclides exist or not, and whether they are poorly or well known, one should acknowledge the fact that these isotopes have been produced and used in nuclear medicine treatment for many years. Nevertheless, the improved quality of the nuclear data that will be generated during this CRP will make their production much more efficient and should also enhance their quality through improved purity.

There are a significant number of radioisotopes in use or being proposed for therapeutic applications. As a consequence of the work undertaken during the course of this CRP, the resulting completeness and accuracy of the nuclear data for the production of these nuclides to appropriate specific activities and purity along with the re-definition of their decay data should be adequate for safe and efficient medical applications.

2. BACKGROUND

2.1 Uses of radioisotopes in therapy

Cancer management is a major medical and economical issue because of (1) the incidence of the disease and (2) selection and optimization of the treatment strategy. As an example, one million new cancer cases were detected in the United States during 1991 (i.e., 400 per 100,000 of the population per year). The probability of death due to cancer increases with the longevity of the population: present estimates range between 25 and 30% for industrialized countries. These percentages are lower in developing countries, but can be expected to increase as longevity is extended.

Experience shows that at the time of first prognosis, 30% of patients are found to have contracted extensive forms of cancer, and survival rates are low. Only 5% of these patients are cured, often after application of a complex combination of techniques that include chemotherapy, radiation therapy, immunotherapy and sometimes surgery. Among 70% of the patients who have localized variants of the disease at the time of their first prognosis, 40% can be cured by surgery, radiation therapy or a combination of both techniques. However, as indicated, 30% of these patients die from their cancer - this group of patients with local failure constitutes the main challenge for new therapeutic approaches, particularly new developments in radiation therapy.

2.2 Need for nuclear data

There is a wide range of radioisotopes in use or being proposed for therapeutic applications. The issue to be addressed is whether the completeness and accuracy of the nuclear data for the production of these nuclides to appropriate specific activity and purity as well as their relevant decay data are adequate for safe and efficient medical applications. Even though a number of appropriate publications exist that define the nuclear properties of these radionuclides, there has been no systematic evaluation of the published data, and experimental data are missing in many cases. In addition, there is a trend towards the use of high-energy accelerators (100 MeV or more) for the production of radioisotopes useful in therapeutic applications through routes that have not been properly characterised.

Accurate and complete knowledge of nuclear data are essential for the production of therapeutic radioisotopes with the necessary specific activity and purity required for efficient and safe clinical purposes. The selection of targets, isotope purity of targets, and nature and energy of projectiles require careful study. No serious effort has been devoted to the evaluation of nuclear data for reactor and accelerator production of therapeutic radioisotopes, and no other organization has addressed this need (e.g., NEA, International Radiological Society, or Society of Nuclear Medicine). Thus, the IAEA is in the unique position of being able to address this important need with respect to public health.

A Consultants' Meeting on Nuclear Data for the Production of Therapeutic Radioisotopes was held at the IAEA Headquarters in Vienna, Austria, from 27 February to 1 March 2002. The

purpose of that meeting was to discuss scientific and technical matters related to the subject, and to focus on a description of the specific research objectives that would serve as the basis for the preparation of the official proposal of an approved IAEA CRP.

The group of consultants included world-renowned scientist with the necessary expertise in the fields of medical treatment with radioisotopes, production of radioisotopes for medical applications with reactors and accelerators, and evaluation of neutron and charged-particle cross sections. Recommendations and conclusions of the meeting were summarised in INDC(NDS)-432, April 2002. The requested CRP was approved by the IAEA in July 2002 for implementation from 2003 to 2006. Overall and specific research objectives and the expected research outputs of the CRP were also considered (see Appendix 3).

3. DISTRIBUTION OF TASKS

The radioisotopes to be considered in the CRP were divided into two categories:

- Therapeutic radioisotopes that have established clinical uses (Appendix 3, Table 1) - ***Established Radioisotopes*.**
- Less-commonly used but potentially interesting radioisotopes for which medical applications have been demonstrated (Appendix 3, Table 2) - ***Emerging Radioisotopes*.**

The assignments of tasks related to each of the reactions in Tables 1 and 2 of Appendix 3 were discusses by e-mail between the participants and technical officer. Participants presented a summary of the results achieved (see Appendix 4), and the meeting discussed scientific and technical details. Consensus was reached on the distribution of the tasks and the conclusions are surmised below.

3.2 Established Radionuclides:

Radionuclide	Production Route	Responsibility	R/A*
^{32}P	^{31}P(n, γ)	Choi	R

*R = Reactor, A = Accelerator.

^{31}P(n, γ): JENDL file seems to be best at low and intermediate energies. All the data libraries agree well with the recommended Mughabghab value at thermal energies. High-energy data do not agree with the experimental 14 MeV data points, and the junction between the resonance and high-energy ranges is poor. Further investigation and a comprehensive literature search are needed.

General remark: the results of prompt gamma measurements may not correspond to all the products, and this could lead to an underestimation of activation measurements.

^{32}P	$^{32}S(n, p)$	Shubin	R, A

Although the $^{32}S(n, p)$ reaction is in IRDF-90, further studies are required to address discrepant data in the plateau region. JENDL dosimetry file seems to be the best evaluation, but according to BME-NTI-251/2001 (September 2001) there is a lack of consistency between File 3 (lower-energy limit 0.92 MeV) and File 33 (lower-energy limit 1.5 MeV, page 14); although there is a newer evaluation, data in File 33 were taken from superseded IRDF-85 (page 19). Shibata should be contacted.

Spectrum averaged measurements are available: A. Calamand "Cross Sections for fission neutron spectrum induced reactions", *Handbook on Nuclear Activation Cross Sections*. Technical Report Series No. 156, IAEA Vienna (1974) p. 273; for an updated version compare with JEF Report 14, OECD-NEA, Paris, France (1994).

Choi will perform integral calculations using NJOY-INTER codes.

^{89}Sr	$^{89}Y(n, p)$	Shubin	R, A

New ^{89}Y data; Qaim (measurements not yet in EXFOR).

Sublet: BRC model data will be sent to Shubin. Sublet will also check if JAERI FNS (Fusion Neutron Source) can provide validation data.

^{89}Sr	$^{88}Sr(n, \gamma)$	Choi, Běták	R

^{89}Sr is an important pure beta emitter, produced in large amounts for medical applications. Evaluation will be undertaken by Choi; Běták has carried out preliminary calculations in the high-energy region, and will send his data to Choi.

^{90}Y	$^{90}Zr(n, p)$	Shubin, Carlson	R, A

Shubin has carried out a complete cross-section analysis for $^{90}Zr(n, p)$, and noted that the downward trend above 20 MeV suggested by Pade fitting could be wrong. Model calculations give better results - EMPIRE calculations by Menapace and Carlson are even more peaked.

Why are there such problems with this (n, p) reaction? Should the peak be broader? Shubin and Carlson need to agree on the evaluated curve. Carlson will carry out spectrum averaging

^{90}Y	$^{89}Y(n, \gamma)$	Carlson	R

$^{89}Y(n, \gamma)$ is a difficult channel - Sublet to send LANL and BRC data to Carlson for further analysis.

^{90}Y	^{235}U(n, f) ^{90}Sr → ^{90}Y generator	Sublet	R

Route of production of large amounts of ^{90}Y - this reaction will be analysed by CEA.

^{103}Pd	^{102}Pd(n, γ)	Carlson, Běták	R

^{102}Pd(n, γ): Carlson will undertake analysis, with input from Sublet. Běták will analyse the cross-section data at high-energies regions. Also produced by the ^{104}Pd(γ, n) reaction (Nortier); Menapace will undertake a library search for this reaction and perform new calculation if needed (could be an important production route).

^{103}Pd	^{103}Rh(p, n)	Qaim	A

^{103}Rh(p, n): several measurements exist, and a recommended data set can be generated. Minor problem with characterising the decay of ^{103}Pd, specifically the gamma-ray emission probability.

^{103}Pd	^{103}Rh(d, 2n)	Tarkanyi	A

^{103}Rh(d, 2n): only one experimental data set, but X- and gamma-ray measurements are not in agreement (X-ray data are preferred). Data need to be fitted.

^{125}I	^{124}Xe(n, γ)^{125}Xe → ^{125}I	Carlson, Běták	R

^{125}I is a very important radionuclide in nuclear medicine. Carlson will analyse the low-energy region, and Běták will contribute to the high-energy region.

^{131}I	^{130}Te(n, γ) → ^{131}Te → ^{131}I	Choi, Běták	R

^{130}Te(n, γ) → ^{131}Te → ^{131}I: Choi will analyse this channel, and Běták will deal with the high-energy region.

^{131}I	^{235}U(n, f)	Sublet, Schenter	R

^{131}I via ^{235}U(n, f): one of the most important therapeutic radionuclides, produced and used worldwide. Fission yield will be analysed by CEA.

^{137}Cs	^{235}U(n, f)	Sublet	R

^{137}Cs via ^{235}U(n, f): fission yield will be analysed by CEA.

^{153}Sm	^{152}Sm(n, γ)	Carlson, Běták	R

^{152}Sm(n, γ): significant emphasis is being placed on this radionuclide for medical applications. Carlson will analyse the low-energy region, and Běták will consider the high energies.

^{186}Re	^{185}Re(n, γ)	Sublet	R

^{185}Re(n, γ): work has started on this channel.

^{186}Re	^{186}W(p, n)	Tarkanyi, Shubin	A

^{186}W(p, n): data have been collected, and will be sent to Shubin for fitting.

^{186}Re	^{186}W(d, 2n)	Tarkanyi, Shubin	A

^{186}W(d, 2n): significant emphasis is being placed on this radionuclide for medical applications. Data have been collected, and will be sent to Shubin for fitting. Menapace will perform model calculations on the above two channels.

^{188}Re	^{186}W(n, γ) $\rightarrow$ ^{187}W(n, γ)^{188}W $\rightarrow$ ^{188}Re generator	Sublet, Schenter	R

One integral measurement exists on ^{187}W as performed at Oak Ridge National Laboratory, USA (Mirzadeh et al), and needs to be used in the analysis (see Proceedings of ND1991, Jülich, p 595).

^{188}Re	^{187}Re(n, γ)	Carlson	R

^{187}Re(n, γ): requires analysis.

^{192}Ir	^{191}Ir(n, γ)	Choi, Běták	R

^{191}Ir(n, γ): Choi to analyses the low-energy region, and Běták to analyse the high-energy region.

^{192}Ir	^{192}Os(p, n)	Qaim	A

^{192}Os(p, n): a new measurement will be done at Jülich - enriched material has been bought.

3.2 Emerging Radioisotopes:

Radionuclide	Production route	Responsibility	R/A/Decay *
^{64}Cu	^{63}Cu(n, γ)	Sublet	R

*R = Reactor, A = Accelerator.

^{64}Cu: one of the most important emerging therapeutic radionuclides that permit the application of a combination of therapy and positron emission tomography. Decay data need to be changed to 0.39 β^-, 0.18 β^+ and 0.43 EC decay. Data will be modified as specified.

^{64}Cu	^{64}Ni(p, n)	Qaim	A

^{64}Ni(p, n): one set of experimental data is available – further literature search will be carried out.

^{64}Cu	Zn(d, x)	Bonardi, Menapace	A

Zn(d, x): potentially an important reaction; literature search to be carried out, and new experimental data to be to be taken into account.

^{64}Cu	^{64}Ni(d, 2n)	Nortier	A

^{64}Ni(d, 2n): one set of experimental data is available - further literature search will be undertaken.

^{64}Cu	^{64}Zn(n, p)	Choi	R

^{64}Zn(n, p): Sublet to send excitation curve to Choi. Spectrum-averaged value to be calculated by INTER, and compared with integral experimental data.

^{64}Cu is one of the most important emerging therapeutic radionuclide. It allows a combination of therapy and positron emission tomography

^{67}Cu	^{67}Zn(n, p)	Choi	R

^{67}Zn(n, p): Sublet to send excitation curve to Choi. New Jülich data probably not in EXFOR. Spectrum-averaged value to be calculated by INTER, and compared with integral experimental data.

^{67}Cu	^{68}Zn(p, 2p)	Nortier	A

^{68}Zn(p, 2p): Jülich data are available. All measurements by Levkovski need to be lowered by 20% - Nortier to receive relevant publication from Tarkanyi that describes this normalisation. Theoretical calculation seems to indicate that the contribution of neutron reactions (n, d) + (n, np) can be important for thick targets.

^{67}Cu	^{70}Zn(p, α)	Qaim	A

^{70}Zn(p, α): measurements using 85% enriched target have been made - good excitation function generated, and measured data agree. However, the cross-section values in the tail seem to be low.

^{114m}In	^{113}In(n, γ)	Sublet	R

^{113}In(n, γ)^{114m}In: data file to be produced as specified; work needed on branching ratio.

^{114m}In	^{114}Cd(p, n)	Tarkanyi	A

^{114}Cd(p, n): experimental data exist. Measurements on natural targets have already been completed, and data evaluation is in progress. An enriched target is in preparation for new measurements.

^{114m}In	^{114}Cd(d, 2n)	Tarkanyi	A

^{114}Cd(d, 2n): no experimental cross-section data exist. Measurements on natural targets have already been conducted, with data evaluation in progress. An enriched target is in preparation for new measurements.

^{124}I	^{124}Te(p, n)	Qaim	A

^{124}Te(p, n): new evaluation and data fitting have been undertaken, and yield calculated. Recommended data are available.

^{124}I	^{124}Te(d, 2n)	Nortier	A

^{124}Te(d, 2n): two sets of data exist. Brookhaven data appear to be incorrect, as confirmed by Jülich measurements. Corrected cross-section data need to be produced from the Brookhaven yields in order to obtain two good data sets. Tarkanyi will forward these data to Nortier.

^{124}I	^{125}Te(p, 2n)	Nortier	A

^{125}Te(p, 2n)^{124}I: one of the most important emerging therapeutic radionuclides that permits the application of a combination of therapy and positron emission tomography. A data set was recently produced and is available; an additional literature search is required.

^{166}Ho	^{165}Ho(n, γ)	Choi, Běták	R

^{165}Ho(n, γ): evaluation needs to be checked, and the high-energy region needs to be analysed by Běták.

^{166}Ho	^{164}Dy(n, γ) $\rightarrow$ ^{165}Dy(n, γ) $\rightarrow$ ^{166}Dy $\rightarrow$ ^{166}Ho	Sublet, Schenter	R

^{164}Dy(n, γ) $\rightarrow$ ^{165}Dy(n, γ) $\rightarrow$ ^{166}Dy $\rightarrow$ ^{166}Ho: existing evaluation needs to be re-analysed.

^{169}Yb	^{168}Yb(n, γ)	Sublet	R

^{168}Yb(n, γ)^{169}Yb: wider literature search is needed; branching ratio needs to be corrected

^{169}Yb	^{169}Tm(p, n)	Qaim	A

^{169}Tm(p, n): no experimental data are available. Measurements on this reaction will start in 2004.

^{177}Lu	^{176}Lu(n, γ)	Sublet, Shenter	R

^{176}Lu(n, γ): data need to be assessed.

^{177}Lu	^{176}Yb(n, γ)^{177}Yb $\rightarrow$ ^{177}Lu	Sublet	R

^{176}Yb(n, γ)^{177}Yb $\rightarrow$ ^{177}Lu: data need to be assessed.

^{211}At	^{209}Bi(α, 2n)	Tarkanyi	A

^{209}Bi(α, 2n): experimental data have been compiled. A new measurement by alpha counting has been completed, but not yet evaluated. ^{210}Po production could be critical; therefore the (α, 3n) reaction also needs to be compiled.

^{213}Bi	decay of ^{225}Ac	Carlson	D

^{213}Bi: this important radionuclide exists in the nuclear waste from Th-U fuel cycle, and can be chemically recovered. The decay scheme needs to be re-evaluated.

^{225}Ac	^{226}Ra(p, 2n)	Shubin, Menapace	A

^{226}Ra(p, 2n): no experimental data are available. Measurements are extremely difficult - only model calculations will be performed.

^{225}Ac	decay of ^{233}U → ^{229}Th	?	D

This radionuclide occurs in the ^{233}U fuel cycle. Decay data file to be checked.

4. COMMENTS AND RECOMMENDATIONS

Extensive work needs to be done in the next 12 to 15 months so that the necessary progress can be achieved before the next meeting. References to missing EXFOR data also need to be reported to the IAEA Nuclear Data Section (to the Technical Officer and O. Schwerer) in sufficient time so that these data can be prepared as graphical output for the final report.

Data validation can be carried out with what is available in the literature such as resonance integrals, californium spectrum, and spectrum-averaged and integral experiments.

Action: Sublet to check the EASY (European Activation System) validation data base for neutron reactions.

Calculations of neutron-induced reactions:

- for Maxwellian spectrum, average with T = 300K and integration limits 1.0E-05 to 10 eV;
- for resonance integrals, use 1/E spectrum with limits of 0.55 eV to 2 MeV;
- for fission neutron spectrum, average a Maxwellian fission spectrum with effectivetemperature T = 1.35 MeV, and integration limits from 1 keV to 20 MeV.

These parameters are very important in determining integral quantities that may be extremely sensitive to the integration limits; therefore, the evaluator analysing experimental data and comparing the calculated values should be careful in the interpretation of results. Default input decks for INTER (ENDF utility code) could be used.

Charged-particle reactions:

Validations require well-defined experiments can be or have been performed. Natural targets can also be used for data validation. Literature searchers should be undertaken for fission yields, and used if available.

The evaluated nuclear data file (charged particles and neutron) formulated and assembled by the CRP participants needs to be prepared in ENDF-6 format, and checked through the utility codes STANEF and CHECKR. These files will be provided to the NDS for worldwide distribution and usage.

Decay characteristics of every agreed radionuclide need to be compiled by each evaluator and referenced: half-life, decay mode, average and end-point energies, gamma-ray energies and emission probabilities, Auger and X-ray emissions from MIRD (standard for treatment planning, and available on the IAEA web), ICRU etc. Expert advice on specific decay data (e.g., ^{64}Cu and ^{103}Pd) may be required (from Dr. M.J. Woods (NPL, UK)). Problems related to specific activity need to be checked, addressed and summarized in the technical documentation for each radioisotopic product.

For reactions with resonances, evaluators should include the total and the scattering cross sections in order to make possible self-shielding calculations.

Action: Paviotti-Corcuera will establish a dedicated Web-site with online data and report access.

Expected Outputs of CRP:

- electronic database for use in the production of therapeutic radionuclides – radionuclidic symbol, production route, validated evaluated cross sections as a function of energy, decay data (half-lives, beta-decay energy spectrum, gamma-ray emission probabilities, Auger electron spectra, etc); data in ENDF-6 format.
- printed version of database,
- TECDOC report,
- IAEA-NDS Worldwide Web online access to database.

Timescale:

The second meeting should be held sometime between July and November 2004. By that time, participants are expected to provide:

- all of their evaluated data, as agreed
- contributions to IAEA TECDOC in draft form.

The third and final meeting should be held between October 2005 and March 2006. Participants are expected to provide:

- All TECDOC contributions, and data for final approval

Technical Document:

Action: Qaim to provide a political statement on why this work has been done, and the beneficial consequences – all to be included in the TECDOC.

Structure of the TECDOC:

Contents of TECDOC	**Responsibility**
Foreword	IAEA Technical Officer
1. Introduction	Qaim - Sublet
2. Neutron induced reactions	Sublet
Capture cross section	
Proton emission cross section	

3. Charged-particle reactions Evaluation methodology	Tarkanyi
4. Evaluated Data Base Established Radioisotopes and Emerging Radioisotopes Medical relevance, specific activity Decay Data Neutron capture Proton emission in neutron induced reactions Charged-particle induced reactions Validation with integral measurements, when available	CRP team: Each participant will write his own comments on his evaluation
5. Conclusions Appendix: Dictionaries	

Additional points of note:

The next meeting could be held at CEN Cadarache.

The following conferences are relevant to the CRP, and a suitable paper could be prepared and presented:

- International Conference on Nuclear Data for Science and Technology, Santa Fe, New Mexico, USA, 26 September to 1 October 2004

  http://t16web.lanl.gov/nd2004/

  An abstract should be sent to the organizers by the end of this calendar year.

  Action: Participants should send a summary progress report to Raquel by the end of October 2003 in order to contribute to the preparation of a suitable abstract.
- Workshop on Targetry and Target Chemistry, Wisconsin, USA, August 2004.
- Sixth International Conference on Nuclear and Radiochemistry, 29 August - 3 September 2004, Aachen, Germany

  http://www.fz-juelich.de/nrc6

  Abstract due in February 2004.
- Fifth International Conference on Isotopes, Amsterdam, The Netherlands, Spring 2004.

5. APPENDICES

Appendix 1: Agenda

International Atomic Energy Agency

First Research Coordination Meeting on
"Nuclear Data for the Production of Therapeutic Radionuclides"

IAEA Headquarters, Vienna, Austria
25 – 27 June 2003,
Meeting Room F0123

AGENDA

Wednesday, 25 June

08:30 - 09:20 **Registration** (IAEA Registration desk, Gate 1)

09:30 - 10:45 **Opening Session**

Welcoming address - A.L. Nichols, Head of IAEA Nuclear Data Section (NDS)

Round table self-introduction by participants

Election of Chairman and Rapporteur

Discussion and Adoption of Agenda (Chairman)

Introduction to IAEA CRPs:. (Alan Nichols and R. Paviotti–Corcuera, Scientific Secretary, IAEA/NDS)

10:45 - 11:00 **Coffee break**

11:00 - 12:00 **Session 1: Presentations by Participants and Discussions**

(15 minutes for each presentation, and 5 minutes for discussion)

1. Review of Capture cross-sections for the production of therapeutic radionuclides, **J-Ch Sublet,** *CEA, CE de Cadarache*
2. Preliminary Model Estimates of Possible Production of Selected Therapeutic Radioisotopes A>80 Using the (n,gamma) Reactions with Fast Neutrons, **E. Běták,** *Institute of Physics, Slovak Academy of Sciences, 84511 Bratislava, Slovakia*
3. Nuclear data for production of P-32, **H.D. Choi**,, *Department of Nuclear Engineering, Seoul National University,Seoul 151-742, Korea*

12:00 - 14:00 Lunch and Administrative/Financial Matters Related to Participants

14:00 - 15:30 Session 1: Presentations by Participants and Discussions (cont.)

