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Summary Report of the
Third Research Co-ordination Meeting on

# "Compilation and Evaluation of Photonuclear Data for Applications"

Japan Atomic Research Institute
Tokai, Japan
25 – 29 October 1999

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

February 2000

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## Abstract

The report describes the work performed during the final meeting of the Coordinated Research Project on "Compilation and Evaluation of Photonuclear Data for Applications". Reviewed were results achieved in the project, finalized was a selection of 164 evaluations to be included in the IAEA Photonuclear Data Library, and reviewed was the draft of the TECDOC "Handbook on Photonuclear Data for Applications". Completion and release of all products (library, TECDOC, Web page) is foreseen for the year 2000.

February 2000

## CONTENTS

# 1. Summary of the Meeting

## 1.1 Objectives

The 3rd and final Research Coordination Meeting on Compilation and Evaluation of Photonuclear Data for Applications was held at JAERI, Tokai, Japan from 25 to 29 October 1999. The meeting was hosted by T. Fukahori.

The objective of the meeting was to select evaluations for the IAEA Photonuclear Data Library, review the draft of the TECDOC "Handbook on Photonuclear Data for Applications", and agree on procedures to complete the Coordinated Research Project (see Appendix 1 for the Agenda).

The meeting was attended by Chief Scientific Investigators of all seven laboratories participating in the CRP, one consultant and several local observers (see Appendix 2 for the detailed list).

## 1.2 Main Conclusions

- Evaluations for the IAEA Photonuclear Data Library were selected. The library will contain 164 nuclides, including 124 nuclides evaluated by KAERI, S. Korea. The outstanding contribution of the KAERI group should be complimented.
- The draft of the TECDOC was reviewed. Figures and short description for each nuclide will be added (about 200 pages) to the present version.
- The library, along with the TECDOC, should be prepared for final review in February 2000. Release and submittal for print is foreseen for summer 2000.

# 2. Progress Reports and Presentations

Progress reports were presented by chief scientific investigators of seven laboratories participating in the CRP. Substantial progress in evaluation was done since the previous meeting. Noted and complimented should be in particular the extensive work on 143 evaluations up to 140 MeV reported by Y.-O. Lee (KAERI, S. Korea).

Additional four papers were presented. Of particular interest was the presentation by H. Harada on recent developments in the laser Compton photon beam technology motivated by waste transmutation.

Short summaries of presented papers can be found in Appendix 3.

# 3. IAEA Photonuclear Data Library

## 3.1 Structure of the Library

The library will be composed of two parts. Under 'recommended', selected evaluations will be given. Under 'other_files', national or laboratory libraries will be collected.

- Recommended library.
  Recommended evaluations will be provided for a total of 164 materials. At the moment, there are 17 backup evaluations which would replace the recommended ones should those not be available in time. The full list is summarized below, note that $^{16}O$ is counted twice (JENDL and LANL).

  - BOFOD, Obninsk, 9 evaluations:
    $^{232}Th$, $^{233,234,235,236,238}U$, $^{238,239,241}Pu$

  - CNDC, Beijing, 12 evaluations and 2 backup:
    $^{9}Be$, $^{51}V$, $^{50,52,53,54}Cr$, $^{91}Zr$, $^{92}Zr$, $^{96}Zr$, $^{180,183}W$, $^{209}Bi$
    ($^{182,186}W$)

  - JENDL, Tokai, 11 evaluations and 6 backup:
    $^{2}H$, $^{14}N$, $^{16}O$, $^{54,56}Fe$, $^{58}Ni$, $^{65}Cu$, $^{64}Zn$, $^{181}Ta$, $^{182}W$, $^{186}W$
    ($^{28,29,30}Si$, $^{93}Nb$, $^{235,238}U$)

  - LANL, Los Alamos, 9 evaluations and 3 backup:
    $^{12}C$, $^{16}O$, $^{27}Al$, $^{40}Ca$, $^{63}Cu$, $^{186}W$, $^{206,207,208}Pb$
    ($^{28}Si$, $^{56}Fe$, $^{181}Ta$)

  - KAERI, Taejon, 124 evaluations and 6 backup:
    $^{13}C$, $^{15}N$, $^{17,18}O$, $^{23}Na$, $^{24,25,26}Mg$, $^{27,28,29,30}Si$, $^{32,33,34,36}S$, $^{35,37}Cl$, $^{36,38,40}Ar$, $^{39,40,41}K$, $^{42,43,44,46,48}Ca$, $^{46,47,48,49,50}Ti$, $^{55}Mn$, $^{57,58}Fe$, $^{59}Co$, $^{60,61,62,64}Ni$, $^{66,67,68,70}Zn$, $^{70,72,73,74,76}Ge$, $^{84,86,87,88,90}Sr$, $^{90,93,94}Zr$, $^{93,94}Nb$, $^{92,94,95,96,97,98,100}Mo$, $^{102,104,105,106,107,108,110}Pd$, $^{107,108,109}Ag$, $^{106,108,110,111,112,124,114,116}Cd$, $^{112,114,115,116,117,118,119,120,122,124}Sn$, $^{121,123}Sb$, $^{120,122,123,124,125,126,128,130}Te$, $^{127,129}I$, $^{133,135,137}Cs$, $^{141}Pr$, $^{144,147,148,149,150,151,152,154}Sm$, $^{158,159}Tb$, $^{165}Ho$, $^{197}Au$
    ($^{54,56}Fe$, $^{58}Ni$, $^{63,65}Cu$, $^{64}Zn$)

- Other_files.
  This part of the library will include complete photonuclear data libraries as provided by six laboratories, namely BOFOD (Obninsk), CNDC (Beijing), EPNDL (Moscow), KAERI (Taejon), LANL (Los Alamos) and JENDL (Tokai). An actual overview can be obtained from readme files of the FTP photonuclear site of the IAEA Nuclear Data Section.

