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Summary Report of the 1st Research Co-ordination Meeting on COMPILATION AND EVALUATION OF PHOTONUCLEAR DATA FOR APPLICATIONS

Obninsk, Russia, 3-6 December 1996

Prepared by

Pavel OBLOŽINSKÝ
IAEA Nuclear Data Section
Vienna, Austria

April 1997

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

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Abstract

The present report contains the summary of the 1st Research Co-ordination Meeting on "Compilation and Evaluation of Photonuclear Data for Applications", held in Obninsk, Russia, from 3 to 6 December 1996. The project aims to produce a Technical Document on Photonuclear Data Library for Applications and to develop an IAEA Photonuclear Data Library. Summarized are the conclusions and recommendations of the meeting together with a detailed list of actions. Attached is the information sheet on the project, the agenda of the meeting and the list of participants along with extended abstracts of their presentations.

April 1997

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1 Summary of the Meeting

Objectives and Participation

The 1st Research Co-ordination Meeting (RCM) on "Compilation and Evaluation of Photonuclear Data for Applications" was held in the Institute of Physics and Power Engineering, Obninsk, Russia, from 3 to 6 December 1996. The local host of the RCM was A.I. Blokhin.

The purpose of the meeting was to work out detailed scope and working plan of the Co-ordinated Research Programme (see Appendix 1 for the Information Sheet on the CRP), to report the status of photonuclear data files and related activities in the participating laboratories, and to agree on procedures aimed to develop an internationally available file of evaluated photonuclear data. M.B. Chadwick of the Los Alamos National Laboratory, Los Alamos, U.S.A. was elected as a chairman of the Meeting. The detailed Agenda is attached (Appendix 2) along with the extended abstracts of the presented papers (Appendix 3).

The meeting was attended by the chief scientific investigators of all six laboratories participating in the project, and by several local cost-free experts as observers. The participating laboratories were represented by M.N. Martins (Instituto de Física da Universidade de São Paulo, São Paulo, Brazil), Yan Shiwei (China Institute of Atomic Energy, Beijing, China), T. Fukahori (Japan Atomic Energy Research Institute, Tokai-mura, Japan), A.I. Blokhin (Institute of Physics and Power Engineering, Obninsk, Russia), V.V. Varlamov (Institute of Nuclear Physics of Moscow State University, Moscow, Russia), and M.B. Chadwick (Los Alamos National Laboratory, Los Alamos, NM, U.S.A.). For details see Appendix 4.

Goals of the CRP

There are two main goals of the Co-ordinated Research Programme to be achieved in 3 forthcoming years:

- To produce an IAEA Technical Document (TECDOC) on Photonuclear Data for Applications. An outline of the TECDOC should include status of available experimental data, nuclear modelling and evaluation techniques, and provide description of the IAEA Photonuclear Data Library.

- To develop an IAEA Photonuclear Data Library. This computerized data file will contain selected evaluations for materials according to a priority list, with emphasis on medical applications. Incident energies will basically cover the range up to 25 MeV with extensions to 50 or 140 MeV whenever possible. The library will be prepared in the ENDF-6 format.

Main Conclusions

- TECDOC on Photonuclear Data for Applications will be prepared *(all participants will submit their contributions to M.B. Chadwick by the end of 1997, M.B. Chadwick will prepare the full draft by the end of April 1998).*

- The single Photonuclear Data Library will be created in the ENDF-6 format *(each participant will submit his library to the IAEA by the end of September 1997, T. Fukahori will prepare an intercomparison by the end of 1997).*

- Individual tasks for future work are summarized in Chapter 4 of the present Summary Report.

- The next RCM should be held in July 1998 in São Paulo. M.N. Martins will investigate the possibilities to host the Meeting. Alternative venues are Beijing, Los Alamos or Vienna.

2 Status of Activities

Photonuclear Data Needs

Photonuclear data are important for a variety of applications:

- Radiation protection and dosimetry of photoneutrons produced by electron/photon accelerators in medical applications (vast majority of these accelerators cover the energy range below 25 MeV, only a few go to 50 MeV)
- Calculations of absorbed dose in human body during radiotherapy
- Physics and technology of fission reactors (influence of photoreactions on neutron balance) and fusion reactors (plasma diagnostics and shielding)
- Activation analysis, safeguards and inspection technologies
- Nuclear waste transmutation
- Astrophysics

The most important data needed are γ absorption cross-sections and neutron yields, followed by neutron spectra and their angular distributions. The most important energy range of incident photons needed is up to 25 MeV, up to 50 MeV would be desirable and up to 140 MeV would be welcomed. The priority list of materials is as follows:

1. Structural, shielding and accelerator head/target materials
   Highest priority: Fe, W, Pb, Al, Cu, Be
   Also: Cr, Co, Zn, Ni, Zr, Mo, Sn, Te, Ta
   (Note: beryllium bremsstrahlung targets are used in special clinical accelerators to produce narrow photon beams)
2. Biological materials
   Highest priority: C, O
   Also: N, Ca, Na, S, Cl, P

3. Fission materials
   ^{232}Th, $^{235,238}U$, ^{237}Np, $^{239,240}Pu$
4. Waste transmutation
   ^{90}Sr, ^{93}Zr, also ^{94}Nb, ^{107}Pd, ^{108}Ag, ^{129}I, $^{135,137}Cs$, ^{151}Sm, ^{158}Tb
5. Activation analysis
   ^{29}Si, ^{31}P, ^{36}Ar, ^{39}K, $^{44,48}Ca$, $^{48,49}Ti$, $^{50,52}Cr$, ^{54}Fe, ^{58}Ni, ^{59}Co, ^{63}Cu, ^{64}Zn, ^{70}Ge, ^{100}Mo, ^{110}Pd, ^{116}Cd, $^{121,123}Sb$
6. Astrophysics
   Nuclei such as ^{27}Si, for use as a cosmological chronometer

Status of Compilations

There are two main types of photonuclear data compilations: bibliography indexes and an electronic numerical data base in the exchange format (EXFOR).

Bibliography indexes are being published by two institutions: the Center for Photonuclear Experiments Data (CDFE Moscow) of the Nuclear Physics Institute, Moscow State University, Moscow, Russia; and the Nuclear Data Center of the Japan Atomic Energy Research Institute (JAERI), Japan. The last CDFE index issued [1] covers the period 1976-1995 and presents approximately 2200 entries, based on 25 journals. The last JAERI index issued [2] covers the period 1955-1992 and presents approximately 9000 entries, based on 20 journals.

There is only one source of electronic numerical data, that is the EXFOR photonuclear data base from the IAEA, divided in three series:

- G series, with 14 entries, compiled at the IAEA Nuclear Data Section (G0001 - G0014)
- L series, with 58 entries, compiled by B.L. Berman and revised by V.V. Varlamov (L001 - L0035 and L0037 - L0059)
- M series, with 495 entries, compiled by CDFE Moscow (V.V. Varlamov) (M001 - M0385 and M0391 - M0500)

There are now 567 entries in digital form, most from work published after 1976. For this period, we estimate that approximately 25% of the works are available in EXFOR. For works published before 1976 the situation is poorer. To obtain a complete compilation in EXFOR, many experimental data sets should be added. In the last 3 years, 37 entries were compiled (20 in 1994 and 17 in 1996).

[1] "Photonuclear Data Index 1976-1995", by V.V. Varlamov, V.V. Sapunenko and M.E. Stepanov (Published by CDFE Moscow, Moscow State University, 1996).

[2] "Bibliographic Index to Photonuclear Reaction Data (1955-1992)", by T. Asami and T. Nakagawa. Report JAERI-M 93-195, also report IAEA INDC(JPN)-167/L (Published by JAERI, Tokai-mura 1993).