4. Preliminary results of the evaluation of 89Y(n,g), 90Zr(n,p), 185(n,g) and 187(n,g)', **B. Carlson**, *Depto. de Física – IEF, Instituto Tecnológico de Aeronáutica, São José dos Campos SP, Brazil*
5. Status of the Project "Measurement and Standardization of Nuclear Cross Section Data for Production of some Therapeutic Radionuclides", **S.M. Qaim**, *Institut für Nuklearchemie, Forschungszentrum Jülich, Germany*
6. Nuclear reaction data for accelerator-produced therapeutic radioisotopes. Status report on the activity at ATOMKI in Debrecen**, F. Tárkányi**, *Institute of Nuclear Research of the Hung. Acad. of Sci., ATOMKI, Debrecen, Hungary.*

15:30 - 16:00 Coffee break

16:00 - 17:30 Session 1: Presentations by participants and Discussions (cont.)

7. "Calculation and evaluation of neutron induced threshold reaction cross sections for 32S(n,p)32P, 89Y(n,p)89Sr and 90Zr(n,p)89Y reactions", **Y. N. Shubin**, *Institute of Physics and Power Engineering, 249033 Obninsk, Russia*
8. "Progress Report on Experimental Nuclear Data Evaluations by the LANL Group, **F.M. Nortier**, *Los Alamos National Laboratory, C-INC: Isotopes and Nuclear, Los Alamos, NM 87545, USA*
9. Measurements and Theoretical Calculations of Excitation Functions for The Production of Radionuclides Relevant to Metabolic Radiotherapy, **E. Menapace**, *ENEA, Division for Advanced Physical Technologies, I-40128 Bologna, Italy.*

17:30 Reception –

Thursday, 26 June

09:00 - 010:20 Session 1: Presentations by Participants and Discussions (cont.)

10. Bibliographical (CINDA) and experimental data (EXFOR) on CD-ROM, **V. Zerkin**, *IAEA, Nuclear Data Section, Vienna, Austria.*

09:20 - 18:00 Session 2: Objectives of CRP Revisited

- Established therapeutic radioisotopes
- Emerging therapeutic radioisotopes
- Validation of the data (accelerators, reactors)
- Decay data
- Products of the CRP
- TECDOC: structure and individual writing assignments
- Other issues
- Next RCM
- Drafting of the meeting report

(Lunch and coffee break intervals as appropriate)

Friday, 27 June

09:00 - 18:00 Concluding Session

- Drafting of the meeting report
- Discussion and approval of the meeting report

(Lunch and Coffee break intervals as appropriate)

Appendix 2: List of Participants

International Atomic Energy Agency

First Research Coordination Meeting on

"Nuclear Data for the Production of Therapeutic Radionuclides"

25 – 27 June 2003, IAEA Headquarters, Vienna, Austria

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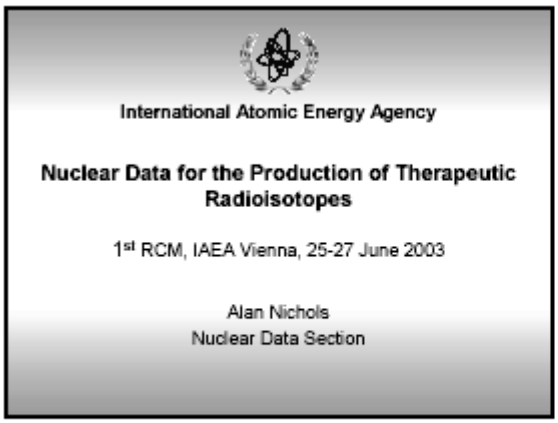
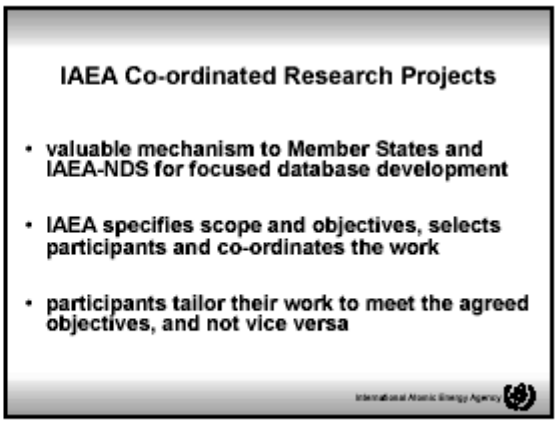
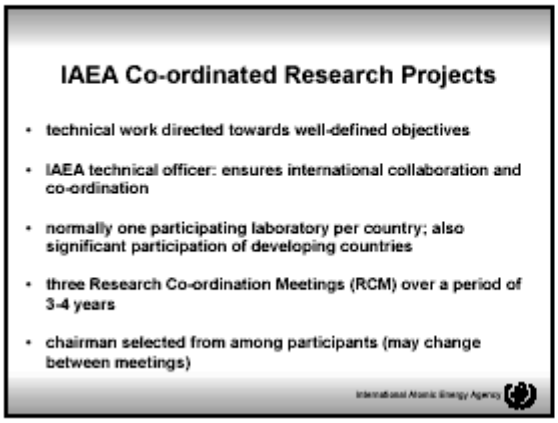
Appendix 3: Introduction to IAEA CRPs

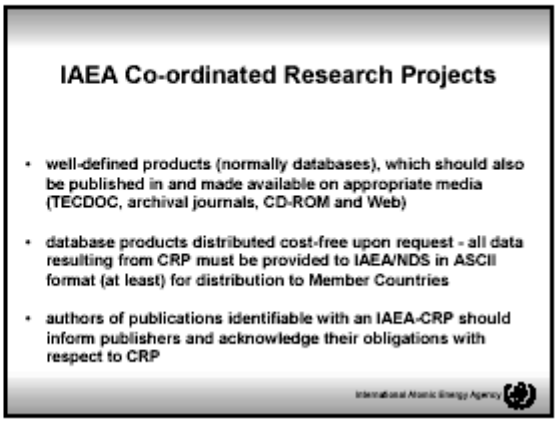
Development and Justification for CRPs

Alan Nichols









Background, Research Objectives and Expected Outputs

R. Paviotti Corcuera

IAEA-NDS

Background

A Consultants' Meeting on Nuclear Data for the Production of Therapeutic Radioisotopes was held at the IAEA Headquarters in Vienna, Austria, from 27 February to 1 March 2002. The purpose of the meeting was to discuss scientific and technical matters related to the subject, and to focus on a description of the specific research objectives that will serve as the basis for the preparation of the official proposal of a CRP to be approved by IAEA.

The group of consultants included world-renowned scientist with the necessary expertise in the fields of medical treatment with radioisotopes, production of radioisotopes for medical applications with reactors and accelerators, and evaluation of neutron and charged-particle cross sections. Recommendations and conclusions of the meeting were summarised in INDC(NDS)-432, April 2002. The proposal to establish this CRP was approved by the IAEA in July 2002 to be implemented from 2003 to 2006. Overall and specific research objectives and the expected research outputs of the CRP are surmised below.

Overall Objective

The goal of the proposed CRP is to improve the accuracy and completeness of the data needed for the optimum production of therapeutic radioisotopes. A sound knowledge of the reaction cross sections will permit the optimum conditions to be realised for the production of the radioisotopes. Accurate cross sections and decay schemes are essential to define both the specific activity with confidence and the purity for safe therapeutic application. The goal will be achieved through compilation of all available experimental data, new measurements when needed, and new evaluations based on the above. The CRP will catalyse highly-relevant relevant studies and the interaction of the resources required to achieve the overall objective.

Specific Research Objectives

The radioisotopes in this proposed CRP are divided into two categories:

- Therapeutic radioisotopes that have established clinical use - ***Established Radioisotopes*.**
- Less-commonly used but potentially interesting radioisotopes for which medical applications have been demonstrated - ***Emerging Radioisotopes*.**

The selected radioisotopes are listed in Tables 1 and 2, respectively.

Production routes include the use of both nuclear reactors and charged-particle accelerators. Reactor facilities are required when thermal neutron capture reactions are involved. Fast

neutron reactions can be produced in reactors as well as in accelerator facilities by means of spallation sources (especially for those reactions with thresholds well above the peak in the fission neutron spectrum). However, many of the radioisotopes of greatest interest can only be produced by means of charged particles.

Data for most of the neutron-induced reactions are presumed to be available in the literature.

Therefore, emphasis will be focused on compilation and evaluation to produce recommended data assembled in a user-friendly form. The same applies to many of the charged-particle reactions; only a few reactions will require new measurements.

Specific Tasks:

Microscopic data represent a basic need, i.e., isotopic cross sections. Energy and spectrum-integrated data are normally used, and therefore the integrated data need to be deduced from the microscopic cross sections and compared with the experimentally-available integral data.

Reactor-produced radioisotopes:

- compile and evaluate the cross section as a function of energy over the energy range from 0 to 20 MeV to generate point-wise numerical data and graphical data with recommended evaluated cross sections,
- deduce spectrum-averaged data in the conventional way for thermal neutrons and validate the data by comparison with experimentally-measured data from the literature (see Note, below),
- undertake new measurements when required.

Accelerator-produced radioisotopes:

- present cross sections as a function of energy up to an energy of 40 MeV (except for a few cases where the upper energy should be 100 MeV) by generating point-wise numerical and graphical data with recommended evaluated cross sections,
- deduce from the microscopic cross sections the integral yield data as a function of incident energy, and generate point-wise numerical and graphical data with recommended evaluated cross sections,
- compare the deduced integral yields with the experimental thick target yields available in the literature,
- undertake new measurements when required.

All systems:

- experimental data and references used in the compilation that are not already in the EXFOR library must be conveyed by the compiler to the IAEA Nuclear Data Section for inclusion in the EXFOR library,
- database should be in the standard form (ENDF-6) to permit retrieval, graphical presentation and checking by the data centres,
- problems related to the specific activity and the presence of impurities should be addressed when these effects are considered important for the therapeutic application,
- decay data (half-lives, beta-decay energy spectrum, gamma-ray emission probabilities, Auger electron spectra, etc.) of the therapeutic radioisotopes must be checked and the data from the most recently published evaluation included (e.g., MIRD, ICRU report on "Absorbed-Dose Specification in Nuclear Medicine" in press).

Expected Outputs

- electronic database for use in Production of Therapeutic Radionuclides. (radionuclide, production route, validated evaluated cross sections as a function of energy, decay data (half-lives, beta-decay energy spectrum, gamma-ray emission probabilities, Auger electron spectra, etc); data in ENDF-6 format),
- printed version of the database,
- TECDOC report,
- IAEA-NDS Worldwide Web online access to database.

Note:

Suggestions for calculations are as follows:

Maxwellian spectrum average with T = 300K and integration limits 1.0E-05 to 10 eV;

resonance integrals - 1/E spectrum from 0.55 eV to 2 MeV;

fission neutron spectrum average - Maxwellian fission spectrum with effective temperature T = 1.35 MeV and integration limits from 1 keV to 20 MeV.

These parameters are very important in determining integral quantities that may be very sensitive to the integration limits; therefore, the evaluator analysing experimental data and comparing the calculated values should be careful in the interpretation of the results

Table 1: Established Therapeutic Radioisotopes.

Radionuclide	$T_{1/2}$	E_{max} in MeV	Production route	R/A *
^{32}P	14.3 d	1.7 β^-	$^{31}P(n, \gamma)$	R
			$^{32}S(n, p)$	R,A
^{89}Sr	50.5 d	1.5 β^-	$^{89}Y(n, p)$	R,A
			$^{88}Sr(n, \gamma)$	R
^{90}Y	2.7 d	2.3 β^-	$^{90}Zr(n, p)$	R,A
			$^{89}Y(n, \gamma)$	R
			$^{235}U(n, f)\ ^{90}Sr \rightarrow\ ^{90}Y$ generator	R
^{103}Pd	17.0 d	Auger electrons, x-rays	$^{102}Pd(n, \gamma)$	R
			$^{103}Rh(p, n)$	A
			$^{103}Rh(d, 2n)$	A
^{125}I	60.0 d	Auger electrons	$^{124}Xe(n,\gamma)^{125}Xe \rightarrow\ ^{125}I$	R
^{131}I	8.0 d	0.6 β^-	$^{130}Te(n, \gamma) \rightarrow\ ^{131}Te \rightarrow ^{131}I$	R
			$^{235}U(n, f)$	R
^{137}Cs	30.97 y	0.5 β^-	$^{235}U(n, f)$	R
^{153}Sm	1.9 d	0.8 β^-	$^{152}Sm(n, \gamma)$	R
^{186}Re	17.0 h	1.1 β^-	$^{185}Re(n, \gamma)$	R
			$^{186}W(p, n)$	A
			$^{186}W(d, 2n)$	A
^{188}Re	17.0 h	2.0 β^-	$^{186}W(n, \gamma) \rightarrow\ ^{187}W(n, \gamma)^{188}W \rightarrow\ ^{188}Re$ generator	R
			$^{187}Re(n, \gamma)$	R
^{192}Ir	73.8 d	0.7 β^-	$^{191}Ir(n, \gamma)$	R
			$^{192}Os(p, n)^{192}Ir$ **	A

*R = Reactor, A = Accelerator; reactors are usually used for (n, p) reactions, but accelerator production would also be possible if the neutron production is sufficiently intense.

** New measurement required.

Table 2: Emerging Therapeutic Radioisotopes.

Radionuclide	$T_{1/2}$	E_{max} in MeV	Production route	R/A/Decay *
^{64}Cu	12.7 h	0.6 β^-	$^{63}Cu(n, \gamma)$	R
		0.7 β^+	$^{64}Ni(p, n)$	A
			$^{64}Ni(d, 2n)$	A
			$^{64}Zn(n, p)$	R
^{67}Cu	2.6 d	0.6 β^-	$^{67}Zn(n, p)$	R
			$^{68}Zn(p, 2p)$	A
			$^{70}Zn(p, \alpha)$	A
^{114m}In	49.5 d	Auger electrons	$^{113}In(n, \gamma)$	R
			$^{114}Cd(p, n)$ **	A
			$^{114}Cd(d, 2n)$ **	A
^{124}I	4.2 d	2.1 β^+	$^{124}Te(p, n)$	A
			$^{124}Te(d, 2n)$	A
			$^{125}Te(p, 2n)$	A
^{166}Ho	26.8 h	1.9 β^-	$^{165}Ho(n, \gamma)$	R
			$^{164}Dy(n, \gamma) \rightarrow {}^{165}Dy(n, \gamma) \rightarrow {}^{166}Dy \rightarrow {}^{166}Ho$	R
^{169}Yb	32.0 d	Auger electrons	$^{168}Yb(n, \gamma)$	R
			$^{169}Tm(p, n)$ **	A
^{177}Lu	6.7 d	0.5 β^-	$^{176}Lu(n, \gamma)$	R
			$^{176}Yb(n, \gamma)^{177}Yb \rightarrow {}^{177}Lu$	R
^{211}At	7.2 h	5.9 α	$^{209}Bi(\alpha, 2n)$	A
^{213}Bi	45.6 m	8.4 α	decay of ^{225}Ac	D
^{225}Ac	10.0 d	5.8 α	$^{226}Ra(p, 2n)$ **	A
			decay of $^{233}U \rightarrow {}^{229}Th$	D

*R = Reactor, A = Accelerator; reactors are usually used for (n, p) reactions, but accelerator production would also be possible if the neutron production is sufficiently intense.

** New measurement required.

Appendix 4: Presented Papers

Review of Capture cross-sections for the production of therapeutic radionuclides, ***J-Ch Sublet****, CEA, CE de Cadarache*

Preliminary Model Estimates of Possible Production of Selected Therapeutic Radioisotopes A>80 Using the (n,gamma) Reactions with Fast Neutrons, ***E. Běták****, Institute of Physics, Slovak Academy of Sciences, 84511 Bratislava, Slovakia*

Nuclear data for production of P-32, ***H.D. Choi****,, Department of Nuclear Engineering, Seoul National University,Seoul 151-742, Korea*

Preliminary results of the evaluation of 89Y(n,g), 90Zr(n,p), 185(n,g) and 187(n,g)', ***B. Carlson****, Depto. de Física – IEF, Instituto Tecnológico de Aeronáutica, São José dos Campos SP, Brazil*

Status of the Project "Measurement and Standardization of Nuclear Cross Section Data for Production of some Therapeutic Radionuclides", ***S.M. Qaim****, Institut für Nuklearchemie, Forschungszentrum Jülich, Germany*

Nuclear reaction data for accelerator-produced therapeutic radioisotopes. Status report on the activity at ATOMKI in Debrecen, ***F. Tárkányi****, Institute of Nuclear Research of the Hung. Acad. of Sci., ATOMKI, Debrecen, Hungary.*

Calculation and evaluation of neutron induced threshold reaction cross sections for 32S(n,p)32P, 89Y(n,p)89Sr and 90Zr(n,p)89Y reactions ***Y. N. Shubin****, Institute of Physics and Power Engineering, 249033 Obninsk, Russia*

Progress Report on Experimental Nuclear Data Evaluations by the LANL Group, ***F.M. Nortier****, Los Alamos National Laboratory, C-INC: Isotopes and Nuclear, Los Alamos, NM 87545, USA*

Measurements and Theoretical Calculations of Excitation Functions for The Production of Radionuclides Relevant to Metabolic Radiotherapy, ***E. Menapace****, ENEA, Division for Advanced Physical Technologies, I-40128 Bologna, Italy.*

Bibliographical (CINDA) and experimental data (EXFOR) on CD-ROM, ***V. Zerkin****, IAEA, Nuclear Data Section, Vienna, Austria.*

REVIEW OF CAPTURE CROSS-SECTIONS FOR THE PRODUCTION OF THERAPEUTIC RADIONUCLIDES

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Abstract

Worldwide libraries search and comparison of a set of important capture reactions for the productions of therapeutic radionuclides has been conducted in order to assess their quality and performance toward the goal of their usage in radioisotopes therapy. Experimental data library (EXFOR) search has been started as well for $^{63}Cu(n,g)^{64}Cu$, $^{113}In(n,g)^{114m}In$, $^{168}Yb(n,g)^{169}Yb$ and $^{176}Yb(n,g)^{177}Yb$ channels to assess the now-a-days data file quality and when possible, associated uncertainties, both of which are strongly energy dependant. Integral experiments will be use, when available, to determine a quality score of each reaction. Such wide-ranging sequenced analysis is likely to allow prioritizing and establishing further evaluation works that will be deemed necessary.

INTRODUCTION

An accurate and complete knowledge of nuclear data are essential for the production of radionuclides for therapy to achieve the specific activity and purity required for an economical production followed by an efficient and safe clinical application. The capture reaction pathways of a set of important radionuclides are analyzed with emphasis on the possibility of engineering those emerging therapeutic radioisotopes through such route of production. The capture reaction being the highest at low incident neutron energies a thermal reactor environment is foreseen has preferable to optimize productivity.

Copper 64 production

The $^{63}Cu(n,g)^{64}Cu$ reaction exists in ADL-3, EAF-2003, CENDL-2, EFF-2.4, FENDL/A-2, ENDF/B-VI-8, IRDF-90, JEFF-3.0 and JENDL-3.2/A,-3.3,-99D libraries. The ^{64}Cu isotope with a half life of 12.702h +/-2%, decay as follow; β-: 38.86% (Zn-64 s), β+: 61.14%(Ni-64 s) with a $<\beta>$ of 125.75Kev and a $<\gamma>$ of 190.56Kev [1]. This isotope is associated with rather low ingestion and inhalation indices of 1.2 10^{-10} Sv/Bq.

In essence, only one resonance parameter file exists (MF-2 MT-151), with the resolved resonance parameters for MLBW mainly taken from the work of Mughabghab (1981) up to 153 KeV, with a 50 KeV cutoff for JENDF-3.2 (-3.3, 99D) and a 99.5 KeV one for ENDF/B-VI r2 (r6 and r8 up to 150 MeV). This first cutoff has been made because a lot of the levels are missing above 50 KeV. This could be explained by the fact that only the total has been measured (Rohr G. et al.(1968), the gamma-gamma are inexistent. The 99.5 KeV of ENDF/B-VI cutoff is there because of an even poorer fit occurs above this range.

Mughabghab [2] 4.52 +/-0.2 barns thermal value seems to stand well with others thermal measurement, and a capture resonance integral of 5.008 (JENDL-.3.3) or 4.924 (EAF-2003) is in agreement with most of the measurements.

Resonance Integral			
En. Min.	Barns	Uncert.	Lab.
0.5	5.3	0.1	ORL77
0.55	5.0	-	ANL64
0.5	5.15	0.10	LRL78
0.1	2.79	0.18	NPL74
0.55	4.7	0.3	GHT72

2.53E-2 eV cross section		
Barns	Uncert.	Lab.
4.45	+/-0.5	ORL77
4.66	+/-0.5	ORL60
4.44	+/-0.2	NPL74
4.52	+/-0.2	Mu01
4.50		JENDL-3.3

Indium-114 metastable production

The $^{113}In(n,g)^{114}In$ (^{114m}In) reaction exits in the following libraries ADL-3, EAF-2003, EFF-2.4, FENDL/A-2, ENDF/B-VI-8, JEFF-3.0, JENDL-3.2/A,-3.3. The ^{114}In isotope with a half life of 1.198 m +/- 0.1%, decay as follow β-: 99.5% β+: 0.5% with <β> 769.23 Kev and <γ> 4.369 Kev. The ^{114m}In metastable with a half live of 50.0 d +/- 0.4%, decay as follow β+: 3.5(Cd-114) and IT:96.5% (In-114) with a <β> of 140.90 Kev and a <γ> of 88.98 Kev. One should note the likely presence of ^{114n}In with a half-life of 42 ms. This isotope is associated with indices for ingestion and inhalation of respectively 4.1 10^{-9} and 9.3 10^{-9} Sv/Bq.