  - BOFOD, Obninsk (60 evaluations)
  - CNDC, Beijing (24)
  - EPNDL, Moscow (20)
  - JENDL, Tokai (51)
  - KAERI, Taejon (143)
  - LANL, Los Alamos (12)

Complete lists of cross sections contained in the 'recommended' evaluations and 'other_files' are given in Table 1.

**Table 1.** Status of the evaluated photonuclear data files. Quantities refer to cross sections as explained by MT numbers of the ENDF-6 format. Dark shadows indicate evaluations selected as 'recommended'. Light shadows indicate backups. Total numbers of nuclei in the Table is 166.

| Nuclides | Quantities | | | | | | |
|---|---|---|---|---|---|---|---|
| | BOFOD (< 20 MeV) | CNDC (< 30 MeV) | EPNDL (various) | JENDL (<140 MeV) | LANL (< 150 MeV) | KAERI (< 140 MeV) | Experimental Data |
| H-2 | | | 3 | 3,4,50,T | | | 1n |
| Li-6 | | | 3,28,41,105, 115 | | | | abs,sn,xn,1n,1p,1t,1nx, np,2p,pd,2nx,2np,1a |
| Li-7 | | | 3,32,41,105 | | | | abs,sn,xn,n,p,t,1nx, nd,pt,2nx,2np,a |
| Be-9 | 4,201,T | 3,16,28,29, 102-106,T | 3 | 3,5,201,203-207,T | | | abs,xn,n,1nx,2n,2nx, 1p,1d,1a |
| C-12 | 4 | | 3 (C-nat) | 3,5,201,203-207,T | 5,50,600,T | 5,T | abs,xn,n,1nx,np,1p,xp,xd,xt, xh,xa,x |
| C-13 | | | | | | 5,T | none |
| N-14 | 4 | | | 3,5,201,203-207,T | | 5,T | abs,xn,1n,1nx,np,xp, xd,xh,xa |
| N-15 | | | | | | 5,T | none |
| O-16 | 4 | | 3 (O-nat),4 | 3,28,201, 203-207,T | 5,T | 5,T | abs(O-nat),sn,xn,1n, 1nx,2n,2nx,np,1p,xp,xd,xt, xh,xa |
| O-17 | | | | | | 5,T | none |
| O-18 | | | | | | 5,T | none |
| Na-23 | 4 | | | Planned | | 5,T | sn,xn,1n,1p,1nx,2n,2nx |
| Mg-24 | | | | Planned | | 5,T | xn,1p,1nx,x |
| Mg-25 | | | | Planned | | 5,T | sn,xn,1nx,2nx,x |
| Mg-26 | | | | 3,5,201,203-207,T | | 5,T | sn,xn,1p,1nx,2n,2nx,x |
| Al-27 | | 3,4,16,22,28, 50-79,91, 102-107,111,T | 3 | 3,5,201,203-207,T | 5,T | 5,T | abs,sn,xn,1n,1nx,2n,2nx,xp,x |
| Si-27 | | | | | | 5,T | none |
| Si-28 | | | 4 | 3,5,201,203-207,T | 5,T | 5,T | xn,1p,1a,1nx,x |
| Si-29 | | | | 3,5,201,203-207,T | | 5,T | 1nx |
| Si-30 | | | | 3,5,201,203-207,T | | 5,T | xn,1nx,(2n),2nx |
| S-32 | 28 | | | | | 5,T | 1nx,2n,np,xn |
| S-33 | | | | | | 5,T | none |
| S-34 | | | | | | 5,T | none |
| S-36 | | | | | | 5,T | none |
| Cl-35 | | | | | | 5,T | none |
| Cl-37 | | | | | | 5,T | none |
| Ar-36 | | | | | | 5,T | none |
| Ar-38 | | | | | | 5,T | none |
| Ar-40 | | | | | | 5,T | none |
| K-39 | | | | | | 5,T | 1nx,2nx,xn |
| K-40 | | | | | | 5,T | none |
| K-41 | | | | | | 5,T | none |
| Ca-40 | | | | 3,5,201,203-207,T | 5,T | 5,T | n,1nx,x |
| Ca-42 | | | | | | 5,T | none |
| Ca-43 | | | | | | 5,T | none |
| Ca-44 | | | | | | 5,T | none |
| Ca-46 | | | | | | 5,T | none |
| Ca-48 | | | | Planned | | 5,T | 1n,1p |
| Ti-46 | | | | Planned | | 5,T | none |
| Ti-47 | | | | | | 5,T | none |
| Ti-48 | | | | Planned | | 5,T | none |
| Ti-49 | | | | | | 5,T | none |
| Ti-50 | | | | | | 5,T | 1n+2n |
| V-51 | | 3,4,16,22,28, 103-107,111,T | | 3,5,201,203-207,T | | | sn,xn,1n,1nx,2n,2nx,x |
| Cr-50 | 3 | 3,4,16,22,28, 50-56,91,102-107,111, T | | | | 5,T | 1n |
| Cr-52 | 3,4 | 3,4,16,22,28, 50-68,91, 102-107,111,T | 4 | Planned | | 5,T | 1n+2n,1p+np |
| Cr-53 | | 3,4,16,22,28, 50-71,91, 102-107,111,T | | | | 5,T | none |
| Cr-54 | 3 | 3,4,16,22,28, 50-68,91, 102-107,111,T | | | | 5,T | none |
| Mn-55 | 4 | | | Planned | | 5,T | sn,xn,1nx,2nx,3xn |