Status of Evaluations

At present, six evaluated photonuclear data files are available. They are BOFOD (CJD IPPE Obninsk), EPNDL (CDFE Moscow), Shubin's file (IPPE Obninsk), a file from LANL (Los Alamos), one from CNDC (Beijing) and the Photonuclear Data File JENDL-PDF (JAERI Tokai-mura). Maximum incident γ-ray energy, physical quantities, reaction types, number of isotopes, format and considered applications of those files are summarized in Table 1. Elements included in each file are indicated in Table 2.

Since all the files adopt the ENDF-6 format except Shubin's file, this format was chosen for the IAEA Photonuclear Data Library.

The IAEA Photonuclear Data File should include absorption, fission and angular-energy correlated spectra of light particle (n, p, d, t, ^{3}He, α) emission reaction. In addition, (γ, 1n) and (γ, 2n) reactions should be included in a fission reactor application. A summary of the recommended format is given in Table 3.

Table 1. Status of Evaluated Photonuclear Data Files

File name	Maximum E_γ	Quantity	Reaction	Number of Isotopes	Format	Application
BOFOD	20 MeV	σ dσ/dE	(γ, abs) (γ, n+np) (γ,2n+2np) (γ, f)	63 (+17)†	ENDF-6	Fission reactors
EPNDL-1 (EPNDL-2)	< 30 MeV	σ	(γ, abs) (γ,n), (γ,xn) (γ,p), (γ,xp) (γ,2n) (γ,n_i), (γ,p_i)	15(+7)	ENDF-6	Fission and Fusion reactors Transmutation Activation Medical Astrophysics
Shubin	100 Mev	σ $d^2\sigma/dEd\Omega$	(γ,abs) (γ,n), (γ,2n)	~20	Special	Transmutation of fission products
LANL	150 MeV	σ $d^2\sigma/dEd\Omega$	(γ,abs) (γ,xn), (γ,xz)* (γ,n_0), (γ,p_0) (γ,isotope)**	2(+2)	ENDF-6	Radiation transport Medical
CNDC	30 MeV	σ $d^2\sigma/dEd\Omega$	(γ,γ), (γ,abs) (γ,n), (γ,z) (γ,2n), (γ,np) (γ,nα), (γ,2p) (γ,3n)	8(+6)	ENDF-6	Accelerator shielding Fission
JENDL-PDF	140 MeV	σ $d^2\sigma/dEd\Omega$	(γ,abs) (γ,xn), (γ,xz) (γ,isotope) (γ,f)	26(+24)	ENDF-6	Shielding Radiation transport Activation

* z means any charged particle

** Isotope production cross sections

† Number of isotopes under evaluation is given in brackets

Table 2. Elements Included in Evaluated Files

	BOFOD	EPNDL-1,-2	Shubin	LANL	CNDC	JENDL-PDF
D		+				+
Li		+				
Be	+	+				
C		+				+
N						+
O		+				+
Na	+					+
Mg						+
Al		+			+	+
Si		+				+
Ca		+				+
Ti						+
V						+
Cr	+					+
Mn	+					+
Fe	+				+	+
Co						+
Ni	+	+				+
Cu		+			+	+
Zn						+
Sr	+		+			
Zr	+	+	+			+
Nb	+		+			+
Mo	+					+
Tc	+		+			
Pd	+		+			
Ag	+		+			
Sn	+		+			
Te	+					
I	+		+			
Cs	+		+			+
Pr		+				
Sm	+					
Gd						+
Tb	+					
Ho	+					
Ta						+
W	+			+		+
Au						+
Pb	+	+		+		+
Bi	+				+	+
Th	+					
U	+	+				+
Np	+					
Pu	+					
Am	+					

Evaluation Methodologies

There are two approaches to evaluation of photonuclear data: (1) evaluation of experimental data, and (2) use of theory and modelling, along with experimental data, to generate evaluated data libraries.

The methods for evaluating measured data have been developed by the CDFE Moscow group. This procedure includes the reprocessing of the data obtained by different experimental methods to a unique representation using the realistic photon spectrum and scale corrections. These methods are particularly useful for evaluating discrepant measurements.

The evaluation procedures using both nuclear theory and experimental data, that have been utilized in the data library work at Beijing, JAERI, Los Alamos and Obninsk are rather comparable. They consist of first evaluating the photonuclear absorption cross-section (via giant dipole resonance and quasi-deuteron mechanisms) from measurements (or systematics) and using these results as an input into the calculational codes. After photoabsorption is established, nuclear model calculations which include preequilibrium and equilibrium mechanisms are used to determine the various decay channel cross-sections and emission spectra. After this, the calculated results are compared with measured data for benchmarking purposes, and in some cases the results are modified to better describe measurements. Finally, the results are put in the ENDF-6 format.

3 Conclusions and Recommendations

Priority List

The priority list should follow the list shown in Chapter 2 of the present report. Of most importance are structural and shielding materials (Fe, Pb, W, Al, Cu and Be) and biological materials (O and C). It is understood that the evaluations should be done on the isotopic basis, for the most abundant isotopes of a given element. In terms of the photon energies, of most importance is the energy range up to 25 MeV.

Note added after the present meeting: Photonuclear reactions are of interest, in selected cases, as alternative ways for medical radioisotope production. This was concluded at the IAEA Consultants' Meeting on "Production Technologies for Mo-99 and Tc-99m", Cape Town, South Africa, 10-12 April 1997. Specifically requested were cross sections for photon-induced reactions leading to Mo-99. It was recommended that the present CRP include this data request in its priority list.

Selection Procedures and Format

Evaluated data files in the ENDF-6 format, suitable for use in applications are being developed at Beijing, JAERI, Los Alamos, Moscow and Obninsk. It was discussed how to combine these evaluations into one recommended IAEA evaluated Photonuclear Data Library. The CRP felt that a selection should be made for each target isotope. This selection process will begin at the next CRP meeting after various evaluated library results have been compared against each other, and against measured data. To this end, each CRP participant will submit his library to the IAEA (end of September 1997). Then, T. Fukahori will make plots for intercomparison of Be, C, O, Al, Fe, Ni, Cu, Zr, W, Pb, Bi and U consisting of (γ, abs) and γ, xn) cross-sections (end of 1997). T. Fukahori indicated that he would be prepared to ensure that the final IAEA library is composed of evaluations in a consistent ENDF-6 format.

The following use of the ENDF-6 format was recommended for the future IAEA Photonuclear Data Library, see Table 3.

Table 3. Format of IAEA Photonuclear Data Library

MF	MT	Explanation
1	451	Descriptive data and dictionary
3	3	Total photo-absorption cross-section
3	4	One neutron emission cross-section
3	5	Total cross-section related to branching ratios of isotope production cross-section and particle yields
3	16	Two neutrons emission cross-section
3	18	Fission cross-section
6	5	Branching ratios of isotope production, multiplicity, normalized DDX, all for particle emission
6	4	Normalized DDX for (γ,1n) reaction
6	16	Normalized DDX for (γ,2n) reaction
6	18	Normalized DDX for (γ,fission) reaction

TECDOC on Photonuclear Data Library

The outline of the IAEA Technical Document (TECDOC) on Photonuclear Data Library was discussed in detail. The total length of TECDOC should be limited to about 150 pages, possibly with the attached CD ROM containing the data file. The detailed outline is given below, responsible CRP participants are indicated in brackets:

Executive Summary (2 pages) (PO)

Chapter 1: **Introduction** (10 pages)
- 1.1 Data needs for applications (VV)
- 1.2 Nuclei studied (priority isotopes) (VV)
- 1.3 Overview of present TECDOC (MC)

Chapter 2: **Definitions** (2 pages) (VV)

Chapter 3: **Available experimental data** (25 pages)
- 3.1 Experiments (MM+VV)
  - 3.1.1 Bremsstrahlung
  - 3.1.2 Positron annihilation in flight
  - 3.1.3 Bremsstrahlung tagging
  - 3.1.4 Electron-induced reactions (MM)
- 3.2 Bibliographic data (VV+MM)
- 3.3 Compiled data in EXFOR system (VV+MM)
  - 3.3.1 Cross sections
  - 3.3.2 Emission spectra
  - 3.3.3 Angular distributions
  - 3.3.4 EXFOR format
- 3.4 Additional data in other formats (VV+MM)
- 3.5 Access to data via Internet (PO)