This particular reaction channel is rarely splitted, but in EAF and JENDL-3.2/A, where the energy dependant branching ratio has been calculated from systematic. However, experimental information in the thermal and MeV ranges seems to point to some other branching ratio values of 0.42, at thermal climbing to 0.5 at 14 MeV. Clearly the first metastable has been better measured than the ground although the existence of other identified levels does seems to find support in the literature. Mughabghab [2] total thermal value of 12.0 +/- 1.1 agree reasonably well with the different measurements. The calculated resonance integrals seem to be too high.

2.53E-1 eV cross section		
Barns	**Uncert**	**lab**
9.45	0.4	GHT72 m
7.5	0.7	ROS68 m
8.1	0.8	MTR63 m
3.1	0.7	ROS68 g
3.9	0.4	MTR63 g
12.04		EAF-2003

Resonance Integral			
En. Min.	**barn**	**Uncert**	**Lab**
0.55	258	18	GHT73
0.55	258	10	GHT69
0.5	243	29	CNE70
	321	(134+186)	EAF-2003

Branching ratio			
Energy	**B.r.**	**Uncert.**	**Lab.**
2.53E-01	2.6	0.1	ROS68
2.53E-01	2.1	0.1	MTR63
7.80E+03	2.14	0.3	KFK66
3.00E+04	2.67	0.5	KFK66
6.40E+04	5.05	1.0	KFK66
3.68E+05	3.2	0.3	LOK68
1.00E+06	3.5	0.3	LOK68

Ytterbium-169 production

The $^{168}Yb(n,g)^{169}Yb$ reaction exits in the ADL-3, EAF-2003, FENDL/A-2, TALYS-2 [4] libraries. The ^{169}Yb with an half-life of 32.010 days +/- 0.6%, decays as follow: β+ (Tm-169 s) with a <β> of 106.36 KeV and a <γ> 326.84 KeV. The ^{169m}Yb with an half-life of 46.0s decay by IT with a <β> of 24.2 KeV . This isotope is associated with indices for ingestion and inhalation of respectively 7.1 10^{-10} and 3.0 10^{-9} Sv/Bq.

This evaluation performed with SIGECN-MASGAM [3] model calculation has been splitted by systematic; 0.5 up to 30 KeV, going up to 0.8 for the ground thereafter. It has been based on rather old and reduced sets of experimental differential measurements. There is room for improvement for this evaluation both in term of cross section values and branching ratio.

2.53E-1 eV cross section		
Barns	**Uncert.**	**Lab.**
3660	50	CPO70
5500	2640	TNC61
2840	600	LAS68
2600	60	LRL78
4400	200	OSL70
2305		EAF-2003

Resonance Integral			
En. Min.	**Barns**	**Uncert.**	**Lab.**
	35706	1714	CNE70
	38000	2000	OSL70
	23040	5440	GHT73
0.55	19800	4200	CPO70
0.55	21000	4200	CPO70
0.5	16600	1700	LRL78
0.5	14700	1900	KJL69
	21212		EAF-2003

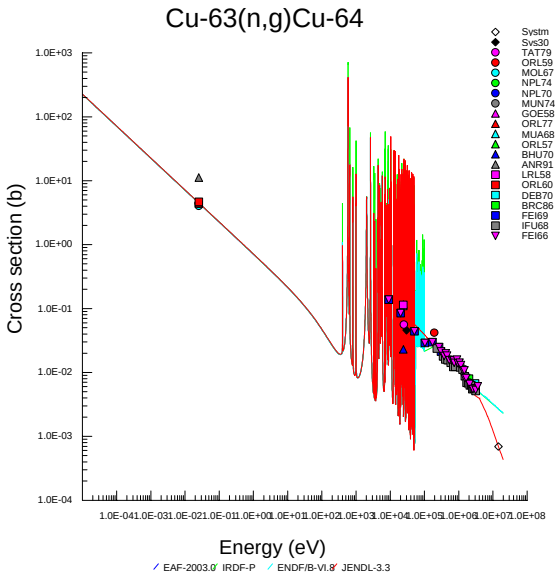
Lutetium-177 production

The $^{176}Yb(n,g)^{177}Yb$ reaction exist in the ADL-3, EAF-2003, FENDL/A-2, TALYS-2 [4] libraries. The ^{177}Yb with an half-life of 1.889 hours +/-6% decay as follows: β- (Lu-177) with a <β> of 420.0 Kev and a <γ> of 186.0 Kev. The metastable ^{177m}Yb with a half-life of 6.410 s +/-0.3% decay by IT with a <β> 178.0 Kev and a <γ> 149.4 Kev. The target radionuclide being the ^{177}Lu with a half-life of 6.7 days +/- 0.3% decaying by β- (100%) to Hf-177 (stable) with a <β> 147.42 Kev and a <γ> 36.862 Kev. This isotope is associated with indices for ingestion and inhalation of respectively 5.3 10^{-10} and 1.2 10^{-9} Sv/Bq.

Resonance Integral			
En. Min.	**Barns**	**Uncert**	**Lab.**
0.5	1.33	0.13	LRL70
0.4	2.7	0.3	OSL70
0.5	9.2	1.8	KJL75
0.55	14.4	1.2	GHT73
	6.81		EAF-2003

2.53E-1 cross section		
Barns	**Uncert.**	**Lab.**
3.02	0.5	LRL78
2.40	0.2	OSL70
2.85		EAF-2003

This evaluation done with SIGECN-MASGAM [3] model calculation further splitted by systematic (0.5 up to 30 KeV, going up to 0.76 for the ground thereafter) has been based on a better set of experimental differential measurements than its predecessor, particularly above the resonance region. There are room for improvement for this evaluation in term of branching ratio and may be resonance integral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TAT79
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MOL67
NPL74
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MUN74
GOE58
ORL77
MUA68
ORL57
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ANR91
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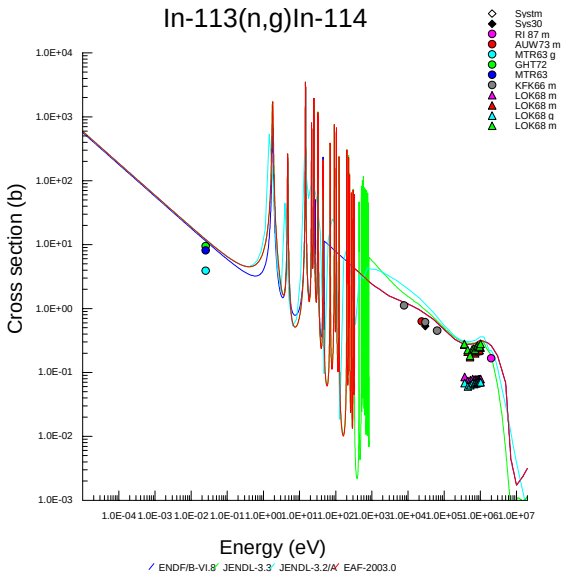
JENDL-3.3


In-113(n,g)In-114
Cross section (b)
Energy (eV)
Systm
Sys30
RI 87 m
AUW73 m
MTR63 g
GHT72
MTR63
KFK66 m
LOK68 m
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LOK68 m
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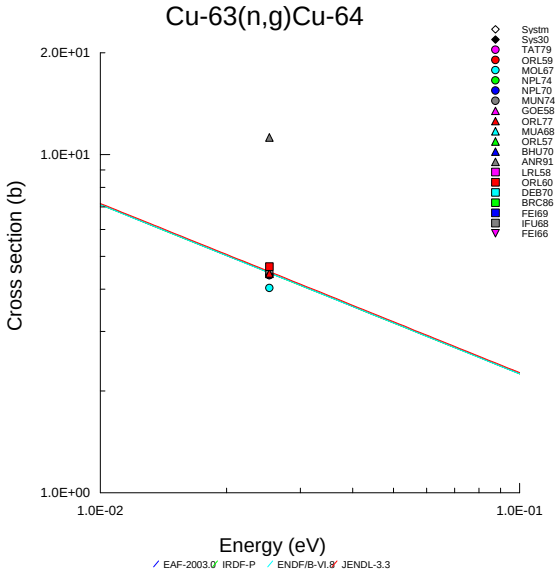
Cu-63(n,g)Cu-64
Cross section (b)
Energy (eV)
Systm
Sys30
TAT79
ORL59
MOL67
NPL74
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MUN74
GOE58
ORL77
MUA68
ORL57
BHU70
ANR91
LRL58
ORL60
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FEI66
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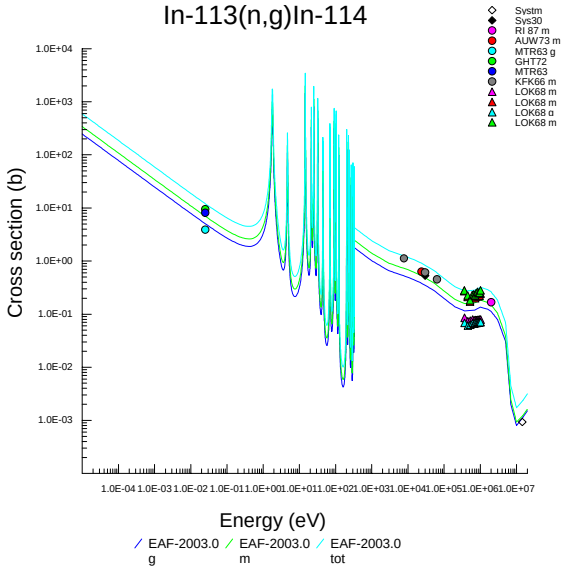
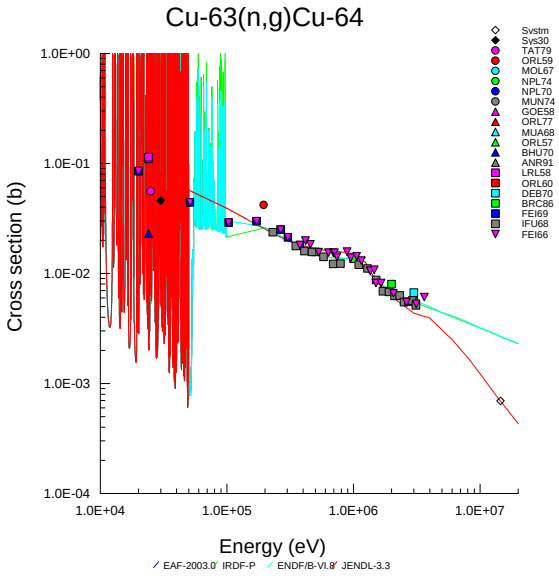
IRDF-P
ENDF/B-VI.8
JENDL-3.3


In-113(n,g)In-114
Cross section (b)
Energy (eV)
Systm
Sys30
RI 87 m
AUW73 m
MTR63 g
GHT72
MTR63
KFK66 m
LOK68 m
LOK68 m
LOK68 g
LOK68 m
EAF-2003.0 g
EAF-2003.0 m
EAF-2003.0 tot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GOE58
ORL77
MUA68
ORL57
BHU70
ANR91
LRL58
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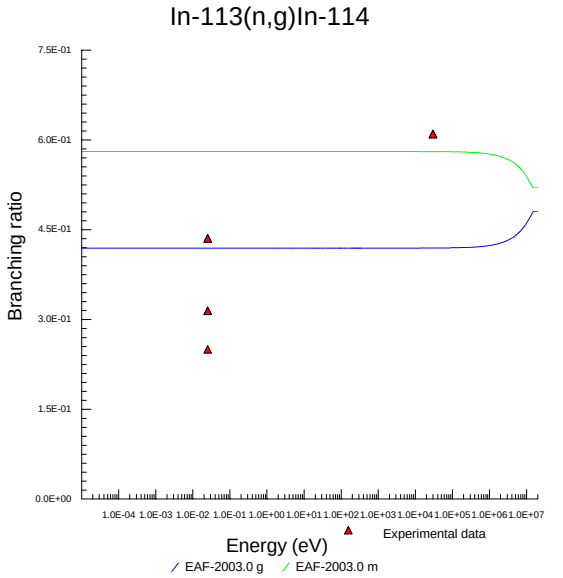
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Branching ratio
Energy (eV)
Experimental data
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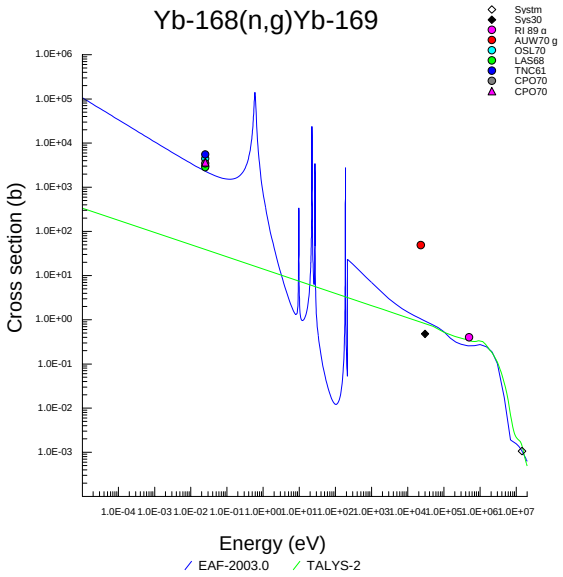
EAF-2003.0 m


Yb-168(n,g)Yb-169
Systm
Sys30
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AUW70 g
OSL70
LAS68
TNC61
CPO70
CPO70
Cross section (b)
Energy (eV)
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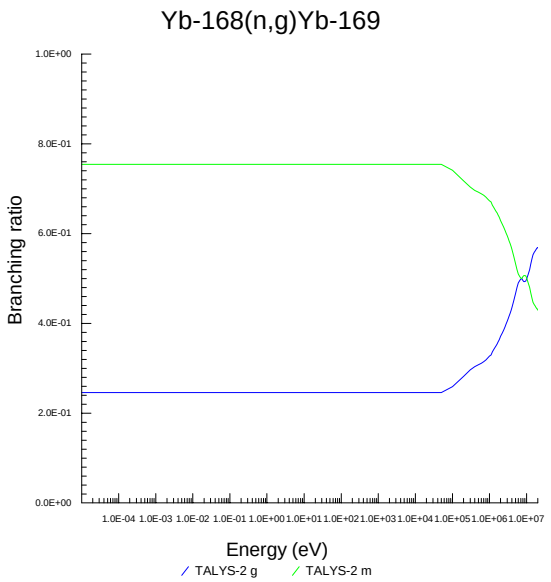
TALYS-2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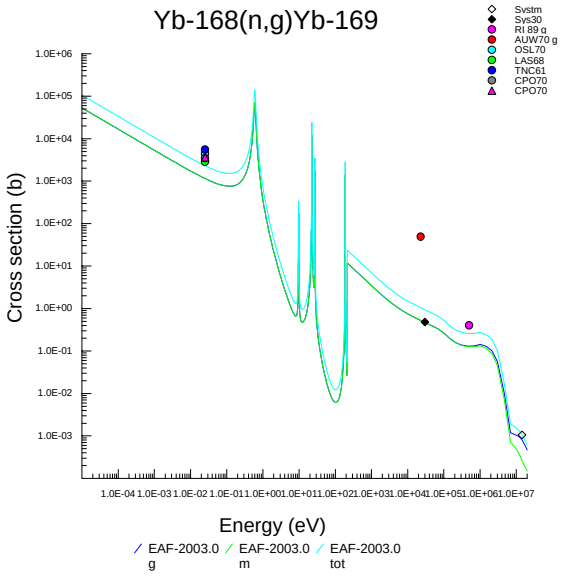
Branching ratio
Energy (eV)
TALYS-2 g
TALYS-2 m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Systm
Sys30
RI 89 g
AUW70 g
OSL70
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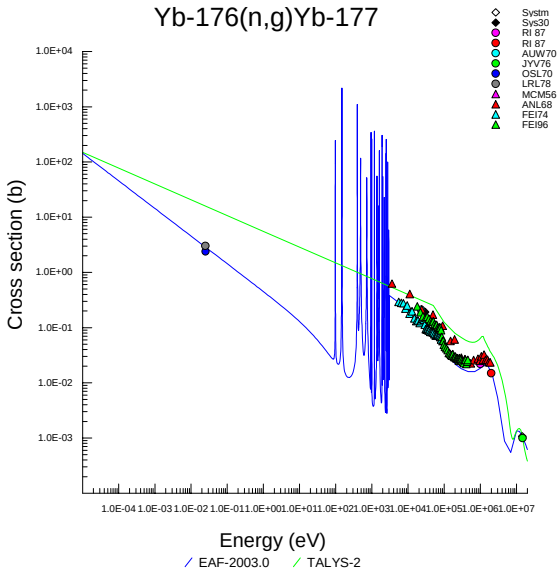
TNC61
CPO70
CPO70
Cross section (b)
Energy (eV)
EAF-2003.0 g
EAF-2003.0 m
EAF-2003.0 tot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FEI96
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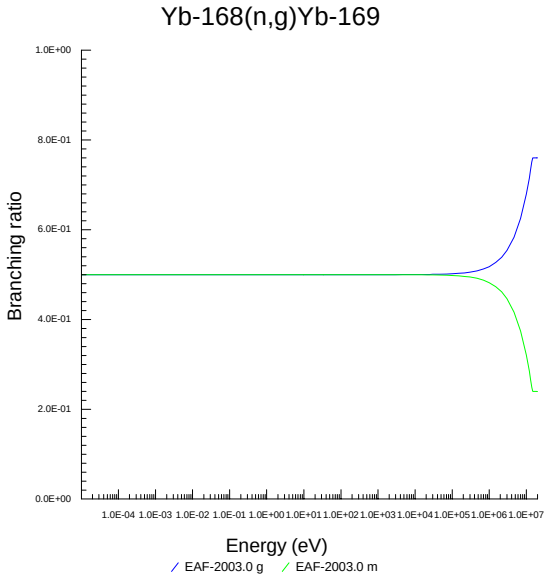
Energy (eV)
EAF-2003.0
TALYS-2


Yb-168(n,g)Yb-169
Branching ratio
Energy (eV)
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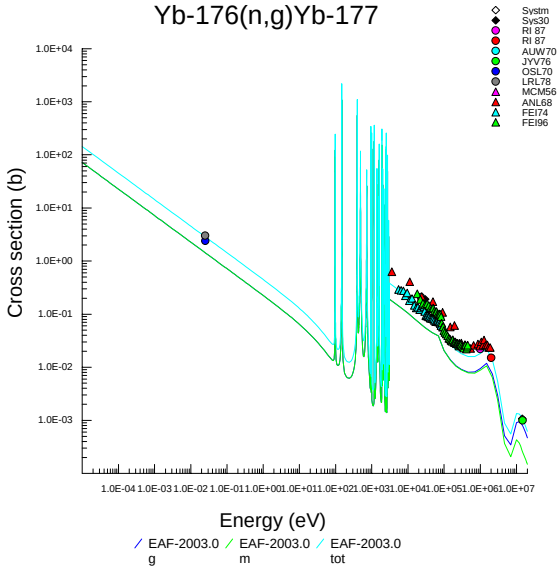
EAF-2003.0 m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Cross section (b)
Energy (eV)
EAF-2003.0 g
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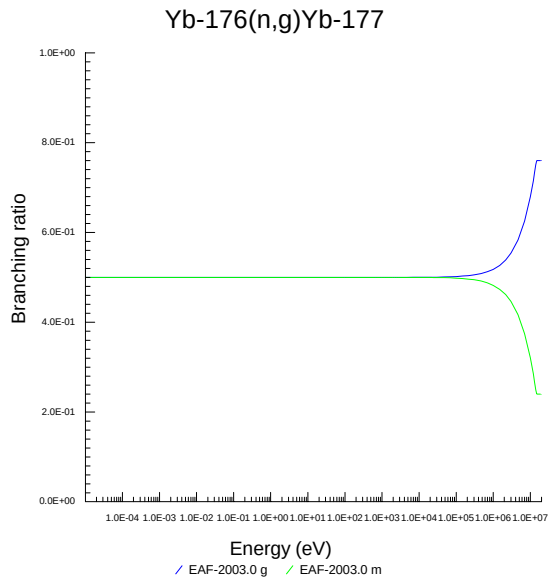

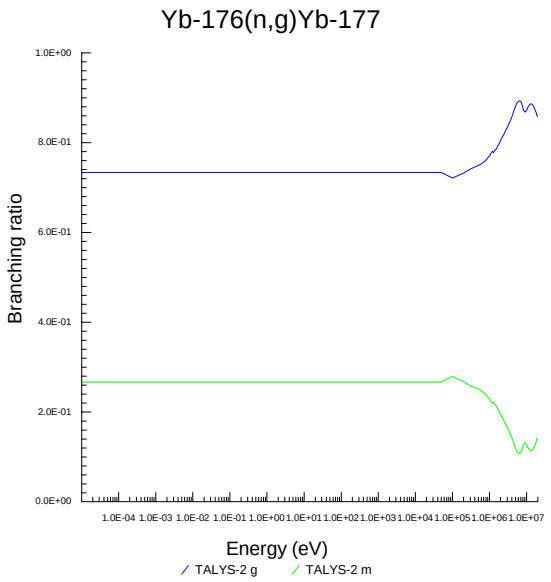

CONCLUSIONS

All the four reactions channels reviewed can be improved starting from the best available data file. Uncertainty data can be added, when missing and branching ratio assessed with better precision, although this tasks is the most difficult in view of the lack of energy dependant experimental differential information. File generation, including spectrum-averaged data can start, pending an overall agreement is found for the prior.

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Preliminary Model Estimates of Possible Production of Selected Therapeutic Radioisotopes A>80 Using the (n,gamma) Reactions with Fast Neutrons

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Introduction

The (n,γ) reactions may serve as the means of production of some radiopharmaceuticals either directly (89Sr, 103Pd, 153Sm and others) or via suitable generators (e.g. 125Xe serves as a generator for 125I). In some cases, this way of production is well established and used (89Sr or 125I), but sometimes (and more often) the necessary isotope is produced by other reactions [1,2]. The question is not only the possibility to create the needed isotope, but to produce it in sufficient amounts and – what is probably still more important – not polluted by other isotopes which arise either from the target impurities or from competing reactions. The task of our Contract is to estimate the cross sections of the corresponding (n,γ) reactions from few MeV to about 20 MeV.