| Nuclides | Quantities |
|---|---|

| Nuclides | Quantities | | | | | | |
|---|---|---|---|---|---|---|---|
| | BOFOD (< 20 MeV) | CNDC (< 30 MeV) | EPNDL (various) | JENDL (<140 MeV) | LANL (< 150 MeV) | KAERI (< 140 MeV) | Experimental Data |
| Fe-54 | 3,28 | 3,4,16,22,28, 50-55,91, 102-107,111,T | | 3,5,201,203-207,T | | 5,T | xn,1n,1p |
| Fe-56 | 3 | 3,4,16,22,28, 50-59,91, 102-107,111,T | | 3,5,201,203-207,T | 5,T | 5,T | abs,xn,1n |
| Fe-57 | | 3,4,16,22,28, 50-61,91, 102-107,111,T | | | | 5,T | none |
| Fe-58 | 3 | 3,4,16,22,28, 50-55,91, 102-107,111,T | | | | 5,T | none |
| Co-59 | | | | Planned | | 5,T | xn,1n,1nx,2n,2nx,3n |
| Ni-58 | 3 | | | 3,5,201,203-207,T | | 5,T | sn,xn,1n,1nx,2nx |
| Ni-60 | 3 | | | 3,5,201,203-207,T | | 5,T | sn,xn,1nx,2n+2nxpxp |
| Ni-61 | | | | 3,5,201,203-207,T | | 5,T | x |
| Ni-62 | 3 | | | 3,5,201,203-207,T | | 5,T | x |
| Ni-64 | 3 | | | 3,5,201,203-207,T | | 5,T | x |
| Cu-63 | 4 | 3,4,16,22,28, 50-65,91, 102-107,111,T | 4,28,103 | 3,5,201,203-207,T | 5,T | 5,T | sn,xn,1n,1nx,2n, 2nx,np,1p |
| Cu-65 | 4 | 3,4,16,17,22,28, 50-63,91, 102-107, 111,T | 4,28,103 | 3,5,201,203-207,T | | 5,T | sn,xn,1n,1nx,2nx,1p |
| Zn-64 | | | | 3,5,201,203-207,T | | 5,T | sn,xn,1n,1nx,np+d,2n, 2nx |
| Zn-66 | | | | | | 5,T | none |
| Zn-67 | | | | | | 5,T | none |
| Zn-68 | | | | | | 5,T | none |
| Zn-70 | | | | | | 5,T | none |
| Ge-70 | | | | | | 5,T | 1nx,2nx,xn,1n,2n,sn,abs,1p, np |
| Ge-72 | | | | | | 5,T | 1nx,2n,xn,1n,sn,abs, np |
| Ge-73 | | | | | | 5,T | n |
| Ge-74 | | | | | | 5,T | 1nx,2n,xn,1n,sn,abs |
| Ge-76 | | | | | | 5,T | 1nx,2n,xn,1n,sn,abs, np |
| Sr-84 | | | | | | 5,T | 1n |
| Sr-86 | | | | | | 5,T | 1n |
| Sr-87 | | | | | | 5,T | 1n |
| Sr-88 | 3 | | | | | 5,T | 1n,2n,sn,1nx+2n |
| Sr-90 | | | | | | 5,T | none |
| Zr-90 | 3 | 3,4,16,22,28, 103-107, 111,T | | 3,5,201,203-207,T | | 5,T | sn,xn,1n,1nx,2n,2nx |
| Zr-91 | 3 | 3,4,16,22,28, 103-107, 111,T | | | | 5,T | sn,xn,1nx,2nx |
| Zr-92 | 3 | 3,4,16,22,28, 103-107, 111,T | | | | 5,T | sn,xn,1nx,2nx |
| Zr-93 | | | | | | 5,T | none |
| Zr-94 | 3 | 3,4,16,17,22,28, 103-107,111,T | | | | 5,T | sn,xn,1nx,2nx,3n |
| Zr-96 | 3 | 3,4,16,17,22,28, 103,-107,T | | | | 5,T | none |
| Nb-93 | | | | 3,5,201,203-207,T | | 5,T | xn,1n,1nx,2n,2nx, 2p,3n,4xn |
| Nb-94 | | | | | | 5,T | none |
| Mo-92 | 3,4 | | | Planned | | 5,T | sn,xn,1n,1nx,2n, 2nx |
| Mo-94 | 3,4,16 | | | 3,5,201,203-207,T | | 5,T | sn,xn,1n,1nx,2n, 2nx |
| Mo-95 | | | | | | 5,T | none |
| Mo-96 | 3,4,16 | | | 3,5,201,203-207,T | | 5,T | sn,xn,1n,1nx,2n,2nx, 3n |
| Mo-97 | | | | | | 5,T | none |
| Mo-98 | 3,4,16 | | | 3,5,201,203-207,T | | 5,T | sn,xn,1n,1nx,2n,2nx, 3n |
| Mo-100 | 3,4,16 | | | Planned | | 5,T | xn,1n,1nx,2n, 2nx |
| Pd-102 | | | | | | 5,T | none |
| Pd-104 | | | | | | 5,T | 1nx+2n |
| Pd-105 | | | | | | 5,T | 1nx+2n |
| Pd-106 | | | | | | 5,T | 1nx,2n,1nx+2n,sn |
| Pd-107 | | | | | | 5,T | none |
| Pd-108 | | | | | | 5,T | 1nx+2n |
| Pd-110 | | | | | | 5,T | none |
| Ag-107 | | | | | | 5,T | 1nx,2nx,xn,sn |
| Ag-108 | | | | | | 5,T | none |