Chapter 4: **Nuclear modelling techniques** (25 pages)
- 4.1 GDR and QD absorption mechanisms (MC+YS)
- 4.2 Equilibrium, preequilibrium and direct emission mechanisms
  - 4.2.1 Emission spectra
  - 4.2.2 Angular distributions
- 4.3 Photofission models (AB)
- 4.4 Nuclear modelling codes
  - 4.4.1 ALICE-F, MCPHOTO (TF)
  - 4.4.2 GNASH (MC)
  - 4.4.3 Obninsk-code (AB)
  - 4.4.4 GUNF (YS)

Chapter 5: **Evaluation Techniques** (30 pages)
- 5.1 Evaluations
  - 5.1.1 Evaluations of experimental data (VV)
  - 5.1.2 Evaluations based on theory calculations (MC+TF+AB+YS)
- 5.2 Methods used for producing evaluated libraries
  - 5.2.1 JAERI libraries (TF)
  - 5.2.2 Obninsk libraries (AB)
  - 5.2.3 Beijing libraries (YS)
  - 5.2.4 Los Alamos libraries (MC)
- 5.3 Intercomparison of results in libraries (TF)

Chapter 6: **Summary of the IAEA Photonuclear Data Library** (25 pages)

6.1 Selection procedure (PO)
6.2 Contents of library (List of elements + type of info included) (TF)
6.3 Illustration of evaluated photonuclear data compared with measurements for important elements (TF)
6.4 ENDF-6 format (TF)
6.5 Procedure for obtaining libraries (PO)

Procedures for writing text for TECDOC are as follows:

1. Deadline for submittal of drafts of subchapters from individual participants to M.B. Chadwick is the end of 1997.

2. Participants should send their contributions in LATEX, or ASCII form to Mark B. Chadwick (mbchadwick@lanl.gov). A minimum of equations should be used - if LATEX equations are not provided, the formula should be faxed to M.B. Chadwick so he can put them into LATEX.

3. References should be provided in LATEX form, i.e. one should use citations in the text in the form "\cite{feshbach80}", with references listed at the end in the form "\bibitem{feshbach80} H.Feshbach, Phys. Rev. C20, 111 (1980)". Formats of Phys. Rev. C should be used for references.

4. Figures should be produced in postscript format with axis labeling according to Phys. Rev. C, and electronic files supplied to M.B. Chadwick.

5. P. Obložinský will determine whether a TECDOC has special format requirements, and will communicate his findings to the CRP participants.

Individual Technical Tasks

In addition to the contributions to the IAEA Photonuclear Data Library and to the TECDOC document, the individual technical tasks of laboratories participating in the CRP were agreed. Related work plans are given below for somewhat varied time periods, reflecting individual contractual commitments of a laboratory to the IAEA.

A.I. Blokhin (IPPE Obninsk), work plan for 1997

1. To improve theoretical methods for evaluation of photoneutron and photofission cross-sections and particle energy spectra, resulting from photonuclear reactions at energies below 20 MeV.

2. To calculate (γ,n), (γ,2n), (γ,fis) photonuclear reaction cross sections using the above modified model.

3. To perform analysis of experimental photonuclear reaction cross sections and to produce complete evaluated photonuclear data file for ^{232}Th and ^{233,235,238}U for γ-ray energies up to 20 MeV.

4. To prepare, for the materials mentioned above, the evaluated photonuclear data file in the ENDF-6 format, and to submit the file to the IAEA Nuclear Data Section.

M.B. Chadwick (LANL Los Alamos), work plan until middle of 1998

1. To continue improving LANL nuclear models for photonuclear reactions in the GDR and QD range.

2. Additionally, if funding permits, to initiate a programme to produce ENDF photonuclear libraries on major isotopes of Fe, W, Pb, Cu, Al and Be.

3. To act as an editor for the TECDOC, combining and editing individual participant's contributions.

T. Fukahori (JAERI Tokai-mura), work plan until middle of 1998

1. To compile 24 remained nuclides of the JENDL-PDF file into the ENDF-6 format as much as possible.

2. To intercompare existing evaluated files for important nuclei by plotting (γ,abs) and (γ,xn) reaction data at least with experimental data.

M.N. Martins (University São Paulo), work plan until middle of 1997

1. To compile (γ,x) and (e,x) reaction cross sections on ^{28,30}Si, ^{63,65}Cu and ^{238}U in the energy range up to 60 MeV.

2. To produce a file with these data in the computerized EXFOR format, and to submit the file to the IAEA Nuclear Data Section.

3. To write a report, including details of the compilation.

V. Varlamov (CDFE Moscow), work plan for 1997

1. To combine together bibliographical indexes of CDFE and JAERI and to produce a single complete bibliographical data file.

2. To produce new addition (new CDFE trans) to EXFOR, with about 20 entries based on both new and old publications.

3. To review the EPNDL-1 and EPNDL-2 library with the contents as shown at the present meeting, including altogether 22 materials.

4. To prepare new evaluated data for ^{14}N, ^{20}Ne, ^{54,56}Fe, and ^{58,60}Ni in the ENDF-6 format for inclusion into EPNDL-3, and to submit the file to the IAEA Nuclear Data Section.

5. To investigate the possibility of evaluating data for highest priority elements (Fe, Pb, W, Al, Cu, Be). Of particular importance are (γ,abs) cross sections in view of their need as an input into model calculations.

Yan Shiwei (CNDC Beijing), work plan for 1997

1. To evaluate and calculate the photonuclear data set for ^{180,182,183,184,186}W and possibly also for ^{90,91,92,94}Zr and ^{51}V for photon energy up to 30 MeV.

   Included will be the following quantities: (a) Cross-sections for absorption, inelastic scattering and all reaction channels including discrete level emission and continuum emission, and (b) double differential cross-section for all emitted particles.

2. To prepare the final results in the recommended ENDF-6 format, and to submit the file to the IAEA Nuclear Data Section.

International Atomic Energy Agency
Co–ordinated Research Programme on

"Compilation and Evaluation of Photonuclear Data for Applications"

Information Sheet

1. Scientific Background

Photons are most commonly produced as bremsstrahlung radiation by electron accelerators. These are relatively simple machines available at many laboratories, industries and hospitals. For example, electron accelerators with energies up to 50 MeV are used to produce bremsstrahlung beams in many oncology radiation facilities worldwide. Photo-induced reaction cross section data are of importance for a variety of applications, including:

- radiation shielding design and radiation transport analyses
- safeguards and inspection technologies (sensitive materials like U can be identified after inducing photonuclear reactions by portable bremsstrahlung devices)
- medical applications (cancer radiation therapy, selected cases of radioisotope production)
- radiobiology investigations (radiobiological efficiency of high–energy bremsstrahlung beams)
- activation analysis of minerals, ores, coal, and other bulk materials of industrial relevance
- nuclear waste transmutation
- thermonuclear reactors (plasma diagnostics, structural integrity, and induced activation)

Other areas, where accurate photonuclear data are needed, are reactor in–core dosimetry (to take into account contributions from photofission events in monitor foils), radiation damage estimates in reactor structural materials (both for displacement and transmutation calculations), safeguards (for taking into account photon induced neutron production on light nuclei) and fast reactor calculations (impact on uranium–thorium cycle).

Because of the absence of evaluated data sets, specialists working in these fields are using raw photonuclear data, primarily reaction cross sections from different (and often discrepant) measurements. Needed are evaluated cross section data for exclusive photonuclear reactions (γ, n), $(\gamma, 2n)$, (γ, p) and $(\gamma, fiss)$ as well as for inclusive photoneutron production $(\gamma, tot\, n)$ and photoabsorption (γ, abs) reactions. Most important are the natural elements in biological, structural and shielding materials, actinides and several fission products. Data in the energy range of the giant dipole resonance are required with a desirable extension up to the π-meson threshold.