The Model and the Code

The γ emission from the (n,γ) reactions at incident energies below about 10 MeV proceeds via equilibrated compound nucleus. At slightly higher energies – including those typical for the neutron generators – the pre-equilibrium effects start already play their role. We use the single-particle radiative mechanism [3,4], which has been proved to be very successful at the incident energies below about 30 MeV and which – on the other hand – gives also a good and reliable description at energies as low as about 5 MeV [5,6]. Therein, the γ emission rates can be expressed as $\lambda'_{\gamma}(n,E,\varepsilon_\gamma)=\frac{\varepsilon_\gamma^{\,2}\sigma(\varepsilon_\gamma)}{\pi^2\hbar^3c^2}\frac{\Sigma_m b(m,\varepsilon_\gamma)\omega(m,E-\varepsilon_\gamma)}{\omega(n,E)}$ and the branching ratios are $b(n-2,\varepsilon_\gamma)=\frac{\omega(2,\varepsilon_\gamma)}{g(n-2)+\omega(2,\varepsilon_\gamma)}$ and $b(n,\varepsilon_\gamma)=\frac{gn}{gn+\omega(2,\varepsilon_\gamma)}$. With inclusion of spin, however, they become much more complicated, but – fortunately – they factorize [7].

For the case of evaluation of the cross sections of production of specified isotopes, a simple spin-independent approach is more relevant. The code PEQAG [8] has been successfully used to analyze a whole set of excitation curves of (n,γ) and (p,γ) reactions. It has shown an extreme importance of proper level density parameters (see [5], where just a slight shift of these parameters can change the cross sections by more than one order of magnitude) and also influence of the temperature-dependent width of the GDR, which is rather surprising at excitation energies well below 50 MeV.

As our main tool, we have benefited from the PEQAG code, which is based on the set of master equations of the pre-equilibrium exciton model. After performing the calculations

using different sets of parameters and finding the optimal one for each reaction calculated, we plan to include also calculations using EMPIRE-II [9] and if justified,also with the spin-coupling pre-equilibrium code DEGAS (an extended version of [10]).

Input Parameters and Calculations

There are two groups of parameters for our calculations. First, they are the parameters specific for the pre-equilibrium emission. Here, two of them play the essential role, namely the initial exciton number n_0 and the squared average matrix element $|M|^2$ of the residual interaction, which governs the equilibration process. For the initial exciton number, we have applied the general philosophy of the model and used $n_0 = 1$, and the matrix element has been assumed to have its exciton number dependent form with $K' = 100 MeV^3$ (see also [5,6]).

Somewhat more complicated is the situation with the usually standard parameters. Our plan is to evaluate the cross sections for (n,γ) reactions on six different targets ranging from 88Sr to 191Ir. One needs therefore – at least – reliable data for 18 involved nuclei (the composite system plus nuclei after the neutron and after the proton emissions). Assuming that the best available information is contained in RIPL [11] and other IAEA NDS libraries, we started there, but only a half of nuclei have their level density parameters listed there (and only for the reaction on 88Sr we have the data for all three involved ones). Practically the same stuff is for the GDR parameters. Therefore, we had to supplement these sources with other available and possibly some interpolation over blank spaces. Thus, we have used the old tables of Gilbert and Cameron [12] and more recent ones by Rohr [13] for the level density parameters, and a kind of interpolation among the published values of the GDR parameters. The inverse neutron cross sections have been supplied by the default of the PEQAG code, whereas the optical model calculations with Perey data using the code SCAT-2 [14] has been used.

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Nuclear data for production of P-32

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Seoul 151-742, Korea

1. Introduction

P-32, a pure β^--emitter, is used for the medical application, trace analysis, and genetics study in Korea. Recently the collaboration of medical and research works is developing techniques for therapeutic applications. The P-32 is now produced in the HANARO research reactor of KAERI (Korea Atomic Energy Research Institute). The radioisotope can be produced by the reactions of P-31(n,γ)P-32 and S-32(n,p)P-32. The (n,p) reaction is mainly used in KAERI, while the (n,γ) reaction is used in special case. For the first half of planned annual work, cross sections of P-31(n,γ) reaction have been reviewed.

In this abstract, the cross sections and relevant nuclear data have been retrieved from various libraries, and are compared each other. A new evaluation of nuclear data, if required, will be performed in the next step.

2. P-31(n, γ)P-32 cross section

P-31(n,γ) cross sections can be retrieved from the libraries of ENDF/B-VI (1977 : year of evaluation), JEF-2 (1987), JENDL-3 (1993), BROND-2 (1989), CENDL-2 (1986) [1]. The resonance parameters are tabulated in the references by Mughabghab [2] and Macklin [3]. The parameters have been determined by the method of nonlinear least-squares fitting of experimental cross sections [3]. The JEF and JENDL libraries have taken these parameters to calculate the pointwise cross sections. The thermal capture cross section and resonance integral in each library are shown in Table I. Some data of resonance integral and fast cross section are taken from JEF report 14 [4]. Resonance integrals have been calculated in energy region of 0.5 eV ~ 500 keV, from Cd cut-off energy to maximum resonance energy.

Fig. 1 shows the neutron capture cross section of each library and the experimental data listed in EXFOR [5]. The EXFOR data of thermal cross section have been averaged with variance-weighting method. The result is 0.172(4) b which is consistent with that of Mughabghab [2]. The most recent PGAA (Prompt Gamma-ray Activation Analysis) database [6], developed from an IAEA coordinated research project, lists the thermal capture cross section of 0.167(5) b. The two values are well consistent. Our recent measurement (SNU 2003 [7]) based on prompt gamma activation method determines the cross section 0.164(2) b, preferring

Table I. P-31(n,γ)P-32 cross section and resonance integral.

Library	σ_γ (2200 m/s) [b]	Resonance integral [b]	Resonance region [b]	Fast cross section [a] [b]	
				14 MeV	Fission average
Mughabghab [2] and Macklin [3]	0.172(6)	0.085(10)	Exp.	-	-
ENDF/B-VI	0.1991	0.1452 [a]	-	0.3000×10^{-3}	0.1473×10^{-2}
JEF-2	0.1664 [a]	0.07569 [a]	Eval.	0.9895×10^{-5}	0.1012×10^{-2}
JENDL-3	0.166	0.081	Eval.	0.9895×10^{-5}	0.1012×10^{-2}
BROND-2	0.181	0.087	Eval.	0.3000×10^{-3}	0.1205×10^{-2}
CENDL-2	0.1741	0.06071 [a]	Eval.	0.1849×10^{-3}	0.1423×10^{-2}

[a] JEF Report 14 [4].
[b] Exp. : experimental data parameterized, Eval. : evaluated cross sections in resonance region.

to the latest IAEA database value. The latest data based on prompt gamma measurement are well consistent with JENDL and JEF cross sections.

Resonance integrals of each library are apparently consistent with 0.085(10) b of Mughabghab [2], just because they have used the same resonance parameters of Mughabghab [2] and Macklin [3]. Fission spectrum averaged cross sections were calculated in the JEF report 14 [4].

Fig. 2 shows the experimental capture cross sections [5] and evaluated data [1] in the energy range of 10^{-4} eV ~ 20 MeV. JENDL resonance region has represented the resonance parameters of Mughabghab [2] and Macklin [3], and is same to JEF. ENDF/B-VI has no resonance structure. All libraries are inconsistent in the epithermal region, but there is a good agreement between CENDL and JENDL in resonance region.

3. S-32(n, p)P-32 cross section

In the case of P-31(n,γ), high purity targets (>99.99%) are irradiated in the reactor, and its natural abundance is 100%. Hence there is no other isotopic reaction, and the half-lives of

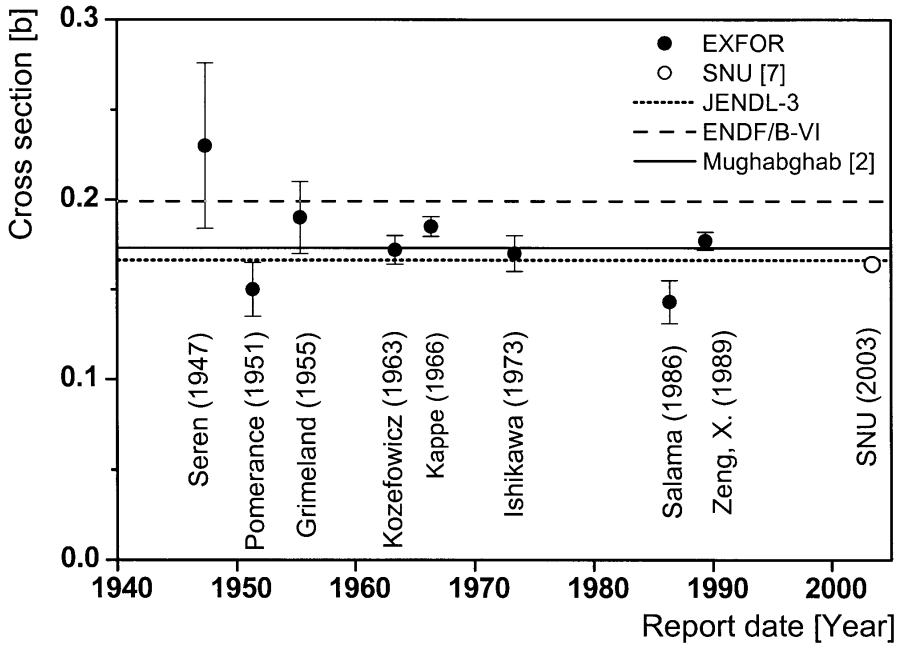

Fig. 1. Thermal neutron capture cross sections of P-31. Solid circles are EXFOR [5] data and open circle is SNU cross section [7].

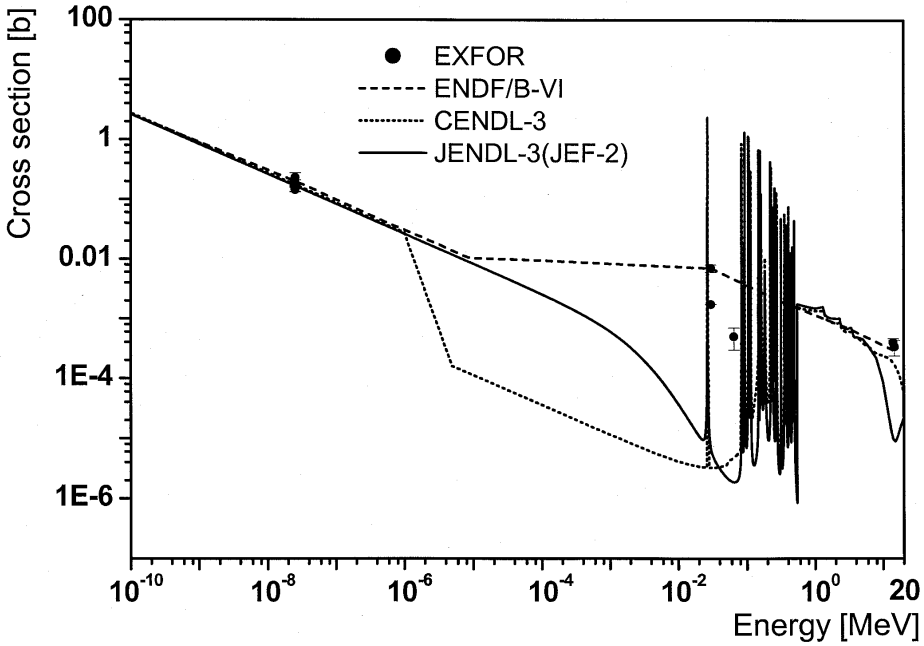

Fig. 2. Neutron capture cross sections of P-31. Solid circles are EXFOR data [5] and lines are taken from the evaluated data libraries [1].

products from (n,2n), (n,α), (n,p) reactions are a few minutes leading to negligible by-product activity. The product in the final stage of chemical treatment, however, has the disadvantage of low specific activity. For higher specific activity, a pure S-32 target (>99.99%) is used with a proper chemical process. The future work will concentrate at the (n,p) reaction and related factors. For the evaluation tool, the statistical model code [8] has been setup and calculation will be performed by the model parameter.

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Preliminary Evaluation of $^{89}Y(n,\gamma)^{90}Y$, $^{90}Zr(n,p)^{90}Y$, $^{185}Re(n,\gamma)^{186}Re$ and $^{187}Re(n,\gamma)^{188}Re$

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Introduction

As part of the Coordinated Research Project on the Production of Therapeutic Radionuclides, we have performed preliminary reaction model calculations of the ^{90}Y producing reactions, $^{89}Y(n,\gamma)^{90}Y$ and $^{90}Zr(n,p)^{90}Y$ and of the capture reactions on rhenium isotopes, $^{185}Re(n,\gamma)^{186}Re$ and $^{187}Re(n,\gamma)^{188}Re$ and compared these to the experimental data available in the EXFOR library[1]. These are described in the next section.

We have also calculated unshielded spectrum averaged cross sections for the reactions above using the available ENDF formatted libraries[1]. These are discussed and tabulated below.

Comparisons of the experimental data with previous evaluations in the ENDF formatted libraries were performed as well, but were not available for the presentation at the Research Project meeting.

Model Calculations

The calculations shown here were obtained using the EMPIRE-II computer code[2]. The global spherical optical model of Koning and Delaroche[3] was used for neutrons and protons while the McFadden-Satchler spherical optical potential[4] was used for alphas. The compound nucleus contribution to the cross sections was calculated using the Hauser-Feshbach formalism with width fluctuation corrections. Multistep compound emission of neutrons and protons and multistep direct scattering of the incident neutron were taken into account. As far as possible, the level densities were adjusted to the available discrete states. The default parameters of the EMPIRE-II code were used in the calculations, except as mentioned.

The $^{89}Y(n,g)^{90}Y$ and $^{90}Zr(n,p)^{90}Y$ reactions

The radioisotope ^{90}Y has a $J^{\pi}=2^-$ ground state with a halflife of $T_{1/2}$=64 hrs that decays exclusively by β^- emission. It has an $J^{\pi}=7^+$ isomeric state at E_x=0.682 MeV with a halflife of $T_{1/2}$=3.19 hrs that decays almost exclusively to the ground state but possesses an extremely small branching ratio of 1.8×10^{-5} for β^- emission. The progenitors ^{89}Y and ^{90}Zr and the residual nucleus ^{90}Y are all nearly spherical.

The EMPIRE-II calculation of the $^{89}Y(n,g)^{90}Y$ corss section is compared to the experimental data in Fig. 1. The calculated cross section is generally high and does not describe the trend of the data at higher energies. Since the Koning-Delaroche optical potential describes the existing $n+^{89}Y$ scattering data extremely well, the overestimate of the cross section is probably due to either an overestimate of the photoabsorption cross section or of the density of states of the residual ^{90}Y nucleus. The wrong trend of this preliminary calculation at higher

energies is due to the fact that direct-semidirect/ pre-equilibrium γ emission was not included. Further calculations and, of course, a comparison with the existing evaluations are needed.

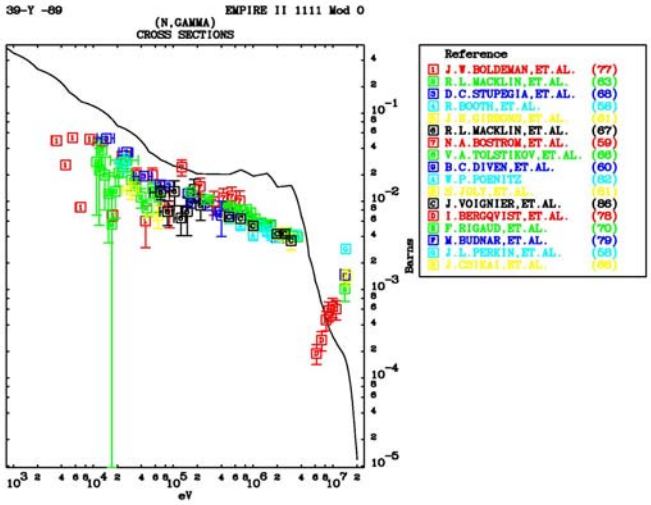

Fig. 1. EMPIRE-II calculation and available experimental data for the ^{89}Y(n,g)^{90}Y reaction

The EMPIRE-II calculation of the ^{90}Zr(n,p)^{90}Y cross section is compared to the experimental data in Fig. 2. The agreement with the data is generally good, with the exception of the two high data point, which will be discarded. The calculation underestimates the data at higher energies. This could be due to increased importance of multistep direct emission of protons at these energies, which is not included in the calculation. Further calculations and, of course, a comparison with the existing evaluations are needed.

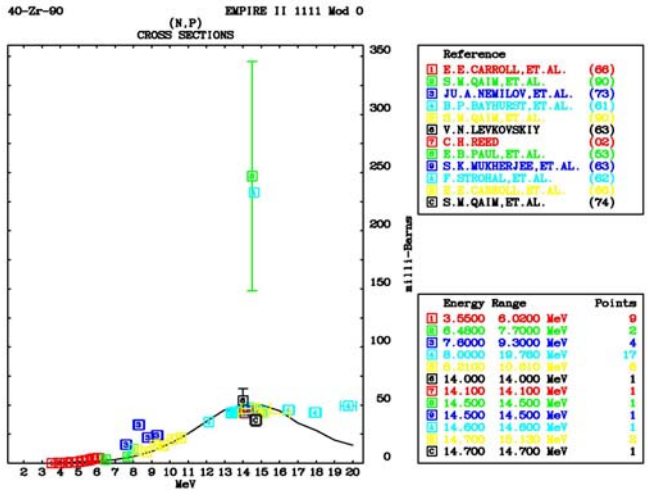

Fig. 2. EMPIRE-II calculation and available experimental data for the ^{90}Zr(n,p)^{90}Y reaction

The neutron capture reactions ^{185}Re(n, γ)^{186}Re and ^{187}Re(n, γ)^{188}Re

The radioisotope ^{186}Re has a $J^{\pi}=1^{-}$ ground state with a halflife of $T_{1/2}$=3.7183 days. It decays by β^{-} emission with a branching ratio of 92.53% and by electron capture/β^{+} emission with a branching ratio of 7.47%. It has an almost stable $J^{\pi}=(8^{+})$ isomeric state at E_x=0.149 MeV with a halflife of $T_{1/2}=2.0\times10^{5}$ years that decays exclusively to the ground state. Both the progenitor ^{185}Re and the residual nucleus ^{186}Re are highly deformed, with a quadrupole moment β≈0.2.

The EMPIRE-II calculation of the ^{185}Re(n, γ)^{186}Re cross section is compared to the experimental data in Fig. 3. All in all, the agreement is quite good. A deviation in the trend of the calculation is expected at higher energies, where no data exist, due to the fact that direct-semidirect/ pre-equilibrium γ emission was not included. Further calculations and, of course, a comparison with the existing evaluations are needed.

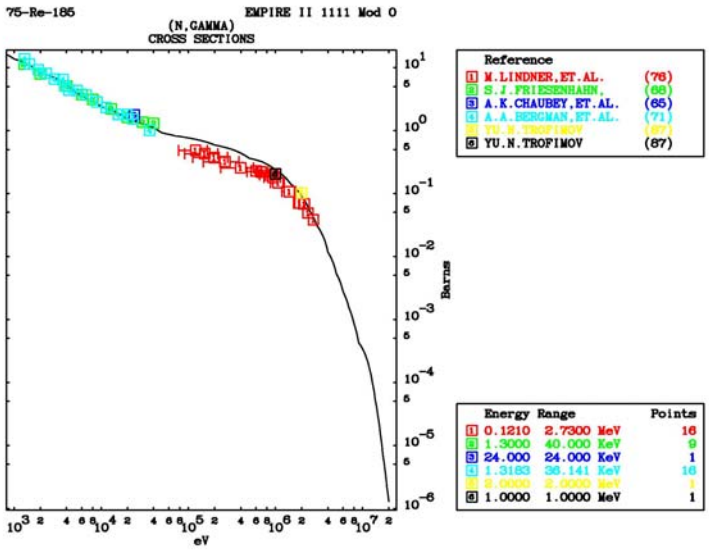

Fig. 3. EMPIRE-II calculation and available experimental data for the ^{185}Re(n,g)^{186}Re reaction

The radioisotope ^{188}Re has a $J^{\pi}=1^{-}$ ground state with a halflife of $T_{1/2}$=17.005 hrs. It decays exclusively by β^{-}. It has a short-lived $J^{\pi}=(6)^{-}$ isomeric state at E_x=0.172 MeV with a halflife of $T_{1/2}$=18.6 min that decays exclusively to the ground state. Both the progenitor ^{187}Re and the residual nucleus ^{188}Re are highly deformed, with a quadrupole moment β≈0.2.

The EMPIRE-II calculation of the ^{187}Re(n, γ)^{187}Re cross section is compared to the experimental data in Fig. 4. Again, the agreement is quite good. A deviation in the trend of the calculation is also expected at higher energies here, where no data exist, due to the fact that direct-semidirect/ pre-equilibrium γ emission was not included. Further calculations and, of course, a comparison with the existing evaluations are needed.

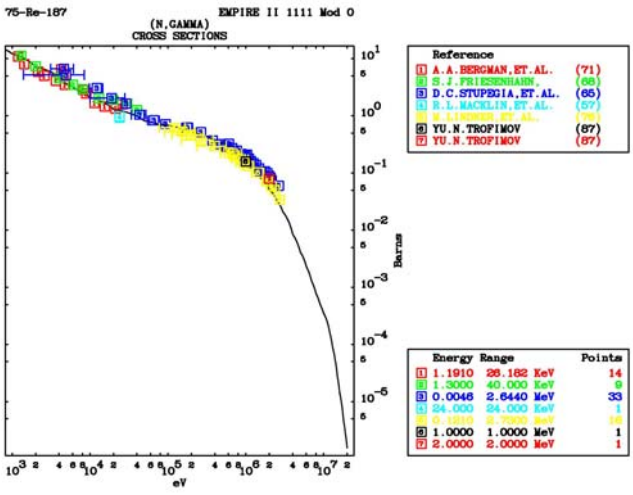

Fig. 4. EMPIRE-II calculation and available experimental data for the ^{187}Re(n,g)^{188}Re reaction

Spectrum Average Calculations

The evaluated nuclear data libraries for the materials ^{89}Y , ^{90}Zr , ^{185}Re and ^{187}Re were taken from the Nuclear Data Services[1] web site using the ENDF W^{3} Retrieval System[5]. LINEAR[6] was used to convert the ENDF/B File 3 cross sections to linearly interpolable form, within 1 percent accuracy, and the RECENT[6] was used to reconstruct cross sections from the resonance parameters, within the same accuracy. The SIGMA1[6] program was applied to Doppler broaden the cross sections to the temperature of 300 K, within the same accuracy, and GROUPIE[6] was then employed to calculate the unshielded one group average cross sections.