| Nuclides | Quantities | | | | | | |
|---|---|---|---|---|---|---|---|
| | BOFOD (< 20 MeV) | CNDC (< 30 MeV) | EPNDL (various) | JENDL (<140 MeV) | LANL (< 150 MeV) | KAERI (< 140 MeV) | Experimental Data |
| Ag-109 | | | | | | 5,T | xn |
| Cd-106 | | | | | | 5,T | 1nx+2n |
| Cd-108 | | | | | | 5,T | 1nx+2n |
| Cd-110 | | | | | | 5,T | 1nx+2n |
| Cd-111 | | | | | | 5,T | 1nx+2n |
| Cd-112 | | | | | | 5,T | 1nx,2n,1nx+2n,sn |
| Cd-113 | | | | | | 5,T | 1nx+2n |
| Cd-114 | | | | | | 5,T | 1nx+2n |
| Cd-116 | | | | | | 5,T | 1nx+2n |
| Sn-112 | | | | | | 5,T | none |
| Sn-114 | 3 | | | | | 5,T | none |
| Sn-115 | | | | | | 5,T | none |
| Sn-116 | 3 | | | | | 5,T | sn,xn,1n,1nx,2n, 2nx |
| Sn-117 | 3 | | | | | 5,T | sn,xn,1n,1nx,2n,2nx, 3n |
| Sn-118 | 3 | | | | | 5,T | sn,xn,1n,1nx,2n,2nx, 3n |
| Sn-119 | 3 | | | | | 5,T | sn,xn,1nx,2nx |
| Sn-120 | 3 | | | | | 5,T | sn,xn,1n,1nx,2n,2nx, 3n |
| Sn-122 | 3 | | | | | 5,T | none |
| Sn-124 | 3 | | | | | 5,T | sn,xn,1n,1nx,2n,2nx, 3n |
| Sb-121 | | | | | | 5,T | 1nx,2nx,xn,sn |
| Sb-123 | | | | | | 5,T | 1nx,2nx,xn,sn, |
| Te-120 | 3 | | | | | 5,T | none |
| Te-122 | 3 | | | | | 5,T | none |
| Te-123 | | | | | | 5,T | none |
| Te-124 | 3 | | | | | 5,T | xn,1nx,2n,2nx |
| Te-125 | | | | | | 5,T | none |
| Te-126 | 3 | | | | | 5,T | xn,1nx,2n,2nx |
| Te-128 | 3 | | | | | 5,T | xn,1nx,2n,2nx |
| Te-130 | 3 | | | | | 5,T | none |
| I-127 | | | | | | 5,T | 1nx,2nx,3n,sn |
| I-129 | | | | | | 5,T | none |
| Cs-133 | | | | 3,5,201,203-207,T | | 5,T | sn,xn,1n,1nx,2n,2nx, 3n |
| Cs-135 | | | | | | 5,T | none |
| Cs-137 | | | | | | 5,T | none |
| Pr-141 | 4 | | 4 | | | 5,T | sn,xn,1n,1nx,2nx, 3n |
| Sm-144 | | | | | | 5,T | 1nx,2nx,xn,sn |
| Sm-147 | | | | | | 5,T | none |
| Sm-148 | | | | | | 5,T | 1nx,2n,xn,sn |
| Sm-149 | | | | | | 5,T | none |
| Sm-150 | | | | | | 5,T | 1nx,2nx,xn,sn |
| Sm-151 | | | | | | 5,T | none |
| Sm-152 | | | | | | 5,T | 1nx,2nx,xn,sn |
| Sm-154 | | | | | | 5,T | abs,1nx,2n,xn,sn |
| Tb-158 | | | | | | 5,T | none |
| Tb-159 | | | | | | 5,T | 1nx,2nx,3n,sn |
| Ho-165 | | | | | | 5,T | abs,1nx,2nx,3n,xn,sn |
| Ta-181 | 201,T | | | 3,5,201,203-207,T | 5,T | | abs,fis,sn,xn,1n,1nx,2n,2nx, 3n |
| W-180 | | 3,4,16,17,22,28, 103-107,111,T | | | | | none |
| W-182 | 4 | 3,4,16,17,22,28, 103-107,T | | 3,5,201,203-207,T | | | abs,sn |
| W-183 | | 3,4,16,17,22,28, 103-107,T | | | | | none |
| W-184 | 4 | 3,4,16,17,22,28, 103-107,T | | 3,5,201,203-207,T | 5,T | | abs,sn |
| W-186 | 4,16 | 3,4,16,17,22,28, 103-107,T | | 3,5,201,203-207,T | | | abs,sn,xn,1nx, 2nx,3n |
| Au-197 | | | | Planned | | 5,T | abs,fis,sn,xn,1nx,2n, 2nx,3n |
| Pb-206 | | | | 3,5,201,203-207,T | 5,T | | sn,xn,1n,1nx,2nx |
| Pb-207 | | | | 3,5,201,203-207,T | 5,T | | sn,xn,1n,1nx,2nx, |
| Pb-208 | | | 4 | 3,5,201,203-207,T | 5,T | | sn,xn,1n,1nx,2n, 2nx,3n |
| Bi-209 | 4,10,16 | 3,4,16,17,22,28, 50-64, 91, 102-107,T | | 3,5,201,203-207,T | | 5,T | abs,fis,sn,xn,1n,1nx, 2nx |
| Th-232 | 3,4,16,18,T | | | | | | abs,fis,sn,xn,1n,1nx, 2n |
| U-233 | 3,4,16,18,T | | | | | | abs,fis,xn,1n,1nx, |
| U-234 | 3,4,10,18,T | | | | | | fis,xn |