In the past, several laboratories (mainly LLNL Livermore in USA, CEN Saclay in France and MSU INP Moscow in Russia) have reported a large body of experimental data. The Centre for Photonuclear Experiments Data in Russia and the Photonuclear Data Group (NIST, former NBS, USA) compiled and transformed a lot of them into the computerized EXFOR format. This major task is not yet completed (only about 20% of the published data is included.

The need for evaluation methods for photonuclear data arises because it is difficult to develop a complete photonuclear data file on the basis of measured cross sections only. These data were often obtained by different kinds of photon sources, causing significant systematic discrepancies, and there is a lack of data in a number of interesting cases. Nevertheless recent developments both in evaluation methods (that would solve most of the experimental discrepancies) and in nuclear reaction theory are promising for use in the generation of evaluated photonuclear data.

2. Supporting Information

The subject was discussed recently in several papers and two IAEA meetings:

- N. Kishida: "Methods Used in Photonuclear Data Evaluation at JNDC", Int. Symp. on Nuclear Data Evaluation Methodology, Brookhaven, 12–16 October 1992 (Ed. C.L. Dunford, World Scientific, Singapore 1993) pp. 598–607
- N.G. Efimkin and V.V. Varlamov: "Photonuclear Data File Development Strategy", Int. Conf. on Nuclear Data for Science and Technology, Proceedings (ed. J.K. Dickens, American Nuclear Society, La Grange Park 1994) vol. 2, pp. 702–708
- A.I. Blokhin et al.: "Preparation and Use of BOFOD Evaluated Photonuclear Data Library", Yadernye Konstanty **3–4** (1992) pp. 3–54; see also Report INDC(CCP)-381 (IAEA, Vienna, August 1994)
- Y. Kikuchi, V. Varlamov and Zhuang Youxiang: "Draft Proposal on CRP on Photonuclear Data: Compilation and Evaluation", Appendix 6 in Report INDC(NDS)-308 (IAEA, Vienna, July 1994)
- Ed. A.B. Pashchenko: "Summary Report of the Specialists' Meeting on Charged–Particle and Photonuclear Data Evaluation for FENDL", Smolenice, Slovakia, 18–21 April 1994, Report INDC(NDS)-306 (IAEA, Vienna, November 1994).

Laboratories in several Member States are currently engaged in large scale evaluations of photonuclear data. In Japan, JAERI is developing a Photonuclear Data File up to 140 MeV. In Russia, extensive evaluations are performed in the Center for Photonuclear Experiments Data, Moscow. IPPE Obninsk is working on the photonuclear BOFOD library up to 20 MeV. In China, Chinese Nuclear Data Center, Beijing is developing methods to calculate photonuclear reactions. In USA, LANL Los Alamos and LLNL Livermore are working on angular distributions from photonuclear reactions.

Considering the above activities, current data needs and promising recent developments in evaluation methods of both experimental and theoretical origin, it was found to be timely and useful to initiate a co–ordinated effort to develop an internationally agreed file of evaluated photonuclear data. An initiation of the Co–ordinated Research Programme (CRP) was endorsed by the International Nuclear Data Committee at its 1993 Meeting and again at its 1995 Meeting. Accordingly, the IAEA Nuclear Data Section prepared the Proposal, and the CRP was approved for initiation in 1996.

3. Scientific Scope and Proposed Programme Goals

The CRP should cover the following areas:

- compilation of experimental photonuclear data using the EXFOR system
- establishing evaluation methods for photonuclear experimental data obtained by different photon beams (bremsstrahlung, quasi–monoenergetical and tagged)
- establishing of evaluation methods based on nuclear reaction and photoabsorption theories
- evaluation of selected photonuclear reaction data
- measurement of selected photonuclear data where large discrepancies exist.

The ultimate goal of the CRP is to develop a data file of evaluated photonuclear reaction cross sections. The list of nuclei should include natural elements and isotopes of importance in biological, structural and shielding materials, as well as actinides, fission products and few others. Photon energies should cover primarily the giant dipole resonance region and extend to the therapeutic region (maximum energies of 50 MeV), possibly including also higher energies up to about 100 MeV. The format of the data file should be ENDF–6.

4. General Information on the CRP and Participation

Where it is deemed desirable that several institute co–operate in furthering research in a given field, Co–ordinated Research Programme (CRP) represents an effective means to bring together researchers to collaborate in a well defined research topic. The role of the International Atomic Energy Agency (IAEA) is to define, co–ordinate and support the programme.

The duration of a CRP is generally 3 years, but an extension is possible, if recommended and approved by the IAEA. The CRP meetings (Research Co–ordination Meetings) are generally convened at the beginning, in the middle and at the end of a CRP with the purpose to define details of the programme, to review the progress, and to formulate the final report.

Due to budgetary limitations only a selected number of laboratories can participate in this CRP. Selection of participants will be based on the relevance of the current and projected work described in the proposals received from potential participants. As soon as the proposals have been evaluated all potential participants will be notified and only at that time a decision be made concerning actual participation in the CRP.

5. Activities

The major activities will be performed by individual participants at their home institutes. Periodically (approximately every 18 months) the IAEA will convene CRP meetings, bringing together all participants to review the status of the activities of the CRP. Between meetings the participants are encouraged to inform the IAEA of all relevant work on the subject and to send copies of all papers, progress reports, etc. to the IAEA which will be distributed to all participants. At least once a year each participant should submit a progress report to the IAEA.

6. Research Agreements/Contracts

In order to participate in this CRP each participant must enter into a research agreement or contract with the IAEA. Participants from Developed Countries (as defined by the IAEA) should enter into a research agreement. Under a research agreement a participant does not receive from the IAEA any direct financial support for research. The only financial support received from the IAEA under a research agreement is transportation and per diem of the principal investigator or his representative to attend periodic CRP meetings. Participants from Developing Countries (as defined by the IAEA) can enter into a research contract. Under a research contract in addition to financial support to attend CRP meetings participants can also receive a small amount of financial support for research (up to US$ 5,000 per contract year). Research agreements and contracts are reviewed (based on annual progress reports and on reports to CRP Meetings) and, subject to approval by the Director General, renewed each year.

7. Duration of the CRP

The CRP will run for three years (1996–1999).

8. Additional Information

Additional information on the CRP may be obtained from:

Mr. P. Obložinský
Nuclear Data Section, IAEA
P.O. Box 100, Wagramerstrasse 5
A–1400 Vienna, Austria

Telephone: (43)-1-2060-21712
Fax: (43)-1-20607
E-mail: oblozinsky@iaeand.iaea.or.at

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Appendix 2

1st Research Co-ordination Meeting on
"Compilation and Evaluation of Photonuclear Data for Applications"
Institute of Physics and Power Engineering, Obninsk, Russia
3-6 December 1996

AGENDA

Tuesday, 3 December

10:00-10:30 **Opening**
- Opening Address (IPPE Representative, IAEA Representative)
- Election of Chairman
- Approval of Agenda
- Announcements

10:30-11:30 **Goals of the CRP**
- IAEA Technical Document on Photonuclear Data
- Photonuclear Library for Use in Transport Calculations

11:30-13:00 **Presentations**
- Papers by the CRP Participants
  1. **A.I. Blokhin (Obninsk)**: BOFOD - Present Status of the Evaluated Photonuclear Data File of CJD
  2. **M.B. Chadwick (Los Alamos)**: Model Calculations of Photonuclear Reactions up to 150 MeV - Plans at Los Alamos for Producing Photonuclear Libraries

13:00-14:30 Lunch

14:30-18:30 **Presentations continued**
- Papers by the CRP Participants continued
  3. **T. Fukahori (Tokai-mura)**: Status of Nuclear Data Evaluation for JENDL Photonuclear Data File
  4. **M.N. Martins (São Paulo)**: Discrepancies between Saclay and Livermore Photoneutron Cross Sections
  5. **V.V. Varlamov (Moscow)**: CDFE Evaluation Task and Methodology
  6. **YAN Shiwei (Beijing)**: Current Status of Photonuclear Data Calculation and Evaluation in CNDC Beijing