S(E)	θ (eV)	E_L (eV)	E_H (eV)
Maxwellian thermal	2.585E–02	1.0E–05	1.0E+01
$1/E$	—	5.5E–01	2.0E+06
Maxwellian fission	1.350E+06	1.0E+03	2.0E+07

Table 1: Weighting function parameters.

Three spectra, $S(E)$, were used as weighting functions to calculate the one group average cross sections, as follows:

i) Maxwellian thermal (T=300 K),

$$S(E) = \sqrt{E}\exp(-E/\theta);$$

ii) $S(E) = 1/E$; and

iii) Maxwellian fission, the same as in i).

Table 1 summarizes the parameters used in the weighting functions, generated with the ACES[7] computer program and displayed in Fig. 5. A value of 0.861735E–04 was taken for the Boltzmann constant.

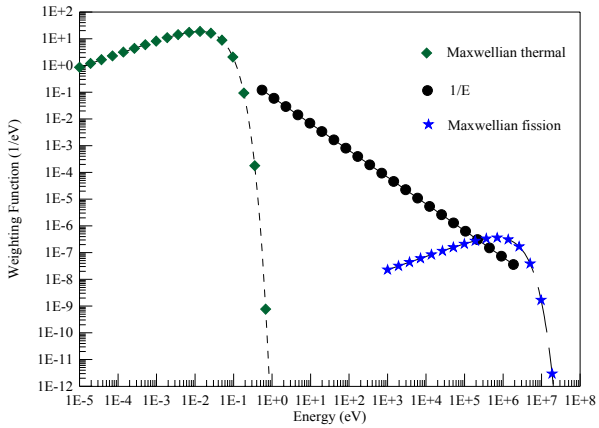

Figure 5: Weighting functions.

The spectrum averaged values are presented in Table 2 below. The thermal cross sections tend to be about 5 to 10% larger than those given by Mughabghab while the resonance integrals are in excellent agreement with his results.

Reaction	Library	Max. Thermal (b)	Res. Integral (b)	Maxw. Fission (b)
$^{89}Y(n,\gamma)^{90}Y$	ENDF/B-VI	1.446706(+0)	8.923346(–1)	4.758695(–3)
	JEF-2	1.446706(+0)	8.944961(–1)	4.766641(–3)
	JENDL-3.3	1.434426(+0)	8.403823(–1)	6.339072(–3)
$^{90}Zr(n,p)^{90}Y$	ENDF/B-VI	0.000000(+0)	0.000000(+0)	4.468960(–4)
	JEF-2	0.000000(+0)	0.000000(+0)	3.690889(–4)
	JENDL-3.3	0.000000(+0)	6.05299(–21)	2.160431(–4)
	BROND-2	0.000000(+0)	6.623000(–6)	4.810209(–4)
$^{185}Re(n,\gamma)^{186}Re$	ENDF/B-VI	1.260902(+2)	1.726757(+3)	1.818378(–1)
	JEF-2	1.281938(+2)	1.742226(+3)	1.473650(–1)
$^{187}Re(n,\gamma)^{188}Re$	ENDF/B-VI	8.614123(+1)	2.928128(+2)	1.171090(–1)
	JEF-2	8.430563(+1)	2.867199(+2)	1.202753(–1)

Table 3: Spectrum averaged values for T= 300 K.

Dedication

The contribution of A.D.C. to this Coordinated Research Project is dedicated to his uncle, Jorge David Filho.

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Status of the Project "Measurement and Standardization of Nuclear Cross Section Data for Production of some Therapeutic Radionuclides", Research Agreement No. 12488

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Introduction

The above mentioned research agreement between the IAEA and our institute was signed in March 2003 and work on the project started in the middle of April 2003. Thus, the CRP activities have just started. However, since the institute has a longstanding programme of nuclear data work, and in recent years considerable attention has been paid to therapeutic radionuclides, some of the CRP-related work is briefly described below.

Compilation and evaluation

Our responsibility stipulates work on four nuclear reactions, namely ^{64}Ni(p,n)^{64}Cu, ^{70}Zn(p,α)^{67}Cu, ^{103}Rh(p,n)^{103}Pd and ^{124}Te(p,n)^{124}I processes. The status of available data is as follows.

For the ^{64}Ni(p,n)^{64}Cu and ^{70}Zn(p,α)^{67}Cu reactions reliable and well-documented studies appear to have been done only at the FZ Jülich [1, 2]. Some older studies on cross sections and yields also exist. A literature search is under way.

Regarding the ^{103}Rh(p,n)^{103}Pd reaction, a thorogh experimental study has been performed under a cooperation between the FZ Jülich and Debrecen University [3]. An evaluation of all the available experimental data has been done and nuclear model calculation has been carried out. The results are shown in Fig. 1. Recommended cross sections are now available.

As far as the ^{124}Te(p,n)^{124}I reaction is concerned, accurate cross section data were measured under a cooperation between the FZ Jülich and ATOMKI Debrecen [4] and a survey of older data was done. Further search of the literature data is under way.

Experimental studies

New reaction cross sections were measured radiochemically for the formation of ^{64}Cu and ^{67}Cu via various nuclear reactions on highly enriched target isotopes, e.g. ^{64}Cu via ^{66}Zn(d,α)^{64}Cu and ^{68}Zn(p,αn)^{64}Cu reactions [5] and ^{67}Cu via the ^{68}Zn(p,2p)^{67}Cu process [6]. Those studies are distantly related to CRP but are not directly part of the CRP work. A further discussion is therefore beyond the scope of this report.

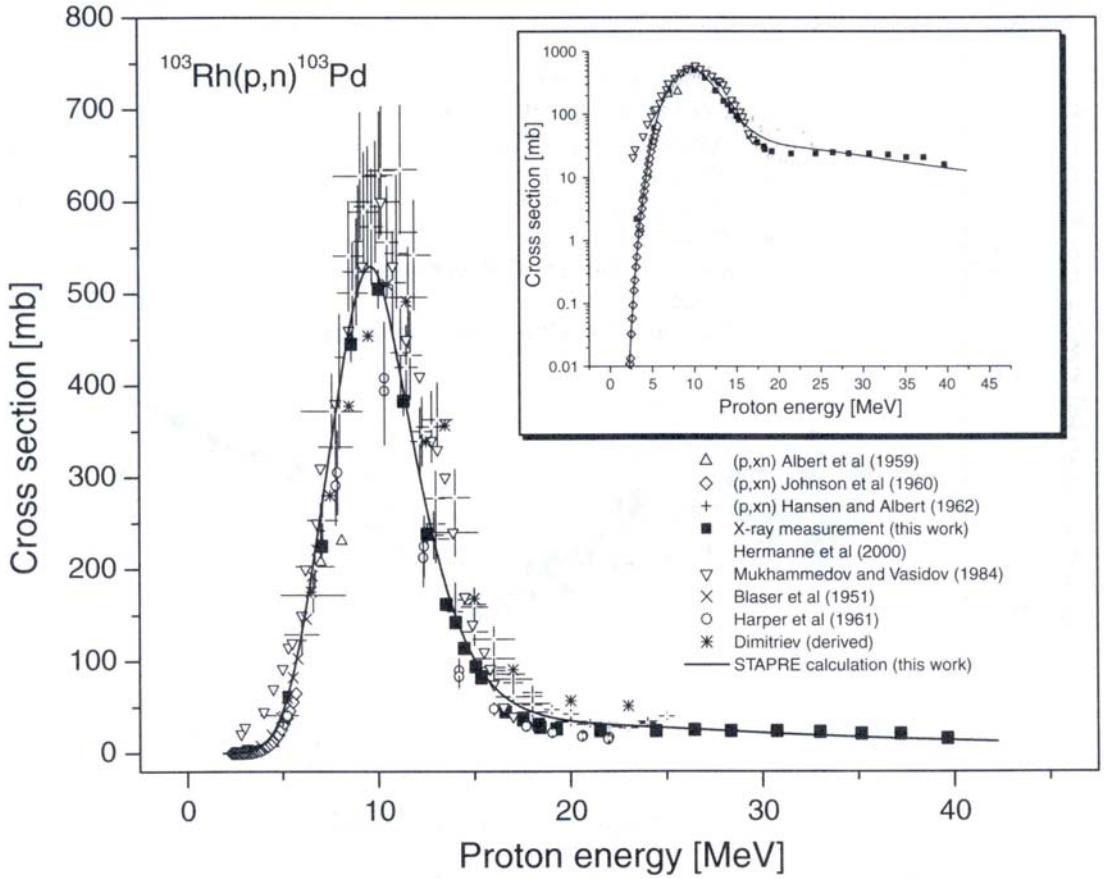

Fig. 1 Excitation function of the ^{103}Rh(p,n)^{103}Pd reaction with all the available data obtained via neuton counting and activation measurements. The results of nuclear model calculation are also given. In the inset the data are shown on a logarithmic scale (after ref. [3]).

An experimental study of the reaction ^{192}Os(p,n)^{192}Ir falls within the responsibility of the FZ Jülich. The enriched target material (84.5% ^{192}Os) has been purchased and work on the sample preparation is under way. Irradiations will be done when samples have been properly prepared and their quality has been tested.

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Nuclear reaction data for accelerator-produced therapeutic radioisotopes. Status report on the activity at ATOMKI in Debrecen

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Introduction

The main activity of the nuclear data group in Debrecen is concentrated on the integral cross sections of light ion induced reactions. The investigated reactions are connected to the following application fields:

- nuclear reactions for production of diagnostic radioisotopes,
- **nuclear reactions for therapeutic radioisotopes**
- nuclear reactions for thin layer applications
- nuclear reactions to monitor beam parameters
- nuclear reactions connected to transmutation of radioactive waste

The investigations include experimental measurements, data compilations, data evaluations, data validations and data applications. The investigations are connected to several applications simultaneously. The experimental measurements and the data evaluations are done in international collaborations. The main partners for measurements of nuclear data for production of therapeutic radioisotopes: VUB Brussels, FZ Jülich, CYRIC Tohoku University.

The task

The responsibility of the Debrecen group in the present CRP project is:

- compilation of selected charged particle induced reactions,
- new cross section and yield measurements,
- preparation a list of works not compiled in EXFOR and coordination of the EXFOR compilation of the charged particle induced reactions,
- preparation of recommended data by fitting.

Status of the nuclear reaction data and of the compilation work

In the following Tables we summarize the status of the related database and the work performed in connection with the IAEA Coordinated Research Project on "Nuclear Data for Production of Therapeutic Radionuclides".

Table 1. CRP related cross-section data for production of therapeutic radioisotopes

Product nuclei	Reaction	Experiment	Year	Literature	Selected	Eval.	Valid.
^{103}Pd	^{103}Rh(d,2n)	0-20 MeV	2001	1	1	no	no
^{114m}In	^{114}Cd(p,n) ^{nat}Cd(p,xn)	in progress 0-34 MeV	(2003) (2003)	7 2	6	no	no
^{114m}In	^{114}Cd(d,2n) ^{nat}Cd(d,xn)	in progress 0-21 MeV	(2003) (2003)	0 0		no	no
^{186}Re	^{186}W(p,n)	0-20 0-70	1998 (2003)	3	3	no	no
^{186}Re	^{186}W(d,2n)	0-21 MeV 0-50 MeV	1999 (2003)	5	4	no	no
^{211}At	^{209}Bi(α,2n)	0-40 MeV	(2003)	4	4	no	no

Remark: The total number of the earlier experimental works doesn't contains the measurements in 2003.

Table 2. Status of the related yield data for validation

Product nuclei	Reaction	Experimental yield	Compilation	Remarks
^{103}Pd	^{103}Rh(d,2n)	2	done	new experiment ?
^{114m}In	^{114}Cd(p,n) ^{nat}Cd(p,xn)	2 1	done done	new experiment ?
^{114m}In	^{114}Cd(d,2n) ^{nat}Cd(d,xn)	1 0	done	
^{186}Re	^{186}W(p,n)	1	done	new experiment?
^{186}Re	^{186}W(d,2n)	1	done	new experiment?
^{211}At	^{209}Bi(α,2n)	1	done	

Table 3. Status of missing EXFOR compilations (including new meas.)

Product nuclei	Reaction	Number of references	Missing Exfor compilations	Remarks
^{103}Pd	^{103}Rh(d,2n)	1	1	in progress
^{114m}In	^{114}Cd(p,n) ^{nat}Cd(p,xn)	8	2	
^{114m}In	^{114}Cd(d,2n) ^{nat}Cd(d,xn)	0 2	0 1	
^{186}Re	^{186}W(p,n)	6	3	
^{186}Re	^{186}W(d,2n)	7	5	in progress
^{211}At	^{209}Bi(α,2n)	6	2	

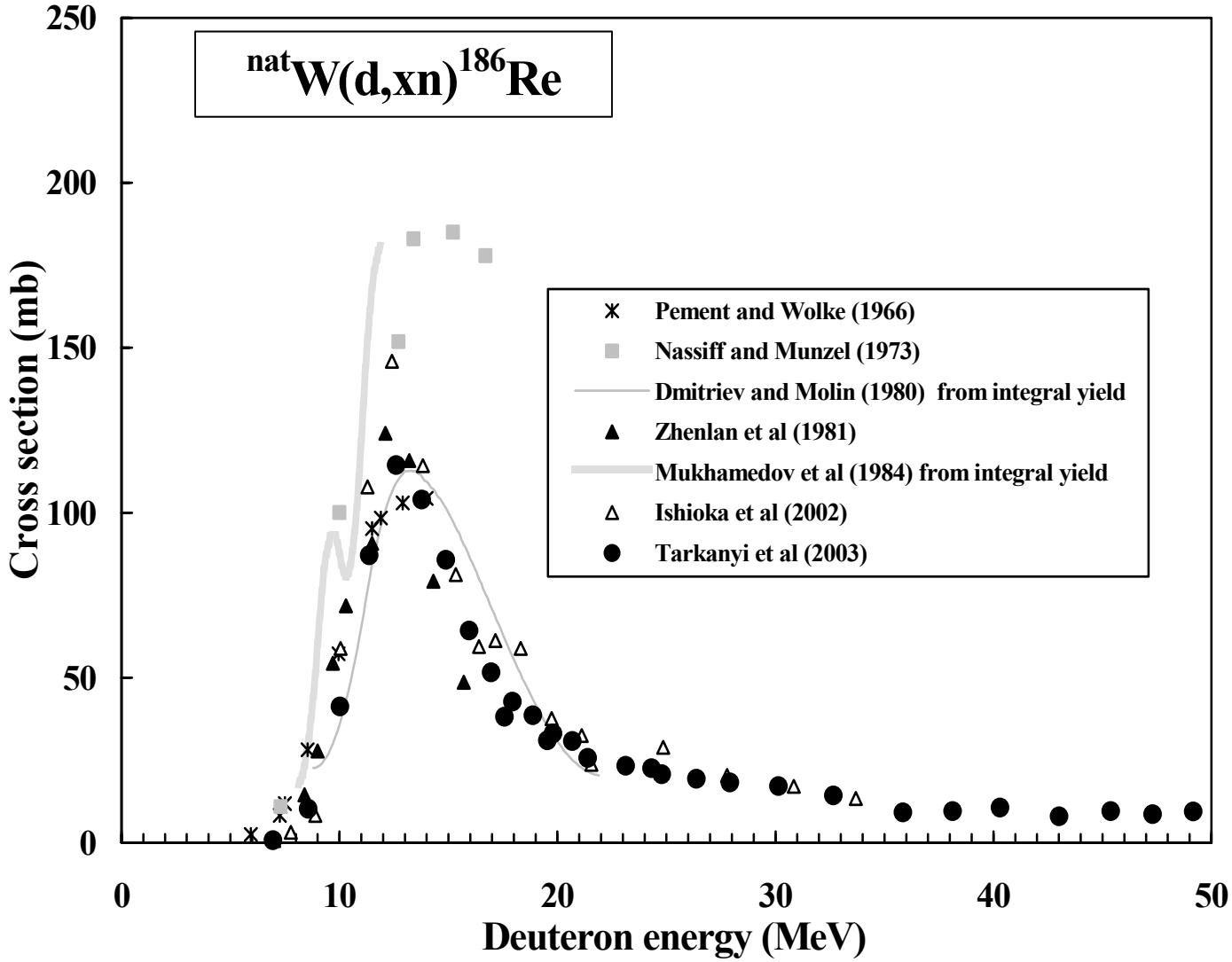

Fig. 1. Experimental data available in the literature for the $^{nat}W(d,xn)^{186}Re$ reaction.

The quality of the experimental data is illustrated on Fig. 1. for the $^{nat}W(d,xn)^{186}Re$ reaction. To get isotopic cross section on ^{186}W target the cross section values have to be multiplied by 1/0.286.

Conclusions and recommendations

New measurements

- Large amount of experimental data related to recent CRP were measured by participation of the Debrecen group already before the start of the CRP and significant progress was made after the start (see Table 1 and list of references). The experiments on the highly enriched ^{114}Cd are still missing. No experimental data on $^{114}Cd(d,2n)^{114m}In$ available, therefore the new measurement has special importance. The new measurements will start in fourth quarter of 2003.
- New experimental yield measurement for data validation seems to be reasonable for the $^{nat}Cd(p,x)^{114m}In$, $^{nat}Cd(d,x)^{114m}In$, $^{nat}W(p,x)^{186}Re$ and $^{nat}W(d,x)^{186}Re$ reactions

Compilation of cross-sections

- Compilation for $^{103}Rh(p,n)^{103}Pd$, $^{103}Rh(d,2n)^{103}Pd$, $^{186}W(p,n)^{186}Re$, $^{186}W(d,2n)^{186}Re$ are practically ready, and can be used for model calculation and fitting. The available experimental data are contradictory (see f. e. Fig. 1), but by investigating the details of the experiment proper selection can be made.
- The situation is clear. The quality of the data in case of all reactions (except $^{114}Cd(d,2n)^{114m}In$) seems to be satisfactory to perform fitting.
- The compilations of the $^{114}Cd(p,n)$, $^{114}Cd(p,n)$ and the $^{209}Bi(\alpha,2n)$ reactions will be ready not earlier than end of 2003, due to the time consuming data evaluation of the new experimental measurements.

Compilation of the experimental yields for validation

- Very few experimental yields were found in the literature, in the journals. To search the secondary sources is very important but very time consuming.
- New experimental measurements are proposed by using target materials with natural abundances (W, Cd).

EXFOR compilation

- Significant part of the connected literature is not compiled into EXFOR format. List of the missing work can be prepared by getting the involved literature from other compilators of the present CRP (Julich, Los Alamos)

CRP related experimental works with participation of the Debrecen group

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F. Tárkányi, S. Takács, F. Szelecsényi, F. Ditrói, A. Hermanne and M. Sonck
Excitation functions of deuteron induced nuclear reactions on natural tungsten up to 50 MeV
Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms (in print)

S. Takács, F. Tárkányi, A. Hermanne and R. Paviotti de Corcuera
Validation and upgrading of the recommended cross section data of charged particle reactions used for production of PET radioisotopes
Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials (in print)

First CRP Meeting on Nuclear Data for Production of Therapeutic Radioisotopes, 25-27 June, 2003.

"Calculation and evaluation of neutron induced threshold reaction cross sections for $^{32}S(n,p)^{32}P$, $^{89}Y(n,p)^{89}Sr$ and $^{90}Zr(n,p)^{89}Y$ reactions".

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Summary

The recent investigation results on the model calculations and evaluations connected with the creation of reference charged particles cross section database for therapeutic radioisotope production is presented. Nuclear reaction models and codes are briefly outlined, which were used in these investigations, the examples of the calculation results are given. Method of statistical optimization of experimental data, based on discrete optimization with rational functions (Pade approximation) is briefly described, and the results of evaluations of excitation functions are presented. The recommendations based on the systematically observed tendencies of experimental data on neutron induced threshold reactions are given also.

Introduction

In evaluation process three main interconnected areas of the activity can be noted:

1. Collection, selection and expert analysis of experimental data.
2. Model calculations with the corresponding codes, the analysis of the results and parameters used, the comparison with experimental data.
3. Working out the recommendations, using the selected and corrected information.

The first stage is not easy to formalize and reduce to algorithm, because it includes a critical analysis of experimental methods. It should be performed by experimentalists as a rule. On this stage the model calculations can help in the selection of experimental data also. The results of model calculation with well-defined parameters can serve as a guide, even when experimental data are not available. On the final stage the selected experimental data and the results of model calculations using various mathematical methods should be analyzed simultaneously.

Creation of a Cross Section Database for Therapeutic Radioisotope Production requires the analysis of both experimental and modeled cross sections. It was recognized during the first Coordinated Research Project of IAEA [1] that modeling will play an important role in predicting cross sections where measurements are either not available or have large discrepancies. It was decided to use modeling as a guide rather than for full evaluation. However in some cases the CRP used the modeled cross sections as the recommended values. Thus the modeling was done using global input parameters.

Calculations and evaluations

The ALICE family of codes is based on the hybrid, the geometry-dependent hybrid (GDH) or the HMS pre-equilibrium models and the Weisskopf-Ewing evaporation formalism. The HMS-Alice code uses a Monte Carlo pre-compound formulation with Weisskopf-Ewing evaporation. The lack of angular momentum and parity treatments in the Weisskopf-Ewing formalism used in these codes may be of some concern for certain aspects of reaction yields, (e.g., isomer yield calculations). But these codes are fast and convenient to use, i.e., when many particles are emitted in the reaction process, and have generally been found to be adequate when cross sections for isomeric states are not needed.