| Nuclides | Quantities | | | | | | |
|---|---|---|---|---|---|---|---|
| | BOFOD (< 20 MeV) | CNDC (< 30 MeV) | EPNDL (various) | JENDL (<140 MeV) | LANL (< 150 MeV) | KAERI (< 140 MeV) | Experimental Data |
| U-235 | 3,4,16,18,T | | 18 | 3,5,18,201, 203-207,T | | | abs,fis,xn,1nx,2n |
| U-236 | 3,4,16,18,T | | | | | | fis,xn,1n,1nx,2n |
| U-238 | 3,4,16,18,T | | 18 | 3,5,18,201, 203-207,T | | | abs,fis,sn,xn,1n,1nx, 2n |
| Pu-238 | 3,4,16,18,T | | | | | | none |
| Pu-239 | 3,4,16,18,T | | | | | | abs,fis,sn,xn,1nx,2n |
| Pu-241 | 3,4,16,18,T | | | | | | fis |
| Total | 60 | 24 | 20 | 51 | 12 | 143 | |

T: Cross sections for transport calculations are included

### 3.2 Selection of Evaluations

The 5 photonuclear data files (BOFOD, CNDC, JENDL, KAERI, LANL) were considered as candidates for selection for inclusion in the IAEA Photonuclear Data Library. EPNDL is based on purely experimental data and does not include information on emission spectra, therefore it could not be considered.

The following criteria were applied to determine which evaluation should be recommended in the cases where more than one evaluation was available. Two most important criteria were quality and completeness of evaluation. Additional criteria were higher upper energy limit available, processability with NJOY for transport codes such as MCNP, MCNPX, consistency between included physical quantities, and presentation of data.

Altogether, evaluations of 164 nuclides were selected for the IAEA Photonuclear Data Library. Full list of evaluations is shown in Table 1 and the summary of selection is given in Table 2.

**Table 2.** Summary of selected evaluations for the IAEA Photonuclear Data Library.

| | BOFOD | CNDC | JENDL | LANL | KAERI | Total |
|---|---|---|---|---|---|---|
| Recommended | 9 | 12 | 11* | 9* | 124 | 164 |
| Back up | 0 | 2 | 6 | 3 | 6 | 17 |

* $^{16}O$ is included twice, final selection will be done after evaluations are completed.

### 3.3 Tasks and Actions

The following tasks and actions were agreed upon.

*A. Blokhin (Obninsk)*

1. Improve relevant parts in Chapters 4 and 5 of the TECDOC:
   - Add text about the prompt neutron spectrum (page 37).
   - Add additional introduction about the energy dependence of photofission product yields and references to experimental data.
   - Add the table with a set of the parameters used for model calculation of photonuclear cross sections for fissile nuclei.
   - Write short description of the BOFOD library.

   Action: Send to Chadwick by 30 November 1999.

2. Prepare a short text about files and experimental data used in evaluations for graphic presentation ($^{232}$Th, $^{233,234,235,236,238}$U, $^{238,239,241}$Pu). Action: Send to Lee by 15 November 1999.
3. Prepare the same for $^{237}$Np, $^{241,243}$Am, $^{243,244,245}$Cm. Action: Send to Lee by 15 December 1999.
4. Finalize 15 files with full description of MF1. Action: Send to IAEA by 15 December 1999.

*V. Varlamov (Moscow)*

1. Finish cross section evaluations for $^{20,22}$Ne.
2. Produce cross section evaluations for $^{54,56}$Fe, $^{60,62(58)}$Ni.
3. Collect all evaluated date into ENDF-6 format.
4. Send all files to IAEA as EPNDL-3 version by 15 December 1999.