- Short Papers
  1. **A.I. Blokhin (Obninsk)**: Evaluation of Photonuclear Cross Sections in the Frame of the MSC + MSD Model
  2. **N.G. Efimkin (Moscow)**: Method of Reduction as Photonuclear Reaction Cross Section Evaluation Tool
  3. **A.S. Soldatov (Obninsk)**: Detailed Measurements of Photofission Yield and Cross-section with γ-rays below 11 MeV
  4. **A.N. Storozhenko (Obninsk)**: Structure of Photonuclear Cross Sections in the Framework of Quasiparticle-phonon Microscopic Model
  5. **K.I. Zolotarev (Obninsk)**: Photofission Correction Factors in Fission Neutron Dosimeters
  6. **Yu. Shubin (Obninsk)**: Photonuclear cross sections for transmutation of long-lived fission products

19:00- Welcome Party

Wednesday, 4 December

09:00-13:00 **General Discussion**
- Data Needs (Discussion Leader Varlamov)
- Status of Compilations (Discussion Leader Martins)
- Status of Evaluations (Discussion Leader Fukahori)
- Evaluation Methodology (Discussion Leader Chadwick)

13:00-15:00 Lunch

15:00-18:00 Visit to Laboratories of the Institute of Physics and Power Engineering

Thursday, 5 December

09:00-13:00 **General Discussion continued**
- Coordination Procedures
- Issues Related to the Release of the Photonuclear Library

13:00-15:00 Lunch

15:00-18:00 **Scope and Workplan of the CRP**
- Detailed Scope of the CRP
- Detailed Working Plan of the CRP

19:00- Meeting Dinner

Friday, 6 December

09:00-13:00 **Drafting the Meeting Report**

13:00-15:00 Lunch

15:00-18:00 **Final Discussion**
- Conclusions and Recommendations
- Adoption of the Meeting Report
- Adjournment

Appendix 3

Extended Abstracts of Presented Papers

BOFOD: Present Status of the Evaluated Photonuclear Data File of CJD

A.I.Blokhin

Institute of Physics and Power Engineering, Obninsk, Russia

BOFOD-90 is one of various kinds of BROND special purpose files. The present status of the BOFOD-90 library is described briefly.
In 1989 two working groups were organized to evaluate the photonuclear cross-sections for stable nuclides ("WG-1" - Working group 1) and for the fission-products ("WG-2" - working group 2).

At present time the WG-1 group constructed the preliminary version of the evaluated photonuclear data library for 63 materials and/or their stable isotopes:

Be-009, Na-023, Cr-50,52-54, Mn-55, Fe-54,56-58, Ni-000, Ni-58,60-62,64, Sr-88, Zr-000, Zr-90-92,94,96, Nb-93, Mo-000, Mo-92,94-98,100, Sn-112,114-120,122,124, Te-120,122-126,128,130, W-182,184,186, Pb-000, Bi-209, Th-232, U-233-236,238, Np-237, Pu-239,241, Am-241,243.

The content of BOFOD-90 library for the photo-neutron and photo-fission cross-sections are given in the table 1. Table 2 gives a list of the isotopes with the evaluated photo-absorption cross-sections.

In 1993 the WG-2 group performed the evaluation of the photoneutron cross-sections for the long-lived fission-products:

Sr-90, Zr-93, Zr-96, Nb-94, Tc-99, Sn-121, Sn-126, Pd-107, Ag-108, Cs-135, Cs-137, I-129, Ho-166, Sm-147, Sm-148, Sm-151, Tb-158.

In 1994 these results and description of this activity were published in ref./4/.

The BOFOD-90 library is in "ENDF-6" format and has N-LIB=42 for identifying the library. We defined such MT's numbers for the photo-nuclear reactions:

MT= 4 for (γ,n+np) - single neutron emission cross-section;

MT= 5 for (γ,abs) - photo-absorption cross-section;

MT=16 for (γ,2n+2np) - double neutron emission cross-section;

MT=18 for (γ,fiss) - photo-fission cross-section;

MT=10 sum of MT=4, MT=16 and MT=18-reactions or their combination;

A part of summary description of the evaluations in the BOFOD-90 library is given in ref./1/. Plots of experimental and evaluated data are published in the ref./2,3/.

References:

1. Blokhin A.I., Buleeva N.N., Nasyrova S.M., Pakhomova O.A., Zabrodskaya S.V., Tsibulya A.M. Formation and application of evaluated photoneutron data library "BOFOD". J., YK.,1992,v.3-4,p.3-54

2. Blokhin A.I., Nasyrova S.M. Plots of experimental and evaluated photoneutron cross-section. R., INDC(CCP)-337(1991),IAEA,Vienna

3. A.I.Blokhin, N.N.Buleeva, S.M.Nasyrova et al. Preparation and Use of "BOFOD" Evaluated Photoneutron Data Library. R., INDC(CCP)-381 (1994).

4. Rabotnov N.S., Shubin Yu.N. et al. J., YK,1994,v.3-4.

Table 1 Contents of the BOFOD-90 library, part 1.
The photo-neutron and photo-fission cross-sections.

NUCLIDE	MAT	MF	MT	CARDS	MOD
Be-009	409	1	451	17	0
	409	3	4	23	0
Na-023	1123	1	451	16	0
	1123	3	4	10	0
Cr-052	2452	1	451	16	0
	2452	3	4	15	0
Mn-055	2555	1	451	16	0
	2555	3	4	11	0
Ni-000	2800	1	451	16	0
	2800	3	4	12	0
Zr-000	4000	1	451	20	0
	4000	3	4	13	0
	4000	3	10	16	0
	4000	3	16	8	0
Mo-092	4292	1	451	16	0
	4292	3	4	14	0
Mo-094	4294	1	451	18	0
	4294	3	4	18	0
	4294	3	16	7	0
Mo-096	4296	1	451	18	0
	4296	3	4	19	0
	4296	3	16	9	0
Mo-098	4298	1	451	18	0
	4298	3	4	19	0
	4298	3	16	10	0
Mo-100	4299	1	451	18	0
	4299	3	4	20	0
	4299	3	16	12	0
W-182	7482	1	451	16	0
	7482	3	4	20	0
W-184	7484	1	451	16	0
	7484	3	4	21	0
W-186	7486	1	451	18	0
	7486	3	4	21	0
	7486	3	16	14	0
Pb-000	8200	1	451	20	0
	8200	3	4	13	0
	8200	3	10	16	0
	8200	3	16	9	0
Bi-209	8309	1	451	20	0
	8309	3	4	12	0
	8309	3	10	13	0
	8309	3	16	8	0
Th-232	9032	1	451	22	0
	9032	3	4	15	0
	9032	3	10	27	0
	9032	3	16	10	0
	9032	3	18	18	0
U-233	9233	1	451	20	0
	9233	3	4	13	0
	9233	3	10	22	0
	9233	3	18	17	0
U-234	9234	1	451	20	0
	9234	3	4	17	0
	9234	3	10	28	0
	9234	3	18	19	0
U-235	9235	1	451	16	0
	9235	3	18	50	0
U-236	9236	1	451	20	0
	9236	3	4	22	0
	9236	3	16	15	0
	9236	3	18	17	0
U-238	9238	1	451	16	0
	9238	3	18	52	0
Np-237	9337	1	451	20	0
	9337	3	4	22	0
	9337	3	16	15	0
	9337	3	18	17	0
Pu-239	9439	1	451	18	0
	9439	3	4	24	0
	9439	3	16	14	0
Pu-241	9441	1	451	16	0
	9441	3	4	24	0
Am-241	9541	1	451	16	0
	9541	3	18	17	0
Am-243	9543	1	451	16	0
	9543	3	18	17	0

ORIGINAL CARD COUNT 1514

Table 2. Contents of the BOFOD-90 library, part 2.
The photo-absorption cross-section for Cr, Fe, Ni, Sr, Zr, Mo, Sn and Te isotopes.