The ALICE-IPPE code is the ALICE-91 code version modified by the Obninsk group to include the generalized superfluid level density model and pre-equilibrium cluster emissions. The corrections were made also for the multiple pre-compound proton emission near the threshold, for gamma-emission and optical model parameters and some others. For the pre-equilibrium nucleon emission the geometry dependent hybrid (GDH) model is used. Calculation of the alpha-particle spectra is performed taking into account both the pickup and knockout processes. A phenomenological approach is used to describe direct emission of the deuteron]. The triton and ^{3}He spectra are calculated according to the coalescence pickup model of Sato, Iwamoto and Harada. The level density formalism includes both collective and non-collective effects, and excitation-energy-dependent shell effects.

When the status of the experimental data is appropriate, meaning that a reasonable amount of independent measurements have been published that do not show inexplicable discrepancies between them and that for all points reliable estimations are available, a statistical fit over the selected data points can be performed. For the approximation of experimental data various analytical functions can be used. The polynomial approximation is the simplest, the best developed and most popular one. Well-known Spline fit method is based on the approximation by polynomials. Rational functions (ratio of two polynomials) represent the more general class of analytical functions as compared with polynomials. In particular, these functions enable to describe in a natural way the nuclear reaction cross sections in resonance region, which are determined by the positions of poles of the corresponding S-matrix and, consequently, are well approximated with the polar expansion, that is, with rational function of the energy.

Results and discussion

All available experimental data [9-30] and previous evaluations have been taken into account in our analysis of the reaction cross sections for the ^{32}S(n,p)^{32}P, ^{89}Y(n,p) ^{89}Sr and ^{90}Zr(n,p) ^{89}Y. The analysis of reaction cross sections was performed with the use of model calculations with the ALICE-IPPE code, statistical approximation with rational functions (Pade approximation) and also taking into account empirical trends. The ALICE-IPPE code and statistical approximation with rational functions (Pade approximation) are briefly described in [1]. In Obninsk Nuclear Data Center the information on the empirical trends in neutron reaction cross sections was accumulated, which have been taken into account in the present analysis [2,3]:

- maximum cross sections of (n,p) reactions in the scale of (lnσ-A) for isotopes of given element with atomic number Z linearly depend on A, where A is atomic number,
- maximum cross sections of (n,p) reaction in the scale of (lnσ-A) for isotopes of different elements with the same neutron excess (N-Z) linearly depend on atomic number Z,
- the shapes of (n,p) excitation functions with the same neutron excess (N-Z) are similar.

At selection of recommended (n,p) excitation function for a given isotope the comparison was made with the excitation functions of neighboring isotopes on Z and A isotopes using criteria of the systematics above mentioned. Besides the position of maximum excitation function on the energy axis was compared relative to effective threshold (threshold+ Coulomb barrier) and difference of thresholds between the main (n,p) and competitive reaction of (n,np).

In process of evaluation preliminary selection of more reliable excitation functions available in the libraries ADL-3, JENDL-3, BROND-2, ENDF/B-VI, EAF-97 [4-8] was made on the basis of criteria pointed above. Further the correction was made taking into account requirements of the systematics or experimental data not used in previous evaluations. All available experimental data were taken into account [9-30]. Below the brief description of recommended excitation functions are given.

^{32}S(n,p)^{32}P reaction.

The results of the analysis for the ^{32}S(n,p)^{32}P reaction are shown in Fig. 1. The results of model calculations with ALICE-IPPE are shown by filled green squares up to incident energy 40 MeV The calculations give satisfactory description near the reaction threshold, however overestimate the excitation function in maximum. The renormalized curve to the maximum of experimental data gives a reasonable energy dependence of the cross section. The Pade approximation obtained taking into account all

experimental data does not give satisfactory results. It means that the severe selection of experimental data should be made to get consistent experimental data set. After selection of experimental data and disregarding some of them (Paul, Klema and Santry) the Pade approximation gives rather reasonable evaluation. The results of previous evaluations from various well-known libraries ADL-3, JENDL-3, BROND-2, ENDF/B-VI, EAF-97 were analyzed, which are shown in Fig.1. The data of systematics [31] denoted as "System" for the (n,p) reaction cross sections at the energy of 14.5 MeV is given also.

At the beginning the excitation function from JENDL-3 library /5/ was considered that describes experimental data well enough and basically correspond to requirements of the systematics. However as a result of more attentive comparison this excitation function with better known excitation function of (n,p) reaction for neighboring nuclide ^{28}Si, having the same number (N-Z), it was recommended to increase this cross section by several percent in the energy region 3-13MeV. The excitation function designated as "RecSys" is recommended on the base of these empirical considerations up to 20 MeV.

The excitation function from other the libraries do not correspond the requirements of the systematics and. The data from ENDF/B-VI /6/ have a structures which can not be explained from physical point of view at least in the energy range above 6 MeV. The data of ADL-3 library /3/ lies too high, their absolute maximum value contradicts of the systematics and besides they do not describe the experimental data in the energy region of 14-15 MeV.

^{89}Y(n,p)^{89}Sr reaction.

The results of our analysis for the ^{89}Y(n,p)^{89}Sr reaction are shown in Fig.2. Points are experimental data, various curves are results of the present analysis and previous evaluations. The data of systematics [31] for the (n,p) reaction cross sections at the energy of 14.5 MeV is shown also.
The experimental data of different authors are scattered and discrepant. Statistical approximation of all experimental data with rational functions does not give satisfactory results. After selection of experimental data and disregarding some of them (Tewes, Csikai, Bayhurst) the Pade approximation gives very satisfactory results up to 40 MeV

The results of model calculations with ALICE-IPPE code overestimate absolute value of the cross section. The renormalized results are shown in Fig. 2 with open circles up to 40 Mev. They have a reasonable energy dependence up to 15 MeV, however, probably, are too high at the energies above 20 MeV.

At first the excitation function from ENDF/B-VI library can be considered and accepted as a basis. For better correspondence to the requirements of the systematics in the energy region above 14 MeV the cross section was increased a little. The data of ADL-3 library are nor acceptable as far as the cross section near reaction threshold is too high and leads to no proper description of excitation function from physical point of view and contradicts the shape of cross section dependence on incident neutron energy, known reliably enough from empirical trends. In the energy range 14-20 MeV the cross section is too high also, that leads to excessive shift of the maximum cross section to more high energies not justified from point of view of the systematics and besides the ADL-3 excitation function does describe experimental data. The excitation function designated as "RecSys" is recommended up to 20 MeV on the base of such empirical considerations.

^{90}Zr(n,p)^{90}Y.

The results of the analysis for the ^{90}Zr(n,p)^{90}Y reaction are shown in Fig. 3. The results of model calculations with ALICE-IPPE renormalyzed by 10 percent are shown open circles up to incident energy 40 MeV The calculations give satisfactory description near the reaction threshold and maximum , however, possibly, overestimate the excitation function above 20 MeV. The renormalized curve to the maximum of experimental data gives a reasonable energy dependence of the cross section.

The statistical approximation of all experimental data does not gives satisfactory results. After selection and disregarding of some of data (Nemilov, Bayhurst at 20 MeV) statistical approximation with rational functions gives rather satisfactory results up to 40 MeV.

Preliminary the excitation function from BROND-2 library/4/ was accepted, that can be recommended also for application. However the data of /8/ stimulated us to decrease a little the cross section in the energy region from threshold to 14 MeV and because the evaluation "recom" is preferable. As far as the data of /8/ have considerable spread and not reliable enough they were not included into evaluation. However we took into account the trend of these data to decreasing the cross section on the slope of the excitation function. The excitation function designated as "RecSys" is recommended on the base of such empirical considerations. In the energy region above maximum of the cross section the evaluation "recom" practically coincides with the BROND-2 evaluation. The experimental points of Bayhurst in the energy region 16-20 MeV was not taken into account as far as they contradict to the systematics of shapes of (n,p) excitation functions and position of maximum of cross section on the energy axis. In this energy region for ^{90}Zr the cross section of (n,p) reaction must be lower because of considerable contribution of competitive (n,np) reaction. Maybe these points are the sum of (n,p) and (n,np) reactions.

Conclusions

The analysis of available experimental data and existing evaluations on the ^{32}S(n,p)^{32}P, ^{89}Y(n,p)^{89}Sr and ^{90}Zr(n,p)^{89}Y reactions has been performed. Model calculations with ALICE-IPPE code in a wide energy range for these reactions were made. Statistical optimization and approximation of experimental data with Pade method enables to obtain reasonable evaluations. The recommendations based on the systematically observed empiric tendencies of experimental data on neutron induced threshold reactions were carried out also. As a result of such analysis the recommended reaction cross sections can be worked out for the reactions considered.

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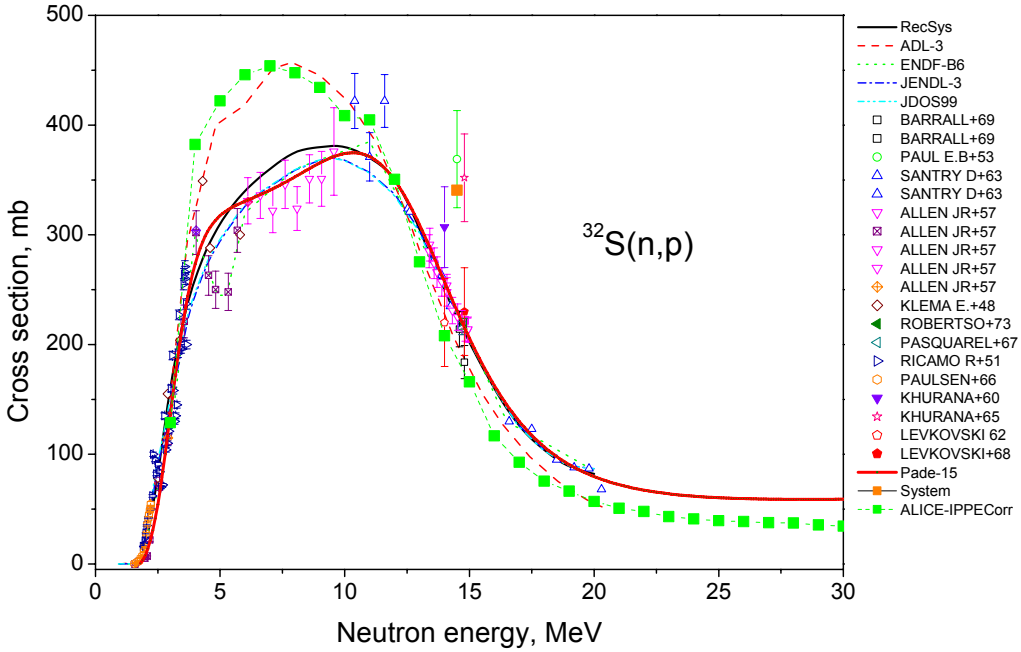

Figure 1. Reaction cross section for $^{32}S(n,p)^{32}P$. Experimental data and evaluated curves.

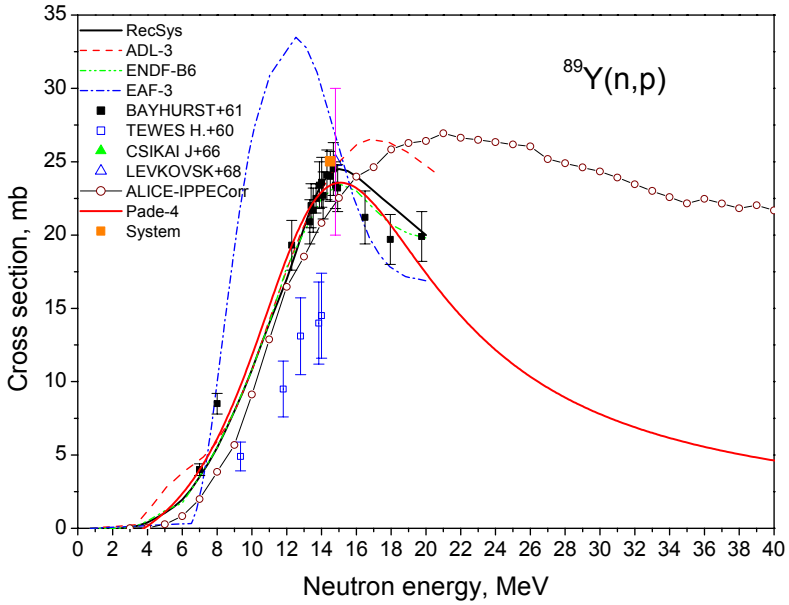

Figure 2. Reaction cross section for $^{89}Y(n,p)^{89}Sr$. Experimental data and evaluated curves.

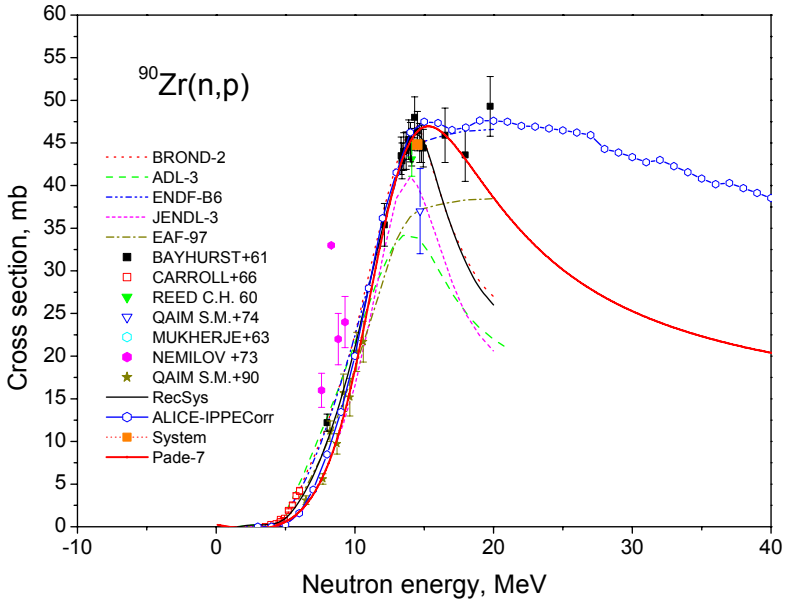

Figure 3. Reaction cross section for $^{90}Zr(n,p)^{90}Y$. Experimental data and evaluated curves.

Progress Report on Experimental Nuclear Data Evaluations by the LANL Group: IAEA Research Agreement No. 12490

F. Meiring Nortier and Dennis R. Phillips

Los Alamos National Laboratory

Current activities at LANL

The Department Of Energy (DOE) is building a new 100 MeV Isotope Production Facility (IPF) at the Los Alamos National Laboratory to replace the existing 800 MeV irradiation facility, which is no longer operational. When completed, the new IPF will support eight months of isotope production annually. Combining its output with similar isotope production capabilities at Brookhaven National Laboratory in New York will ensure doctors and researchers an adequate, year-round supply of accelerator-produced medical and research isotopes. Construction of the new IPF began in February 2000 and first production runs are expected to start by October 2003.

The new facility will use a 100 MeV proton beam with beam currents of up to 250 μA extracted from the existing LANSCE accelerator by means of a pulsed kicker magnet. Since the 100 MeV proton beam is better suited for radioisotope production than the high-energy beam used at the old facility, products with substantially higher purity will be produced. The facility will irradiate a wide range of materials to produce a variety of radioisotopes of value to the DOE's Office of Isotopes for Medicine and Science including Sr-82, Ge-68, Cu-67, Na-22, Si-32, V-48, Zr-88, As-73, etc. Our initial efforts are directed at the development of large-scale production targets for isotopes with commercial applications and revenue potential (Sr-82 and Ge-68), and targets for producing isotopes that have been selected for production as a result of the Nuclear Energy Protocol for Research Isotopes (NEPRI) process. The Sr-82 and Ge-68 isotopes are essential for the clinical application of Positron Emission Tomography (PET), and most of the research isotopes have potential application in nuclear medicine diagnosis and therapy. As the NEPRI process matures, we expect that more research isotopes will be added to the portfolio of products produced at the LANSCE 100 MeV IPF.

The project runs on a very tight schedule and the construction of the facility is now almost complete. Over the past number of months the focus has been shifting to the development of high-current targetry. Up to three targets can be irradiated simultaneously utilizing nominal production energy windows of 90-70 MeV, 65-45 MeV and 30-10 MeV. Cooling water flowing between the targets in the stack provides efficient cooling of the targets. The development of suitable high-current production targets for the new facility includes comprehensive flow analyses of the cooling water through the target chamber and the cooling channels, a detailed transient boiling analysis of the water in the cooling channels and transient analyses thermal heating of the high-current targets by the pulsed proton beam. Practical production schedules will be designed to minimize overall production cost by maximizing the occupation of the three energy slots in such a way that a good mix of long- and short lived isotopes are made available on a regular basis. For this accurate and reliable

excitation function data is needed in the energy range up to 100 MeV on order to develop optimized irradiation schedules.

While experimental data for the production of some of the envisaged isotopes are available in the literature, accuracy is lacking in many cases. For others no experimental data could be found and yield estimates had to be based solely on theoretical cross sections.

Cross Section Data Evaluation Activity

Four nuclear reactions involving accelerator-produced radioisotopes in the *emerging radioisotopes* category have been assigned to the LANL Group for evaluation. They are:

^{64}Ni(d,2n)^{64}Cu
^{68}Zn(p,2p)^{67}Cu
^{124}Te(d,2n)^{124}I
^{125}Te(p,2n)^{124}I

The LANL Group adopted the approach outlined below:

1. Compilation of existing nuclear cross-section data.
    a. First round literature search, which focuses a search of the electronic databases available at LANL and the collection of all electronic copies of literature containing cross-section and thick target yield data.
    b. Second round search, which involves the acquisition and search of relevant Conference Proceedings not covered by electronic databases and which are known to contain published nuclear cross section and thick target yield data.
    c. Third round search, which takes the form of a hand search for those publications referred to by papers collected in the first and second rounds and which are not covered by the electronic databases.
2. Evaluation of measured cross sections
    a. Evaluate experimental methods and error reporting.
    b. Evaluate accuracy of nuclear decay- and monitor data used to calculate cross sections from thin-target yield measurements.
    c. Adjust data values if necessary and where possible.
    d. Prepare plots for comparison purposes.
    e. Convey compiled data to the IAEA Nuclear Data Section for inclusion in the EXFOR library if necessary.
3. Deselect suspect data as appropriate in order to establish the data sets from which recommended excitation function data are to be derived.
4. Deduce from the recommended microscopic cross sections the integral yield data as a function of incident energy, and generate point wise numerical and graphical data with recommended evaluated cross sections.

5. Compare published yield measurements with integral yields calculated for corresponding energy windows.

Progress

The First round literature search is in progress. Measured cross section data found for the ^{68}Zn(p,2p)^{67}Cu, , ^{124}Te(d,2n)^{124}I and ^{125}Te(p,2n)^{124}I nuclear reactions are shown in Figs. 1 through 4. Cross sections for the ^{64}Ni(d,2n)^{64}Cu were measured for deuterons incident on ^{nat}Ni. The data shown in Fig. 2 are adjusted for a enriched ^{64}Ni target.