*Y.-O. Lee (Taejon)*

1. Send the summary of KAERI library to IAEA for Chapter 5.3.
2. Complete the draft of 164 figures and descriptions by middle of January 2000 and send it to IAEA.
3. Send to IAEA 143 evaluations in ENDF-6 format by 15 November 1999.
4. Send to IAEA a list of publications related to the CRP as soon as possible.

*Yu Baosheng and Zhang Jingshang (Beijing)*

1. Revise the evaluation of $^{9}$Be and send it to IAEA by 15 November 1999.
2. Send one or two pages of descriptions of evaluations for accepted 12 isotopes to Lee by 15 December 1999.
3. Send the publication list under this CRP to IAEA as soon as possible.
4. Check the ENDF-6 files, whether the file-4 is to be added in some reaction channel for isotropic distribution.

*T. Fukahori (Tokai)*

1. Evaluations selected for the IAEA Photonuclear Data Library and the other_files will be submitted to IAEA by 15 December 1999.
2. Reference of the JENDL Photonuclear Library will be sent.
3. Three figures for $^{51}$V(γ,xn), $^{181}$Ta(γ,xn) and $^{235}$U(γ,F) will be prepared.
4. List of publications created under the CRP will be sent to IAEA.

# 4. Review of the TECDOC

Draft No. 2 of the TECDOC was reviewed. Comments on each chapter are summarized below.

## 4.1 Chapter 1 – Introduction

Coordinator: Pavel Obložinský

Remove the separation between "priority" and "others" materials, ordering them by atomic number. Mention, at the end, the development of new technologies and facilities for the production of monoenergetic photon beams, which might lead to interesting new applications.

### 4.2 Chapter 2 – Definitions and Notation

Coordinator: Marcos N. Martins

Include definitions of evaluation, inclusive and exclusive cross sections and all the symbols generally used in the other chapters. Include also a list of abbreviations, with the acronyms of the institutions and libraries involved.

### 4.3 Chapter 3 – Available Experimental Data

Coordinator: Marcos N. Martins

Define the relevant quantities in section 3.1.1 and 3.1.2 in terms of the kinetic energy of the electron beam. Use $E_\gamma$ for photon energy. Figures 3.2, 3.4 and 3.5 should be redrawn with better quality. Substitute the symbols used in equation 3.2 for something representing "number of counts". Reduce the explanations concerning electron induced reactions, referring to section 4.4. Make figure 3.5 in accordance to the definitions of chapter 2. Eliminate section 3.2.3 and correct section 3.2.4 according to the suggestions.

### 4.4 Chapter 4 – Nuclear Models

Coordinator: Mark B. Chadwick

Acronyms should be avoided wherever possible. Use the accorded symbol for γ energy and complete equation 4.2. Include the unity of the γ energy in equations 4.4 and 4.5. Item 4.2.5 will have some additions from Blokhin: table, list of references and spectra. Item 4.4 will have the definitions improved and complying with chapter 2.

### 4.5 Chapter 5 – Evaluations

Coordinator: Mark B. Chadwick

Eliminate the use of italic symbols for the atomic elements and comply equations to chapter 2. In item 5.2 eliminate theory-based in quotation marks, using model calculations instead. In item 5.3 use the accorded name for the libraries: BOFOD, CNDC, EPNDL, JENDL, KAERI and LANL.

Item 5.4 should be removed and added at the end of section 6.1. The intercomparison should include $^{181}$Ta(γ,xn), with LANL and JENDL/KAERI evaluations. (Figure should be provided by Fukahori); $^{51}$V(γ,xn), with CNDC and JENDL (fig. by Fukahori); $^{12}$C(γ,$n_0$) with LANL and another evaluation (fig by Chadwick); $^{235}$U(γ,F) with EPNDL, BOFOD, JENDL (fig. by Fukahori). The text accompanying this discussion should be provided by Chadwick.

### 4.6 Chapter 6 – IAEA Photonuclear Data Library

Coordinator: Pavel Obložinský

List the 6 libraries with the correct names and affiliations. In the end of section 6.1 should be included the summary table (translated to LaTex by Lee) with the 164 materials, without the columns of experimental data and comments. After that the intercomparison part should be included (see comments about 5.4 above).

Item 6.2 should be modified according to the actual number of files and materials provided. Item 6.3 is eliminated. New section 6.3 "ENDF-6 format" should include MT 452, 455, 456, and 458 for fission. New section 6.4 should have the file names complying with the respective library names: lanl.dat; bofod.dat; cndc.dat; kaeri.dat; jendl.dat; and epndl.dat.

A final section 6.5 – Graphical Presentation of the Library should be added, with 164 materials. Each one in a one- or two-page presentation with figures (γ,abs) and (γ,xn) reactions as a minimum) and explanation text. References should be corrected.

### 4.7 Chapter 7 – Recommendations and Future Work

No comments.

### 4.8 Appendix – Atlas of GDR

Coordinator: V.V. Varlamov

Introduction to the Atlas should have clear explanation about how the GDR parameters are obtained. An illustrative figure should be added for guidance. Emphasize that entry may be subdivided in two or more lines for complex shaped resonances.