NUCLIDE	MAT	MF	MT	CARDS	MOD
Cr-50	2450	1	451	16	0
	2450	3	5	103	0
Cr-52	2452	1	451	16	0
	2452	3	5	103	0
Cr-54	2454	1	451	16	0
	2454	3	5	103	0
Fe-54	2654	1	451	16	0
	2654	3	5	103	0
Fe-56	2656	1	451	16	0
	2656	3	5	103	0
Fe-58	2658	1	451	16	0
	2658	3	5	103	0
Ni-56	2856	1	451	16	0
	2856	3	5	103	0
Ni-58	2858	1	451	16	0
	2858	3	5	103	0
Ni-60	2860	1	451	16	0
	2860	3	5	103	0
Ni-62	2862	1	451	16	0
	2862	3	5	103	0
Ni-64	2864	1	451	16	0
	2864	3	5	103	0
Sr-88	3888	1	451	16	0
	3888	3	5	103	0
Zr-90	4090	1	451	16	0
	4090	3	5	103	0
Zr-91	4091	1	451	16	0
	4091	3	5	103	0
Zr-92	4092	1	451	16	0
	4092	3	5	103	0
Zr-94	4094	1	451	16	0
	4094	3	5	103	0
Zr-96	4096	1	451	16	0
	4096	3	5	103	0
Mo-92	4292	1	451	16	0
	4292	3	5	103	0
Mo-94	4294	1	451	16	0
	4294	3	5	103	0
Mo-96	4296	1	451	16	0
	4296	3	5	103	0
Mo-98	4298	1	451	16	0
	4298	3	5	103	0
Mo-100	4299	1	451	16	0
	4299	3	5	103	0
Sn-114	5014	1	451	16	0
	5014	3	5	103	0
Sn-116	5016	1	451	16	0
	5016	3	5	103	0
Sn-117	5017	1	451	16	0
	5017	3	5	103	0
Sn-118	5018	1	451	16	0
	5018	3	5	103	0
Sn-119	5019	1	451	16	0
	5019	3	5	103	0
Sn-120	5020	1	451	16	0
	5020	3	5	103	0
Sn-122	5022	1	451	16	0
	5022	3	5	103	0
Sn-124	5024	1	451	16	0
	5024	3	5	103	0
Te-120	5220	1	451	16	0
	5220	3	5	103	0
Te-122	5222	1	451	16	0
	5222	3	5	103	0
Te-124	5224	1	451	16	0
	5224	3	5	103	0
Te-126	5226	1	451	16	0
	5226	3	5	103	0
Te-128	5228	1	451	16	0
	5228	3	5	103	0
Te-130	5230	1	451	16	0
	5230	3	5	103	0

ORIGINAL CARD COUNT 4466

Model calculations of photonuclear reactions up to 150 MeV: Plans at Los Alamos for photonuclear libraries

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

Abstract

I describe a photonuclear reaction theory for photons with incident energies up to 140 MeV. Photoabsorption is modeled through the giant resonance at the lower energies, and the quasideuteron (QD) mechanism at higher energies [1]. After the initial interaction, primary and multiple preequilibrium emission of fast particles can occur, followed by sequential Hauser-Feshbach decay. Preequilibrium decay is calculated with an exciton model, based on a $2p1h$ initial state to approximate correlation effects in the QD mechanism, as proposed by Blann. Theoretical predictions of photonuclear reactions on lead are compared with data [2,3]. The theory is able to account for measured excitation functions of neutron emission reactions, along with neutron emission multiplicities.

An applications-oriented method for determining continuum photonuclear angular distributions for emission of light particles (n, p, d, t, ^{3}He, and α) in the quasideuteron regime ($40 \leq E_{\rm inc} \leq 140$ MeV) is also described. Based on theoretical considerations by Chadwick and Oblozinsky [4] for the angular forward-peaking in preequilibrium reactions, Kalbach's 1988 angular distribution systematics [5] for a neutron projectile can be straightforwardly modified for use in photon-induced reactions. This results in photonuclear angular distributions which are less forward-peaked than their nucleon-induced counterparts, due to the small momentum carried by a photon. Our predictions are compared against double-differential monochromatic ^{12}C(γ, xp) data at 60 and 80 MeV and are seen to describe the measurements fairly well.

A recent calculation was performed using the LANL radiation transport code MCNP to study photoneutron production from a 20 MeV bremsstrahlung LINAC, for radiation protection studies. Cross sections calculated with GNASH were utilized in this calculation, and the corresponding photoneutron dose was found to be significant.

I also summarize the plans at Los Alamos to generate evaluated photonuclear data libraries.

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[1] Chadwick, M.B., Oblozinsky, P., Hodgson, P.E. and Reffo, G.: Phys. Rev. C **44**, 814 (1991).

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[4] Chadwick, M.B. and Oblozinsky, P.: Phys. Rev. C **50**, 2490 (1994); Chadwick, M.B. and Oblozinsky, P.: Phys. Rev. C **46**, 2028 (1992).

[5] Kalbach, C.: Phys. Rev. C **37**, 2350 (1988).

Status of Nuclear Data Evaluation for JENDL Photonuclear Data File

T. Fukahori and Japanese Nuclear Data Committee (Photonuclear Data Evaluation WG)
Nuclear Data Center, Dept. of Reactor Engineering,
Japan Atomic Energy Research Institute,
Tokai-mura, Naka-gun, Ibaraki-ken, 319-11 Japan
fukahori@cracker.tokai.jaeri.go.jp

Nuclear data in the energy range up to a few GeV are necessary to many applications, such as accelerators used for physics research, radiation therapy, medical isotope production and transmutation of radioactive waste. The JAERI Nuclear Data Center has started evaluation work in cooperation with Japanese Nuclear Data Committee (JNDC) to produce files related high energy, which are JENDL High Energy File, JENDL PKA/KERMA File and JENDL Photonuclear Data File.

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

Table 1 The nuclei to be included in the JENDL Photonuclear Data File

H-2, C-12, N-14, O-16, Na-23, Mg-24,25,26*, Al-27, Si-28*,29*,30*, Ca-38,40*, Ti-46,48, V-51*, Cr-52, Mn-55, Fe-54*,56*, Co-59, Ni-58*,60*,61*,62*,64*, Cu-63,65, Zn-64*, Zr-90, Nb-93*, Mo-92,94*,96*,98*,100, Cs-133*, Gd-160*, Ta-181*, W-182*,184,186*, Au-197, Pb-206,207,208, Bi-209*, U-235*,238*

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

Discrepancies between Saclay and Livermore photoneutron cross sections

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

Abstract

The giant dipole resonance has been of central interest in photonuclear reaction studies, both theoretical and experimental, since it dominates the photoabsorption process at energies between 10 and 30 MeV. Over the past three or four decades many studies of photonuclear reactions have been made, for a large number of nuclides, in the attempt to delineate the systematics of photon absorption by nuclei in general and of the giant dipole resonance in particular.

Most of the work in this area, done with the use of monoenergetic photon beams, was carried out at two laboratories, Saclay (France) and Livermore (USA), measuring photoneutron cross sections. The combined studies of these two laboratories span the whole periodic table, in a quite complete systematics of the E1 giant resonance. The use of monoenergetic photon beams has given rise to cross section measurements with high resolution, and especially to an improved knowledge of the cross sections above the peak of the giant resonance.

From those detailed studies many important properties of the E1 giant resonance have been obtained. There is, however, a serious conflict between the data from those laboratories. There are systematic differences in the shapes and magnitudes of their (γ,n) and (γ,2n) cross sections. Because of these differences, from the Saclay data it turns out that for heavy nuclei there is 15-20% of direct contribution in the reaction mechanism, while the Livermore data support a dominant statistical decay of the E1 giant resonance.