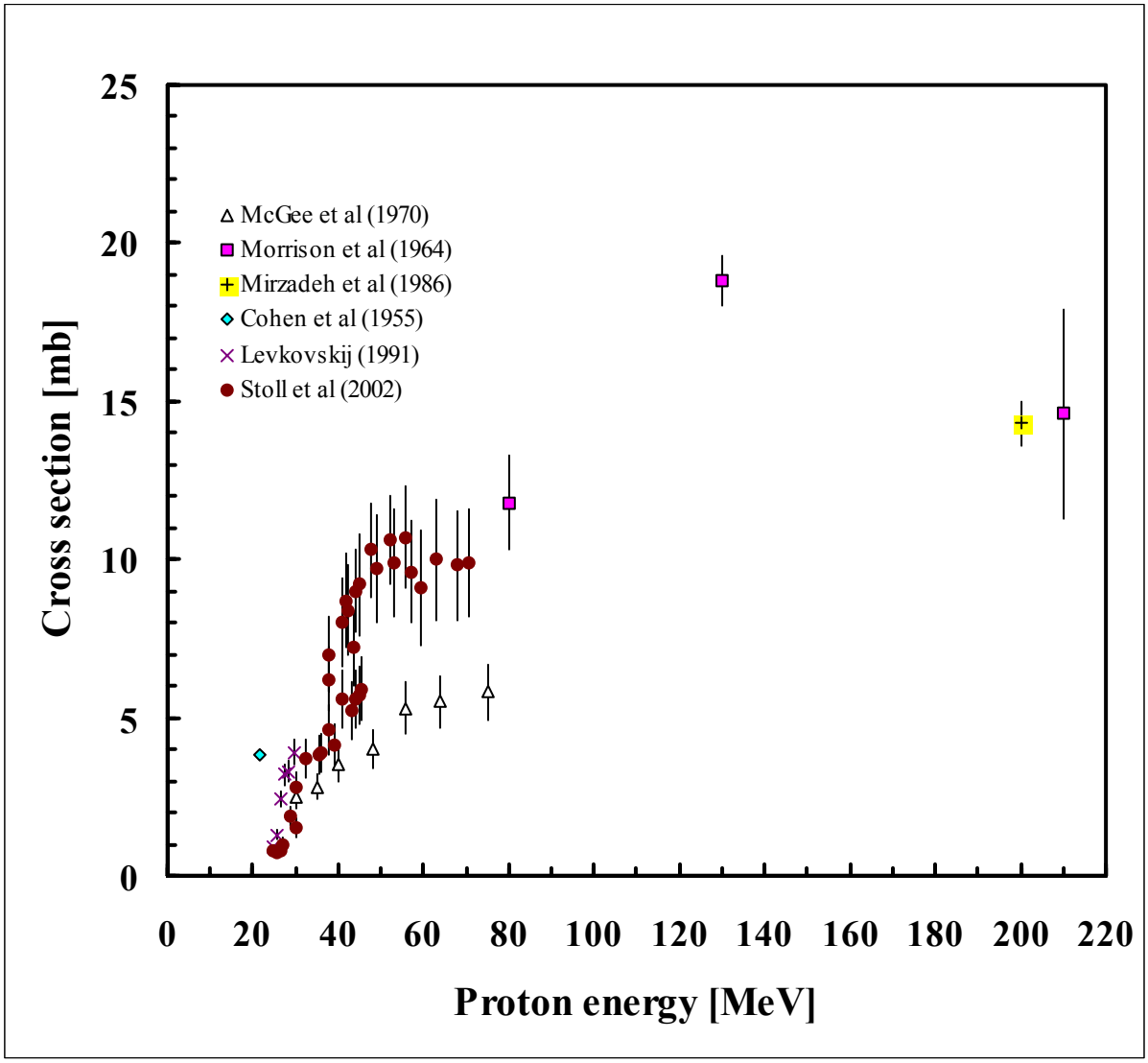

Figure 1. ^{68}Zn(p,2p)^{67}Cu

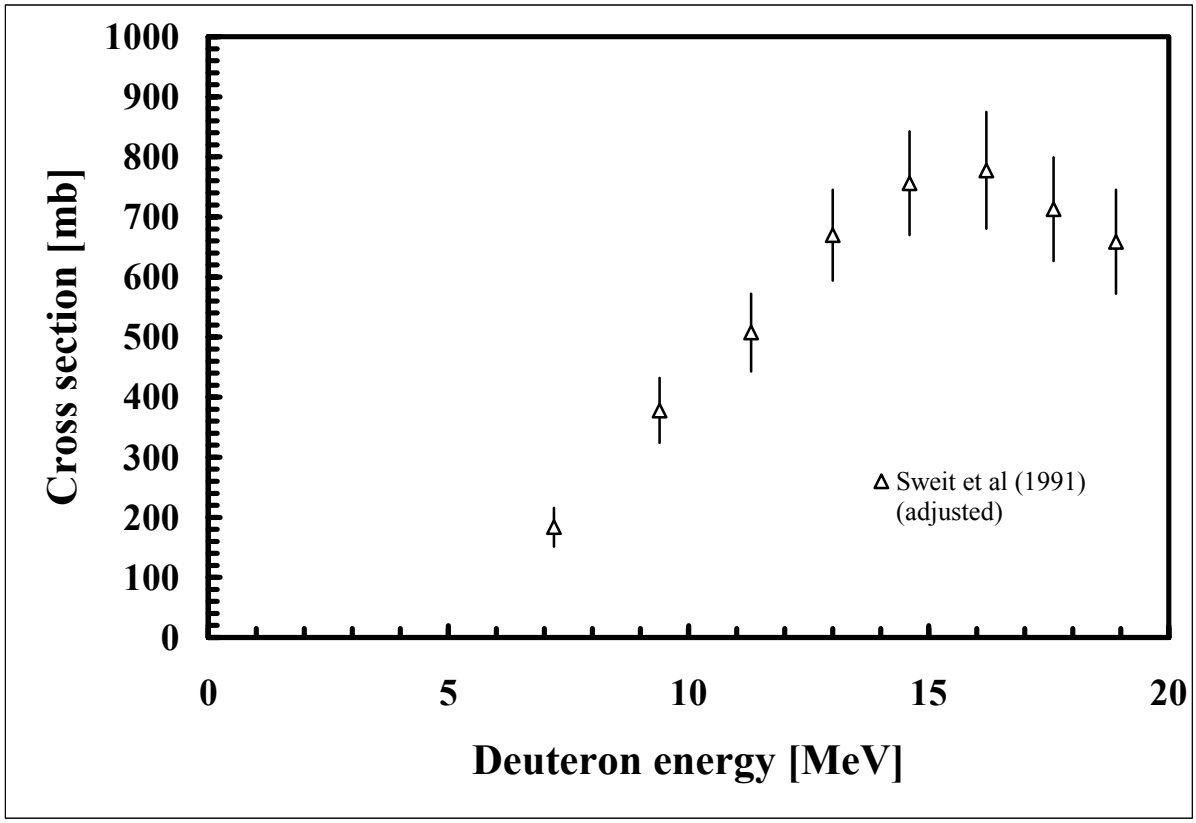

Figure 2. $^{64}Ni(d,2n)^{64}Cu$

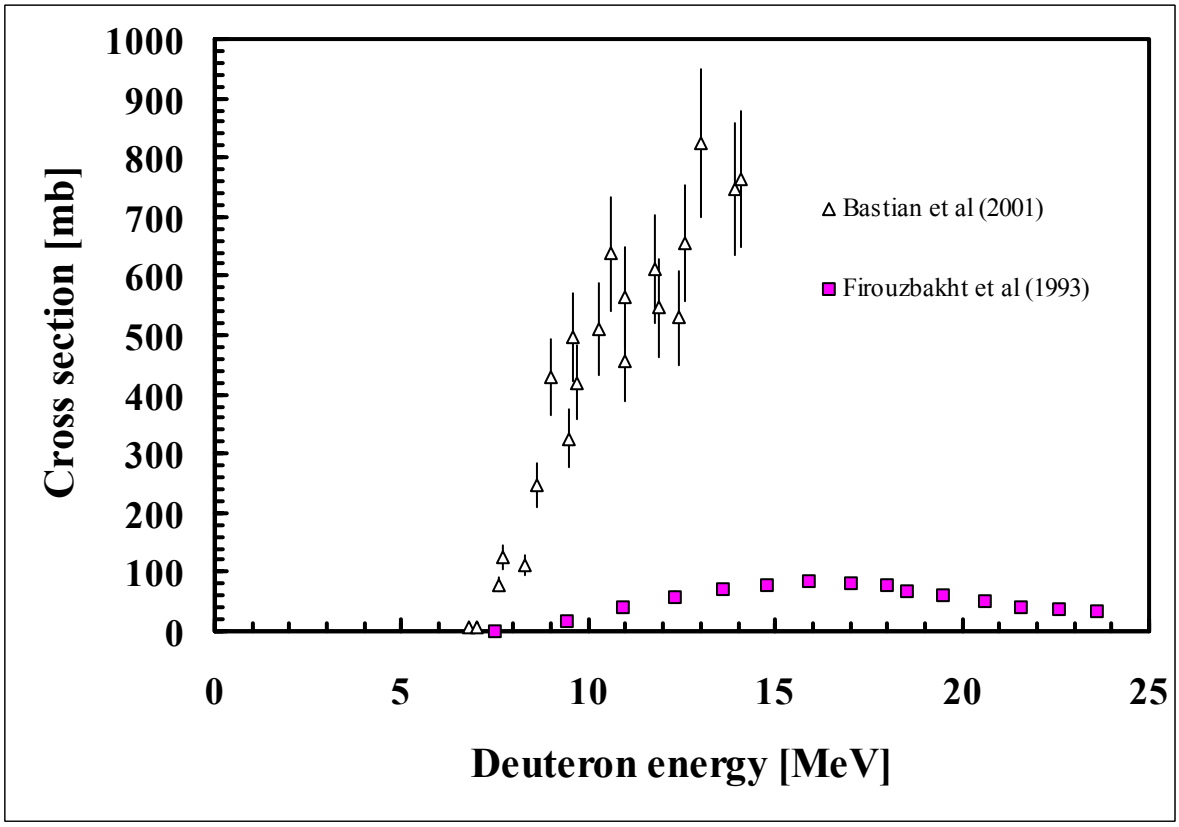

Figure 3. $^{124}Te(d,2n)^{124}I$

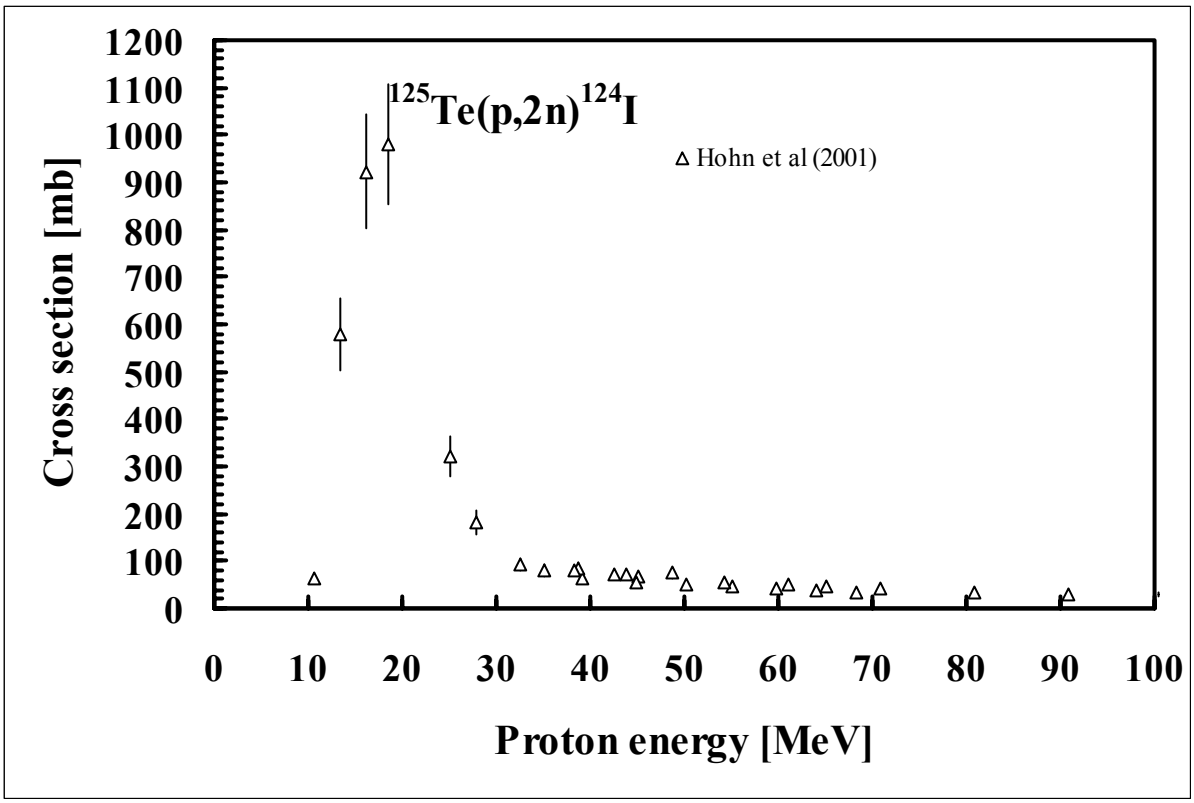

Figure 4. $^{125}Te(p,2n)^{124}I$

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INTERNATIONAL ATOMIC ENERGY AGENCY
IAEA

COORDINATED RESEARCH MEETING

June, 2003

Abstract

MEASUREMENTS AND THEORETICAL CALCULATIONS OF EXCITATION FUNCTIONS FOR THE PRODUCTION OF RADIONUCLIDES RELEVANT TO METABOLIC RADIOTHERAPY

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MEASUREMENTS AND THEORETICAL CALCULATIONS OF EXCITATION FUNCTIONS FOR THE PRODUCTION OF RADIONUCLIDES RELEVANT TO METABOLIC RADIOTHERAPY

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High specific activity accelerator-produced radionuclides in no-carrier-added (NCA) form, for uses in metabolic radiotherapy have been considered (Table 1). 1. NCA ^{64}Cu, produced by ^{nat}Zn(d,αxn) and ^{nat}Zn(d,2pxn) nuclear reactions for negatron/positron metabolic radiotherapy and related PET imaging, also including the short-lived radionuclide ^{61}Cu.
2. NCA ^{66}Ga, high-energy positron emitter (4.2 MeV). 3. ^{186g}Re, produced by ^{186}W(p,n) and ^{186}W(d,2n) nuclear reactions for negatron bone metastases pain palliation by metabolic radiotherapy (1.1 MeV) and related SPET imaging. NCA ^{166}Ho, produced by ^{164}Dy(α,np) for negatron metabolic radiotherapy (1.9 MeV). NCA ^{211}At/^{211}Po, with internal spike of gamma emitter ^{210}At (e.g. negligible amount of ^{210}Po as radiotoxic long-lived impurity), for high-LET targeted radiotherapy and immunoradiotherapy. NCA ^{225}Ac//^{213}Bi/^{213}Po, in-vivo nano-generator for high-LET radiotherapy and immunoradiotherapy.

Table 1 – Main production methods, and applications of the present therapeutic radionuclides.

nuclide	$t_{1/2}$	reactions	gamma emissions	imaging	radiotherapy
^{64}Cu	12.70 h	^{nat}Zn(d,X)	γγ 511 keV	PET	β^+ and β^-
^{61}Cu	3.33 h	^{nat}Zn(d,X)	γγ 511 keV	PET	*impurity*
^{66}Ga	9.4 h	^{nat}Zn(d,xn)	γγ 511 keV many γs	PET γ-camera	β^+, 4.2 MeV
^{186g}Re	89.25 h	^{186}W(p,n) ^{186}W(d,2n)	γ 137 keV other γs	SPET γ-camera	β^- 1.1 MeV
^{166}Ho	26.80 h	^{164}Dy(α,np)	81 keV	γ-camera	β^- 1.9 MeV
^{211}At → ^{211}Po →	7.22 h 516 ms	^{209}Bi(α,2n)	X 79 keV	γ-camera	α 5868 keV α 7273 keV
^{210}At → ^{210}Po →	8.3 h 138.4 d	^{209}Bi(α,3n)	many γs	γ-camera	*as internal spike* α 5304 keV
^{225}Ac → ^{213}Bi → **^{213}Po** →	10.0 d 45.6 m 4.2 μs	^{226}Ra(p,2n)	many γs	SPET γ-camera	α 5829 keV, others α 8375 keV

In this framework, thin target excitation functions (e.g. effective cumulative cross-section σ*) and thick target yields for ^{nat}Zn(d,X)^{61,64}Cu,^{66,67}Ga reactions have been measured at K=38 Cyclotron of JRC-Ispra of European Commission.
In the same context, theoretical calculations for the involved nuclear reactions have been carried out or they are underway at ENEA, above mentioned Division, through the codes EMPIRE, developed by M. Herman at the IAEA-NDS, and PENELOPE, developed by F. Fabbri and G.Reffo at the former ENEA-Nuclear data and Codes Laboratory.

EXFOR and CINDA Databases on CD-ROM

V. Zerkin, IAEA-NDS

This product enhances and replaces EXFOR/Access CD-ROM retrieval system, which was based on Microsoft Access-97 with Visual Basic. Platform-independent programming technology (Java, JDBC) has been adopted to permit easier future updates along with many other advantages to users*. The layout and retrieval process are shown in Figs. 1 and 2. Evaluated data libraries in ENDF format will also be included in future versions of this product.

Major applied features of EXFOR+CINDA/Java2

1. EXFOR/CINDA databases are integrated - EXFOR data can be obtained directly from CINDA-Selection form; CINDA has full authors/title list from EXFOR.
2. User-friendly interface based on Java2-Swing forms; retrieval criteria input are combined with an on-line help system using dictionaries.
3. Fast and powerful search engine (based on SQL) based on variety of criteria (see Figs. 3-9) - combinations are available, including multiple parameters, ranges of values and wildcards.
4. Results of a search can be sorted and displayed in different ways.
5. Summary and bibliographic information are provided with explanations.
6. Plots of selected data are generated on request and appear as a static picture; interactive plotting is provided by ZVView package plugged into the system.
7. Description of the program and instructions for usage are available on-line.

Main features of EXFOR+CINDA/Java2 system

1. Works on any platform that has Java/JDBC (tested on Windows, Linux, VMS).
2. Can work with several local and remote databases at the same time.
3. Does not need any installation or configuration - all programs, Java runtime environment, databases, drivers are located on CD-ROM and can be run there (for Windows and Linux only).
4. Requests of Help-data are executed asynchronously.
5. Installation program optimizes speed and usage of disk memory.

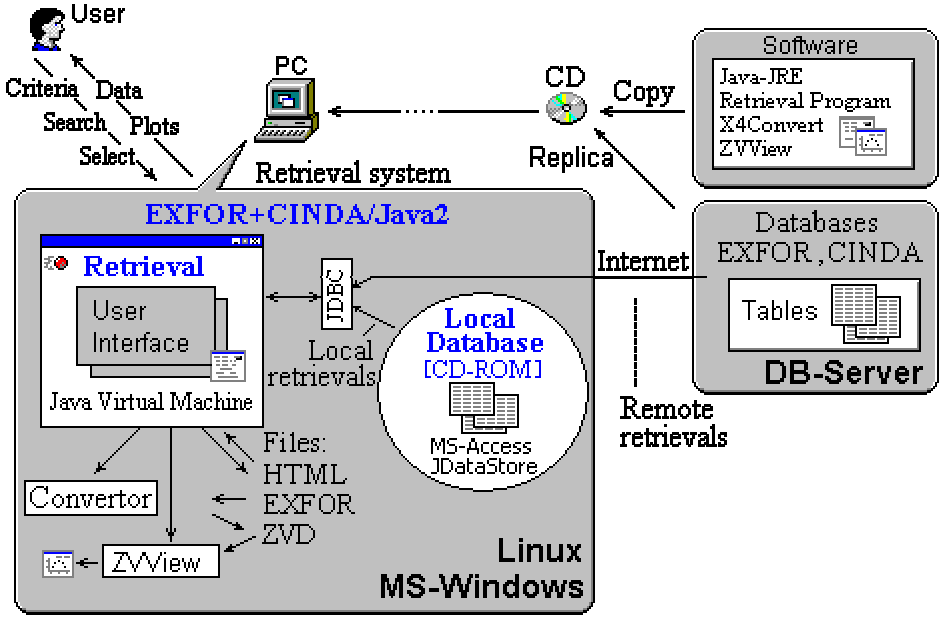


Fig.1. EXFOR+CINDA/Java2: Creation and Functioning.

*Useful Links: Web-EXFOR: http://ndsalpha.iaea.org:8008/exfor2/
EXFOR+ENDF with Plotting: http://www-nds.iaea.or.at/zvd/
Order CD-ROM: http://www-nds.iaea.or.at/cd-catalog.html

Fig.2. EXFOR/CINDA: Retrieval Process.

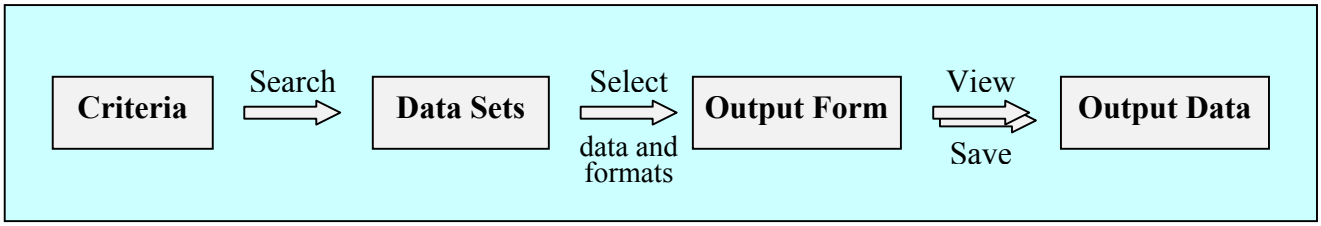


Fig.3. EXFOR: Request Form.

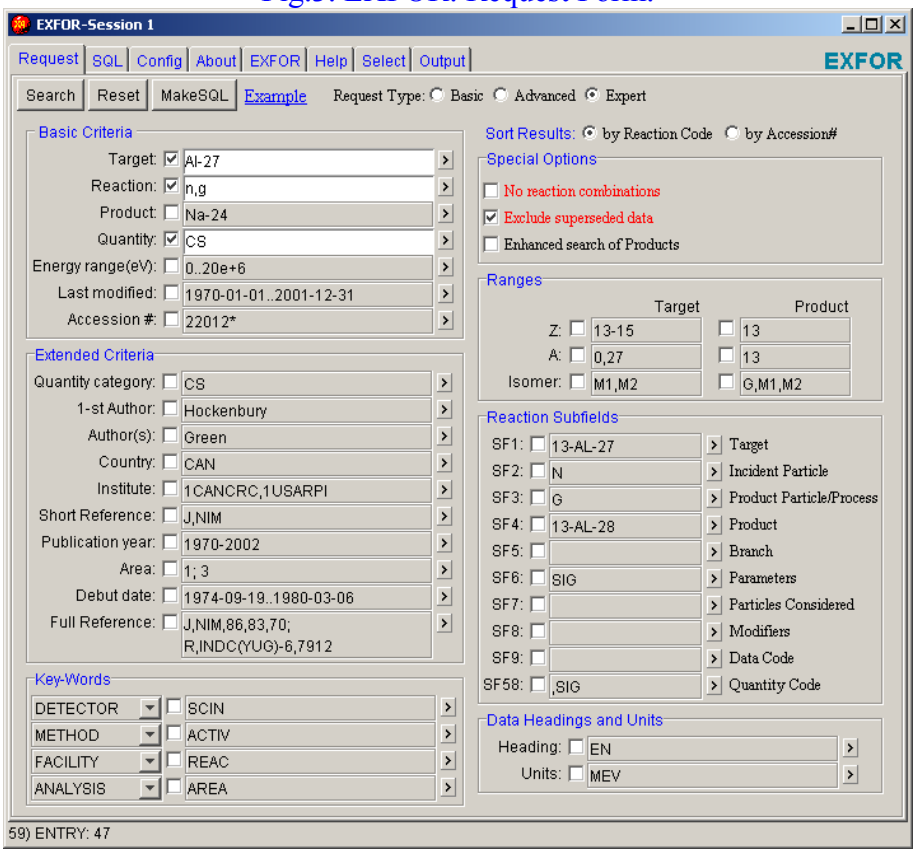


Fig.4. Criteria: Help and Input.

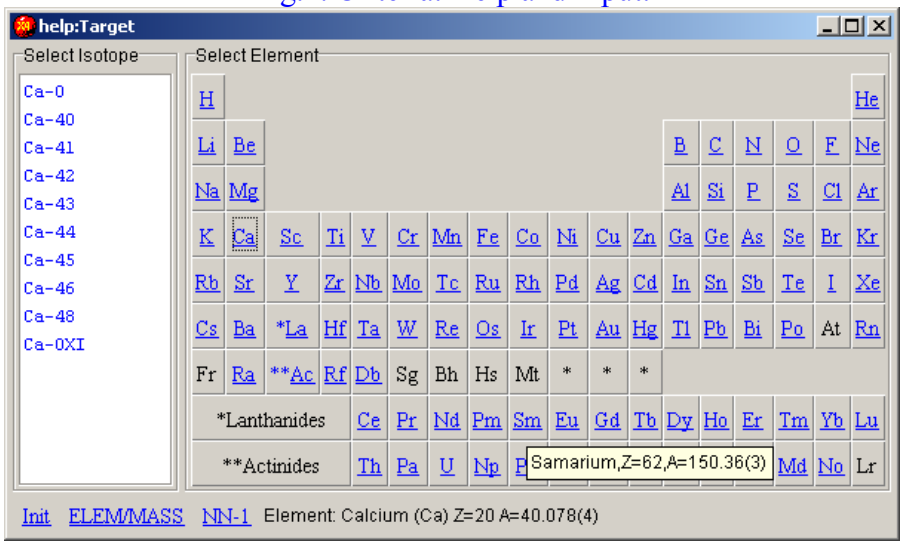


Fig.5. EXFOR Selection Form.