### 4.9 Completion of the TECDOC

The following actions and deadlines were agreed upon:

- Coordinators will revise their chapters (*.tex files) and submit to Chadwick (November 1999).
- Lee will prepare *.tex file with figures and text for each nuclide (about 200 pages). He will closely consult Martins, in particular texts. The results will be sent to Chadwick and IAEA (January 2000).
- Chadwick will prepare the complete *.tex and *.ps documents and send to IAEA (January 2000).
- Obložinský will prepare the complete hardcopy and distribute to all CRP for final comments (February 2000).

## 5. Products of the CRP

The CRP resulted in the following products that are already available or will be completed in the near future.

- IAEA Photonuclear Data Library (164 nuclides, expected release: spring 2000).
- IAEA TECDOC "Handbook on photonuclear data for applications" (about 300 pages, expected submittal for print: spring 2000).
- IAEA Web page including both the library and TECDOC will be prepared (expected release: spring 2000).
- The photonuclear data part of the EXFOR library was considerably improved. This is already available.
- The Atlas of GDR parameters was prepared, published and put on the Web.
- An extensive journal paper will be prepared.
  - Scope: main results of the CRP, about 20-30 pages.
  - Journal: Physics in Medicine and Biology or Nuclear Science and Engineering.
  - Authors: All CRP members plus L. Han (KAERI/CNDC).
  - Cordinator: Chadwick.

## 6. Conclusions and Recommendations

The IAEA Photonuclear Data Library, a major output of the present CRP, is an entirely new product. The IAEA Nuclear Data Section should take care of future updating and maintenance of the library.

There are several important technological developments that may have substantial impact on future applications of photonuclear reactions such as medical (radioisotope production) and waste transmutation. Among them are techniques to produce high intensity monochromatic photon beams, such as the Compton backscattering of laser beams (BNL, Bookhaven, USA; JNCDI, Tokai, Japan) and Compton backscattering of photons (TUNL, Duke University, USA).

Experimental data for several important photonuclear reactions are missing or not well known, including reactions on $^{56}Fe$. These reactions should be put into the High Priority (Nuclear Data) Request List maintained by the NEA Data Bank in Paris.

The participants of the present project appreciate usefulness of the IAEA CRP mechanism towards cost effective production of international evaluated nuclear data libraries for applications.

**Attachment 1**

International Atomic Energy Agency
Third Research Co-ordination Meeting on
**Compilation and Evaluation of Photonuclear Data for Applications**
JAERI, Tokai-mura, Japan
25 – 29 October 1999

## AGENDA

***Monday, 25 October***, 09:30 – 18:00

- Opening
  - ¤ Welcome (M. Nakagawa and A. Hasegawa, JAERI)
  - ¤ Remarks (P. Obložinský, IAEA)
- Approval of Agenda
- Announcements
- Status of the CRP (Obložinský)
- Progress reports/presentations by the CRP participants
  - ¤ A.I. Blokhin (Obninsk): Progress report about photonuclear data activity in 1999
  - ¤ M.B. Chadwick (Los Alamos): Photonuclear data evaluations at Los Alamos
  - ¤ T. Fukahori (JAERI): JAERI Progress report on compilation and evaluation of photonuclear data for applications
  - ¤ Y.-O. Lee (KAERI): KAERI photonuclear data library
  - ¤ M.N. Martins (Sao Paulo): Some photonuclear cross sections relevant for shielding purposes
  - ¤ V.V. Varlamov (Moscow):
    1. CDFE activities under the IAEA CRP on photonuclear data
    2. Evaluation of (γ,n), (γ,p) and (γ,np) reactions for $^{20,22}$Ne
  - ¤ Yu Baosheng (Beijing): Photonuclear data evaluations at CNDC Beijing
- Presentations by other participants
  - ¤ Zhang Jingshang (Beijing): Gamma induced reactions on $^{9}$Be
  - ¤ N. Kishida (JAERI): Present status of the JENDL photonuclear data file
  - ¤ T. Murata (AITEL): Evaluation of photonuclear reactions on light nuclei
  - ¤ H. Harada (JNC): High resolution spectroscopy for photoabsorption cross sections using HHS and LCP
  - ¤ Maruyama (JAERI): Analysis of photonuclear reactions in the QMD approach
- Evening: Reception

***Tuesday, 26 October***, 09:00 – 18:00

- Presentations continued
- Photonuclear Library
  - ¤ Review of the IAEA Photonuclear Data Library
    - General (Obložinský)
    - Intercomparison of evaluated data (Fukahori)

- Selection of evaluated data (Fukahori)
  - ➢ Structural and shielding materials (Fukahori)
  - ➢ Biological materials (Chadwick)
  - ➢ Fission materials (Blokhin)
  - ➢ Other materials (Varlamov)
- ¤ Procedures to finalize the Library

***Wednesday, 27 October***, 09:00 – 18:00

- Photonuclear TecDoc
  - ¤ Review of the draft TECDOC "Compilation and Evaluation of Photonuclear Data for Applications"
    - General (Chadwick)
    - Chapter 1 (Obložinský)
    - Chapter 2 (Martins)
    - Chapter 3 (Martins)
    - Chapter 4 (Zhang Jingshang/Chadwick)
    - Chapter 5 (Chadwick)
    - Chapter 6 (Fukahori)
    - Chapter 7 (Chadwick)
    - Annex (Varlamov)
  - ¤ Procedures to finalize the TECDOC
- Evening: Meeting dinner at T. Fukahori's house