The majority of the results available are compiled in the "Atlas of Photoneutron Cross Sections Obtained with Monoenergetic Photons" [1]. There are also a few review articles on the subject [1,2], but none of these publications has addressed the problem of the differences between the measurements performed at Saclay and Livermore. In this work we show [3,4] that both laboratories measure the same number of neutrons as a function of the photon incident energy, but arrive at different partial cross sections as a consequence of the analysis that separates the observed neutrons into (γ,n) and (γ,2n) events. Experimental results of the (e,n) and (e,2n) cross sections of ^{181}Ta measured at São Paulo indicate that Livermore is the laboratory that performs correctly the neutron multiplicity sorting.

References

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[3] E. Wolynec, A.R.V. Martinez, P. Gouffon, Y. Miyao, V.A. Serrão and M.N. Martins, Phys. Rev. **C29**, 1137(1984) and E. Wolynec and M.N. Martins, Rev. Bras. Fis. **17**,56(1987)

The CDFE Evaluation Task and Methodology

V.V.Varlamov, N.G.Efimkin, M.E.Stepanov

Centre for Photonuclear Experiments Data,
Intitite of Nuclear Physics, Moscow State University,
Moscow 119899, Russia

The CDFE evaluation task is formed by the needs of both basic and applied nuclear physics research.

1. The photonuclear basic research is concentrated primarily on the properties of the atomic nuclei Giant Multipole (monopole, dipole, quadrupole, etc.) Resonances: energy position, amplitude, width, gross, intermediate and fine structure parameters, splitting (deformational, configurational, isospin, etc.).

To study these features the data on various reaction differential and integral cross section energy dependencies are needed.

The main reactions of interest are (γ,abs), (γ,Xn), (γ,n), (γ,p), (γ,np), (γ,2n), (γ,$n_{0,1,2,...}$), (γ,$p_{0,1,2,...}$).

The nuclei with highest priority are that for which the comparison with results of various model theoretical calculations can be done easily - selected lightest nuclei and nuclei with magic (or near magic) numbers of nucleons, such as ^{2}H, ^{4}He, $^{6,7}Li$, ^{9}Be, ^{12}C, ^{16}O, $^{24,26}Mg$, ^{40}Ca, $^{58,60}Ni$, ^{90}Zr, ^{208}Pb.

2. Photo-induced reaction cross section data are of importance for a variety of applications, among them are the following:

- nuclear and thermonuclear reactors (fission and shielding materials, plasma diognostics, personal safety, etc.);
- nuclear waste transmutation;
- activation analysis of minerals, ores, coal, and other bulk materials of industrial relevance;
- medical and biological applications;
- astrophysics applications.

For applied research the evaluated data on total photoabsorption and photoneutron reaction cross sections for majority of natural nuclei (C, N, O, Al, Si, Fe, Ni, Cu, Zn, Mo, Cd, Ta, Pb, W, etc.), selected isotopes, and on photofission reaction cross sections for some transuranic nuclei (Th, U, Pu, Np, Am) are needed.

Therefore the main directions of the CDFE photonuclear data processing activity are the following:

- looking through the scientific literature and preparation of the comprehensive informational Indecies of the "Photonuclear Data" series /1/;
- EXFOR format compilation of the needed experimental data using these Indecies and other concerned publications /2-3/, production of the M0-part of the international EXFOR nuclear data bank;
- development of the special methods /5-8/ for evaluation of the photonuclear data obtained in different experiments under significant sistematic uncertainties;
- analysis and evaluation of the needed photonuclear data, primarily photonuclear reaction cross section data /8/, development of the evaluated cross section EXFOR data sets;

- transformation of the evaluated data sets from EXFOR to ENDF format. There are two main photonuclear reaction cross section evaluation problems: - there is the number of data processing methods to unfold or extract the cross section from observables being measured in experiments with different photon beams;
- there are significant uncertanties in normalization and energy calibration which are smooth functions of energy.

Because photonuclear reaction cross sections obtained in different experiments systematically disagree /4/ with each other the traditional least square techniques fail to provide reliable information on intermediate cross section structure (resonaces of hundreds keV width). The special evalutaion methodology /4,5/ was developed for evaluation of cross sections obtained under significant systematic uncertainties.

The methodology is based on the mathematical method of reduction and consists of two parts:

- using the real apparatus function of each individual experiment to reduce data to the most reasonably achievable monoenergetic representation generated by appropriate apparatus function;
- taking into account the each experiment uncertainties of calibration and normalization procedures (different cross sections should be moved toward each other using a priory information /5/ about systematic error distributions).

Additionally the "multistep compound + multistep direct (MSC+MSD)" theoretical model /6/ was used for cross section evaluation.

The number of evaluated photonuclear reaction cross sections for various reactions ((γ,abs), (γ,Xn), (γ,n), (γ,$n_{0,1}$), (γ,Xp), (γ,$p_{0,1}$), [(γ,n)+(γ,np)], (γ,np), (γ,fis)) and nuclei (^{6,7}Li, ^{16}O, ^{28}Si, ^{63,65}Cu, ^{141}Pr, $^{208,nat.}$Pb, ^{235,238}U) has been obtained and published during several last years.

The evaluated data have been included into two versions of the Evaluated Photonuclear Data Library (Table 1 and Table 2).

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Table 1. The contents of the evaluated photonuclear data library EPNDL1.

ENDF/B FORMAT	MAT	MF	MT	CARDS	MOD	REACTION
^{2}H	102	1	451	19	0	
	102	3	3	36	0	γ,abs
^{6}Li	306	1	451	19	0	
	306	3	3	26	0	γ,abs
^{7}Li	307	1	451	19	0	
	307	3	3	48	0	γ,abs
^{9}Be	409	1	451	19	0	
	409	3	3	51	0	γ,abs
$^{nat.}C$	600	1	451	19	0	
	600	3	3	49	0	γ,abs
$^{nat.}O$	800	1	451	19	0	
	800	3	3	35	0	γ,abs
^{16}O	816	1	451	19	0	
	816	3	4	70	0	γ,n
^{27}Al	1327	1	451	19	0	
	1327	3	3	51	0	γ,abs
^{28}Si	1428	1	451	19	0	
	1428	3	4	66	0	γ,n
$^{nat.}Ca$	2000	1	451	19	0	
	2000	3	3	36	0	γ,abs
^{52}Cr	2452	1	451	16	0	
	2452	3	4	15	0	γ,n
$^{nat.}Ni$	2800	1	451	16	0	
	2800	3	4	12	0	γ,n
^{63}Cu	2963	1	451	88	0	
	2963	3	4	28	0	γ,n
	2963	3	28	9	0	γ,np
	2963	3	103	11	0	γ,p
^{65}Cu	2965	1	451	70	0	
	2965	3	4	34	0	γ,n
	2965	3	28	14	0	γ,np
	2965	3	103	27	0	γ,p
$^{nat.}Zr$	4000	1	451	20	0	
	4000	3	4	13	0	γ,n
	4000	3	10	16	0	γ,n+γ,2n
	4000	3	16	8	0	γ,2n

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Table 2. The contents of the evaluated photonuclear data library EPNDL2.