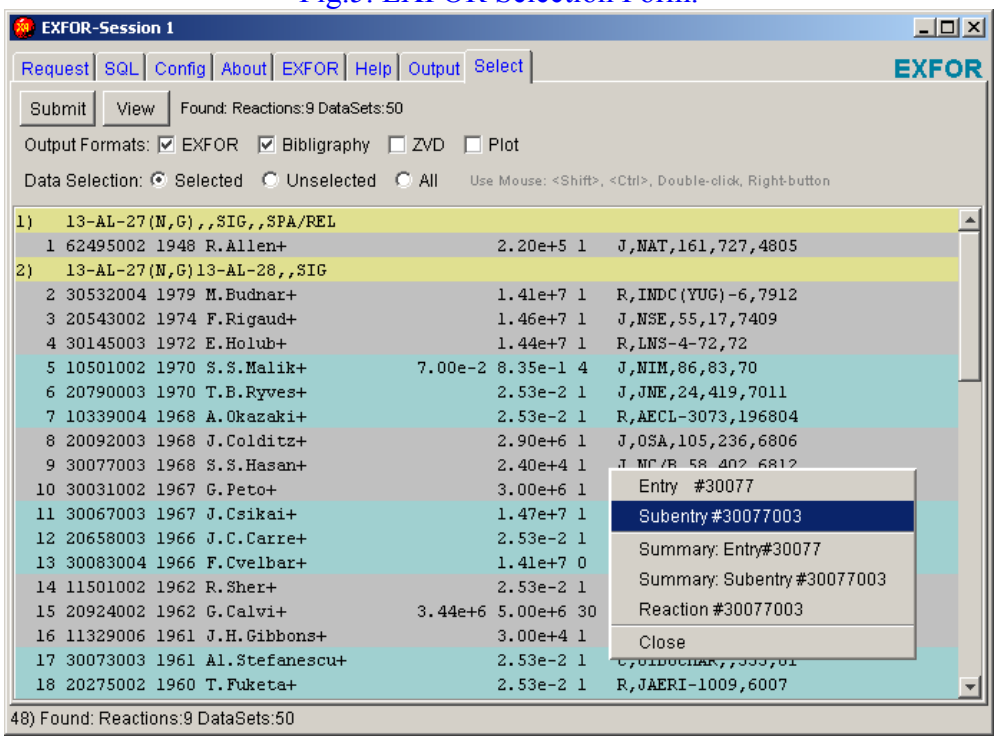


Fig.6. EXFOR Subentry Summary.

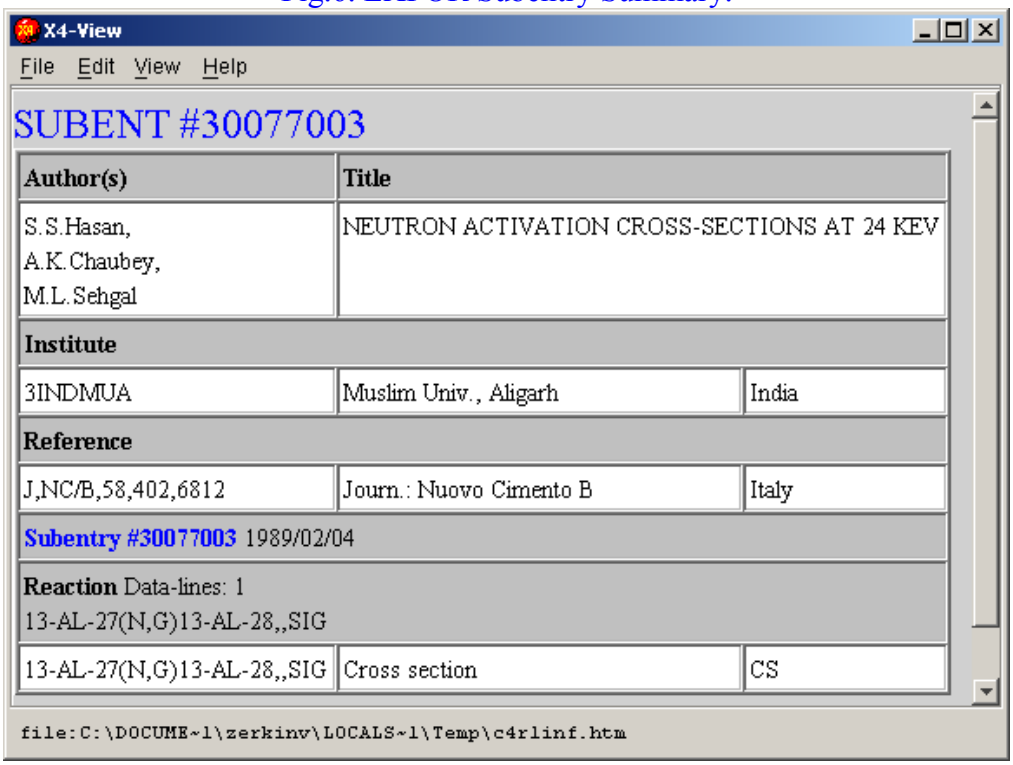


Fig.5. EXFOR Output Form.

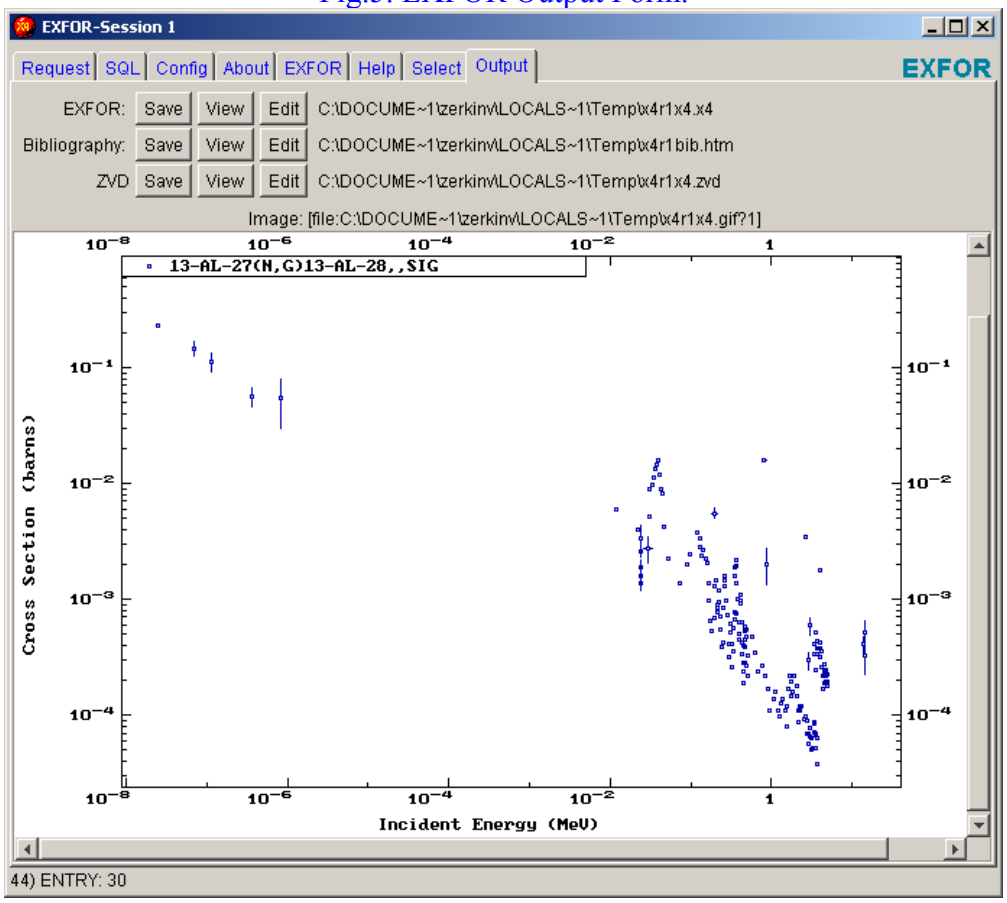


Fig.6. ZVView Interactive Plot.

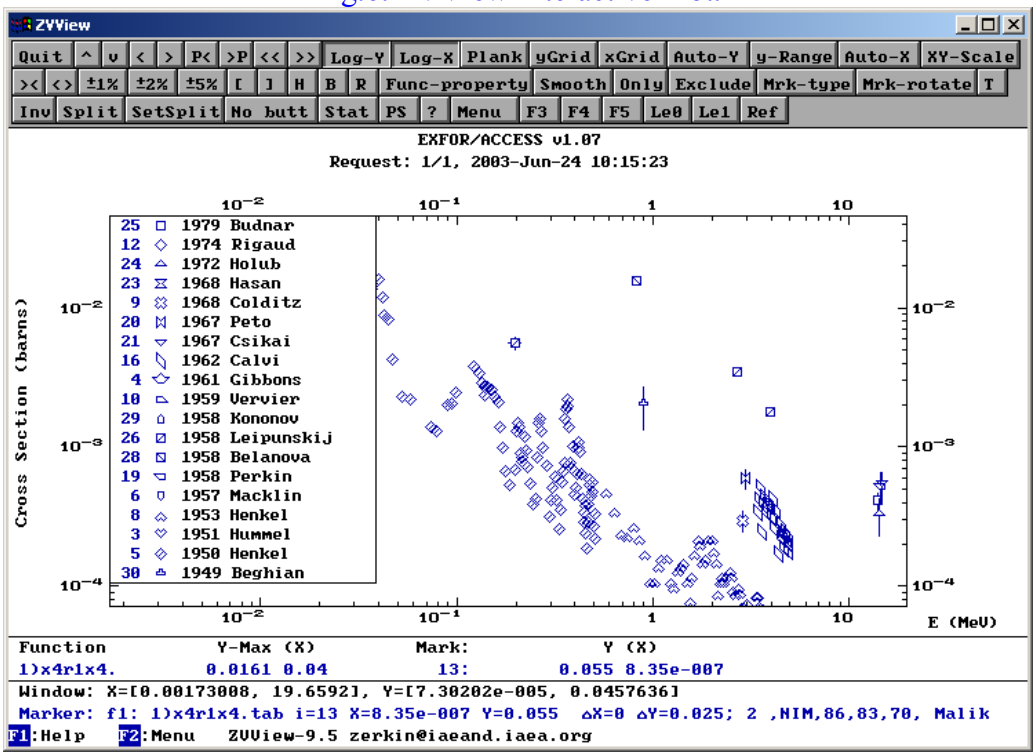


Fig.7. EXFOR Formatted Data.

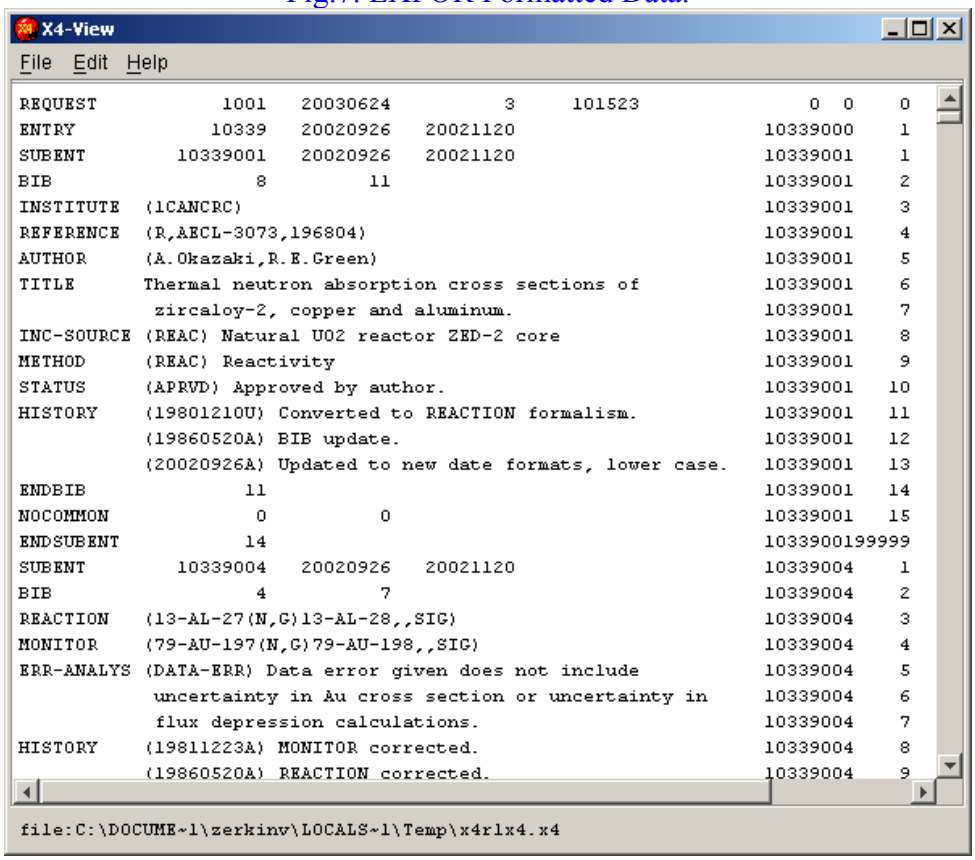


Fig.8. EXFOR: View Bibliography.

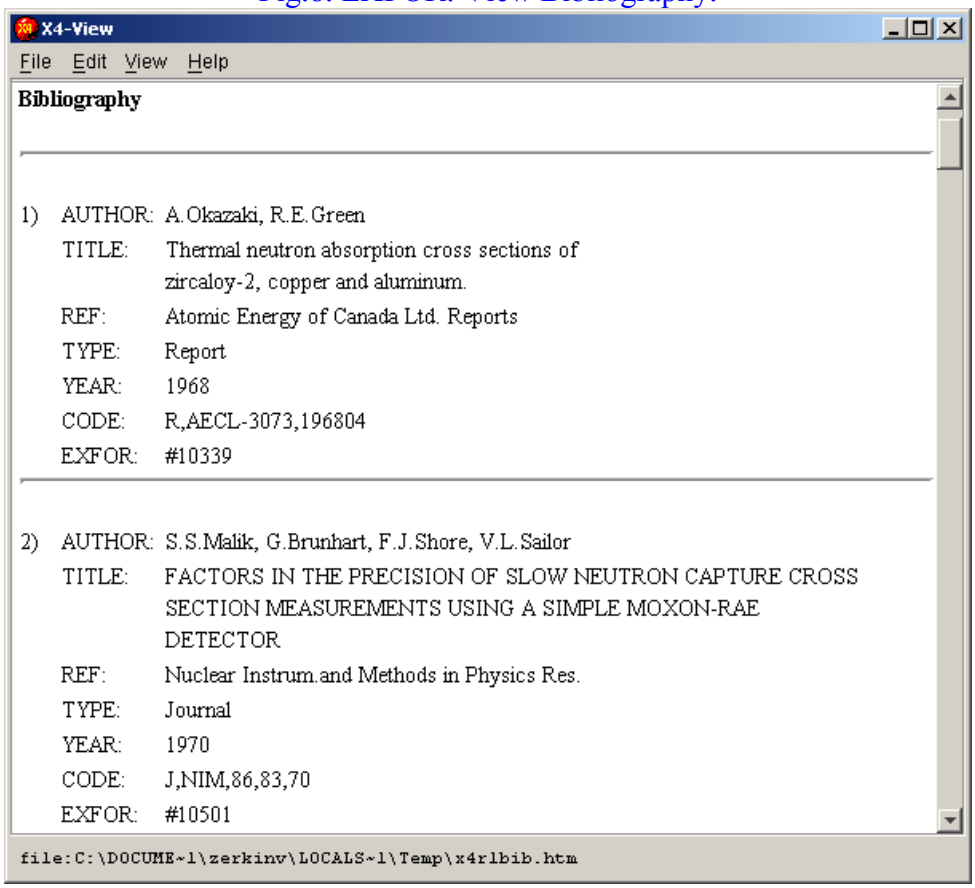


Fig.9. CINDA Request Form.

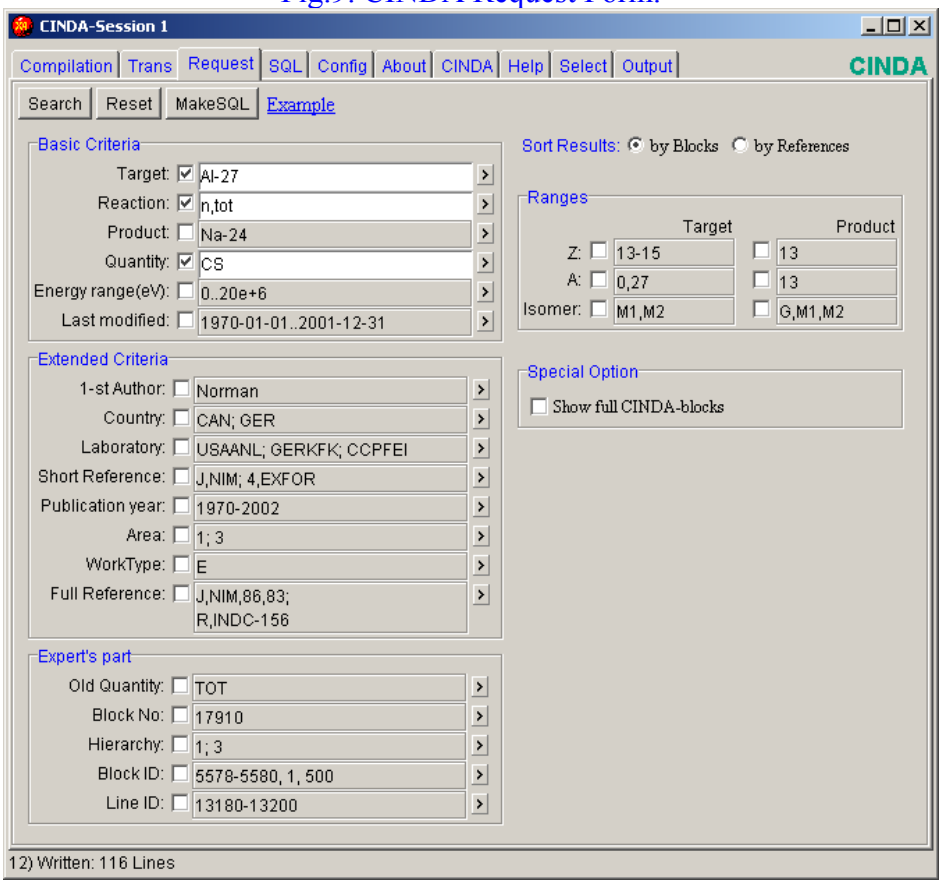
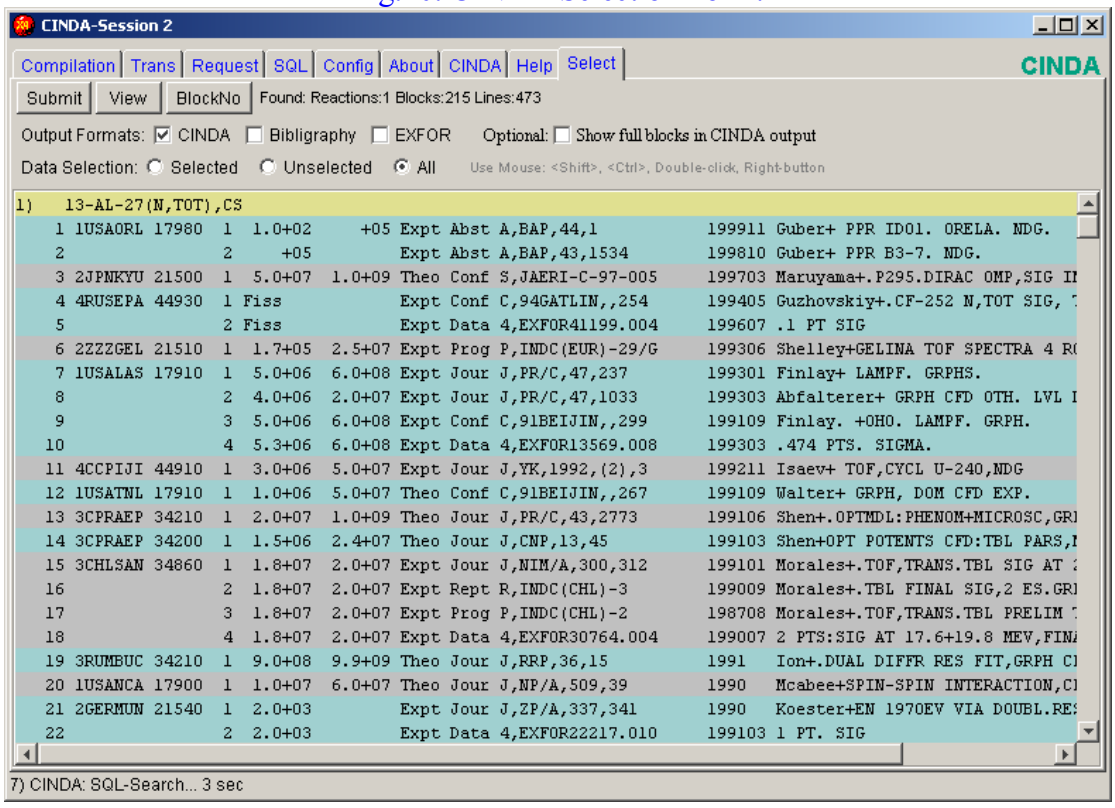


Fig.10. CINDA Selection Form.



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