ENDF/B FORMAT	MAT	MF	MT	CARDS	MOD	REACTION
^{6}Li	306	1	451	107	0	
	306	3	3	26	0	γ,abs
	306	3	28	23	0	γ,np
	306	3	41	14	0	γ,2np
	306	3	50	17	0	γ,n_0
	306	3	51	18	0	γ,n_1
	306	3	105	20	0	γ,t
	306	3	115	13	0	γ,pd
	306	3	600	18	0	γ,p_0
	306	3	601	18	0	γ,p_1
^{7}Li	307	1	451	95	0	
	307	3	3	48	0	γ,abs
	307	3	32	25	0	γ,nd
	307	3	41	24	0	γ,2np
	307	3	50	19	0	γ,n_0
	307	3	51	12	0	γ,n_1
	307	3	105	29	0	γ,t
	307	3	600	24	0	γ,p_0
^{141}Pr	5941	1	451	65	0	
	5941	3	4	98	0	γ,n+γ,np
$^{nat.}Pb$	8200	1	451	43	0	
	8200	3	3	44	0	γ,abs
$^{nat.}U$	9200	1	451	35	0	
	9200	3	3	45	0	γ,abs
^{235}U	9235	1	451	82	0	
	9235	3	18	59	0	γ,f
^{238}U	9238	1	451	89	0	
	9238	3	18	67	0	γ,f

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Current Status of Photonuclear Data Calculation and Evaluation at CNDC

Yan Shiwei, Zhuang Youxiang and Zhang Jingshang

Chinese Nuclear Data Center, P.O. Box 275(41), Beijing 102413, P.R. China

The Chinese Nuclear Data Center started the evaluation of photon-induced reaction data at the beginning of 1993. The photonuclear data set of ^{27}Al, ^{54,56,57,58}Fe, ^{63,65}Cu and ^{209}Bi have been calculated and evaluated in ENDF-6 format. The data set includes the cross sections and double differential cross sections of the photon absorption and particle production of photon-induced reactions on structural materials at incident photon energies below 30 MeV. The photon absorption cross section is evaluated with the giant dipole resonance model, and the particle emission processes with the unified Hauser-Feshbach and exciton model by using GUNF code (written by Zhang Jingshang).

1. Evaluation Method

The present evaluation is performed based on the available experimental data and comprehensive theory calculations.

1.1 Experimental Data

All the available experimental data related to ^{27}Al, ^{54,56,57,58}Fe, ^{63,65}Cu and ^{209}Bi photon-induced reaction have been collected and evaluated.

1.2 Theoretical Method

In this calculation, photon absorption cross section is evaluated with the giant dipole resonance model. It should be pointed out that the quasideuteron mechanism is important for photon energies above 40 MeV. This picture is not considered in this calculation since the energy range considered in this calculation is below 30 MeV.

The particle emission processes are described by the unified Hauser-Feshbach and exciton model, in which the following mechanisms are included:

1. The master equation theory of preequilibrium and compound nuclear reaction has been generalized to the inclusion of the conservation of angular momentum and parity.
2. The pick-up mechanism have been used to describe the complex particle (such as α, ^{3}He, d and t) emission.
3. The discrete level effect of residual nuclei is also included in the model calculation.
4. The full recoil effect is taken into account for every reaction channel.

2. Recommended Data File

The physical quantities included in the data file contain:

1. Cross section of absorption, inelastic scattering and all reaction channels, including discrete level emissions and continuum emissions for all of the reaction channels.
2. Double differential cross sections of all kinds of emitted particles.

The recommended data file is given in ENDF-6 format.

INTERNATIONAL ATOMIC ENERGY AGENCY

First Research Co-ordination Meeting on "Compilation and Evaluation of Photonuclear Data for Applications"

Obninsk, Kaluga Region, Russia
3 to 6 December 1996

Scientific Secretary: Pavel OBLOŽINSKÝ

LIST OF PARTICIPANTS

CRP Participants:

1. Prof. Dr. Marcos Nogueira MARTINS — **Res. Contract No. 9188/RB**
Departamento de Física Experimental
Laboratório do Acelerador Linear
Instituto de Física
da Universidade de São Paulo
Rua do Matão - Travessa R, 187
Caixa Postal 66318
05315-970 - São Paulo
BRAZIL

Fax: +55-11-818-6832
Phone: +55-11-818-7045
Phone: +55-11-818-6933
Net: martins@if.usp.br

2. Dr. YAN Shiwei — **Res. Contract No. 8833/RB**
Department of Nuclear Physics
Chinese Nuclear Data Center (CNDC)
China Institute of Atomic Energy
P.O. Box 275 (41)
Beijing, 102413
CHINA

Fax: +86-10-69357008
Phone: +86-10-69357275
Net: ysw@mipsa.ciae.ac.cn

3. Dr. Tokio FUKAHORI — **Res. Agreement No. 9272/R0**
[will attend the meeting for
Dr. Satoshi CHIBA]
Nuclear Data Center
Department of Reactor Engineering
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun
Ibaraki-ken 319-11
JAPAN

Fax: +81-29-282-6122
Phone: +81-29-282-5907
Net: fukahori@cracker.tokai.jaeri.go.jp

4. Dr. Anatoly I. BLOKHIN
Department of Nuclear Physics
Institute of Physics
and Power Engineering
Ploshchad Bondarenko
249020 Obninsk, Kaluga Region
RUSSIA

Res. Contract No. 8837/RB

Fax: +7-095-230-2326
Phone: +7-08439-98272
Phone: +7-08439-98986
Net: blokhin@ cjd.obninsk.su

5. Dr. Vladimir V. VARLAMOV
Department of Electromagnetic Processes
and Atomic Nuclear Interact.
Institute of Nuclear Physics
of Moscow State University
119899 Moscow
RUSSIA

Res. Contract No. 8839/RB

Fax: +7-095-939-0896
Phone: +7-095-939-3483
Phone: +7-095-939-3686
Net: varlamov@cdfe.npi.msu.su

6. Dr. Mark B. CHADWICK
Group T-2, MS-B243
Theoretical Division
Los Alamos National Laboratory
Los Alamos, NM 87545
U.S.A.

Res. Agreement No. 9273/R0

Fax: +1-505-667-9671
Phone: +1-505-667-9877
Net: chadwick@t2e.lanl.gov

Consultant:

7. Prof. Dr. Constantine N. PAPANICOLAS*)
University of Athens
P.O. Box 17214
Athens 10024
GREECE

Fax: +30-1-7235089
Phone: +30-1-7247181
Net: cnp@atlas.uoa.gr

*)Unable to come

Observers:

8. Dr. A. CHERNJAEV
Institute of Nuclear Physics
of Moscow State University
119899 Moscow
RUSSIA

9. Dr. N.G. EFIMKIN
Institute of Nuclear Physics
of Moscow State University
119899 Moscow
RUSSIA

10. Prof. B. ISHKANOV
Institute of Nuclear Physics
of Moscow State University
119899 Moscow
RUSSIA

11. Dr. Yu. SHUBIN
Institute of Physics
and Power Engineering
249020 Obninsk, Kaluga Region
RUSSIA

12. Dr. A.S. SOLDATOV
Institute of Physics
and Power Engineering
249020 Obninsk, Kaluga Region
RUSSIA

13. Dr. M. STEPANOV
Institute of Nuclear Physics
of Moscow State University
119899 Moscow
RUSSIA

14. Dr. A.N. STOROZHENKO
Institute of Physics
and Power Engineering
249020 Obninsk, Kaluga Region
RUSSIA

15. Dr. K.I. ZOLOTAREV
Institute of Physics
and Power Engineering
249020 Obninsk, Kaluga Region
RUSSIA

Scientific Secretary:

16. Dr. Pavel OBLOŽINSKÝ (Scientific Secretary of the Meeting)
IAEA Nuclear Data Section
Wagramerstrasse 5
P.O. Box 100
A-1400 Vienna
AUSTRIA

Fax: +43-1-20607
Phone: +43-1-2060-21712
Net: oblozinsky@iaeand.iaea.or.at

Nuclear Data Section
International Atomic Energy Agency
P.O. Box 100
A-1400 Vienna
Austria

e-mail, INTERNET: SERVICES@IAEAND.IAEA.OR.AT
fax: (+43-1) 20607
cable: INATOM VIENNA
telex: 1-12645 atom a
telephone: (+43-1) 2060-21710

online: TELNET or FTP: IAEAND.IAEA.OR.AT
username: IAEANDS for interactive Nuclear Data Information System
username: ANONYMOUS for FTP file transfer
For users with web-browsers: http://www-nds.iaea.or.at