***Thursday, 28 October***, 09:00 – 18:00

- Photonuclear TECDOC continued
- Completion of the CRP
  - ¤ Final products
  - ¤ Release of final products
  - ¤ Procedures to finalize the CRP
- Drafting of the Meeting Report

***Friday, 29 October***, 09:00 – 17:00

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

**Attachment 2**

International Atomic Energy Agency
Third Research Co-ordination Meeting on
**Compilation and Evaluation of Photonuclear Data for Applications**
JAERI, Tokai-mura, Japan
25 – 29 October 1999

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**Attachment 3**

## Progress Reports and Presentations

# PROGRESS REPORT ABOUT the PHOTO-NUCLEAR DATA EVALUATION ACTIVITY in 1999

by A.I. Blokhin

Institute of Physics and Power Engineering

Obninsk, Kaluga Region, Russia

*Abstract.* The present work is intended to continue the evaluation of the photonuclear cross-section for the main materials what were proposed by the 2-nd CRP-Meeting on "Compilation and Evaluation of Photonuclear Data for Applications" (23-26 June 1998, LANL, Los Alamos, USA).

The general purpose of this research is to improve the theoretical methods for the calculations and the evaluations of the differential and integral photonuclear cross-sections in the wide excitation energy up to 20 MeV. On that base for the U-234, U-236, Pu-238, Pu-239, Pu-241 elements the evaluated data files were prepared. Some modifications were performed for the Th-232, U-233, U-235 and U-238 evaluated photonuclear data files.

## *1. Actinides.*

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

On the base of the EXFOR library and information published in different journals it was compiled and analysed the experimental data concerning the U-234, U-236, Pu-238, Pu-239 and Pu-241 nuclei.

From analysis of experimental data the modern set of the parameters needed for the theoretical description the photonuclear cross-sections in a wide gamma-ray energy range was obtained and used to produce the complete evaluated data files for fissile nuclei: U-234, U-236, Pu-238, Pu-239 and Pu-241.

The preliminary version of evaluated photonuclear data files for the U-234, U-236, Pu-238, Pu-239 and Pu-241 elements was created in ENDF-6 format and presented in the IAEA Nuclear Data Section (October 1999) for the intercomparision with another similar data in the frame of the CRP-Meeting on "Compilation and Evaluation of Photonuclear Data for Applications" (LANL, June 1998). Those files include the evaluated photonuclear data sets for:

1/451 – description of file;

1/452 – total number of neutrons per fission;

1/455 – delayed neutron data;

1/456 – prompt neutron number per fission;

1/458 – energy realized in fission process;

2/151 – radious of nucleous only;

3/1 - total gamma-cross section;

3/2 - elastic gamma-cross section;

3/3 - photoabsorption c-s;

3 /4 - photo-single neutron c-s;

3/16 - photo-double neutron c-s;

3/18 - photofission c-s;

3/91 - photo-single neutron c-s through continuum;

4/2 - angular distribution for elastic process;

4/16 - angular distribution for (γ, 2n) process;

4/18 - angular distribution for photofission process;

4/91 – angular distribution for (γ, 1n) process through continuum;

5/16 - energy distribution for (γ, 2n) process;

5/18 - energy distribution for photofission process;

5/91 – energy distribution for (γ, 1n) process through continuum;

Some modifications were performed for the Th-232, U-233, U-235 and U-238 evaluated photonuclear data files prepared in previous year. Now these files have the same content and formatted presentation as the files for mentioned above elements.

In progress we performed the evaluation for the Np-237, Am-241, Am-243, Cm-243, Cm-244 and Cm-245 elements. Up to the end of 1999 the similar presentation as above mentioned will be performed for Np-237, Am-241, Am-243, Cm-243, Cm-244 and Cm-245 elements.

The photonuclear data processing by the Njoy-system was performed for the Th-232, U-233, U-234, U-235, U-236, U-238, Pu-238, Pu-239 and Pu-241 elements. The original data were processed to "gendf" and "acer"-format presentation for future data testing. For that process some additional information was inserted to original evaluated data files.

***Experiment and analysis***

New experimental results concerning the measurements of photofission cross section for the Pu-238, Pu-240 and Pu-242 elements were obtained and analized. New set of the theoretical parameters needed for the description of photofission cross section were adopted from that analisys. The article was prepared and sent to J., YF (1999) for publication.

***Cross section for production of radioisotopes***

In the gamma-ray energy range up to 70 MeV the photonuclear cross section for production of radioisotopes needed for the PET task were produced using a combination of fitting of experimental data and theoretical calculations. The list of that is: C12($\gamma$, n), N14($\gamma$, n), O16($\gamma$, n), F19($\gamma$, n), Ne-nat($\gamma$, 2n+p), S32($\gamma$, np), Fe54($\gamma$, np), Cu63($\gamma$, n), Cu65($\gamma$, n), Ga-nat($\gamma$, n), Pr141($\gamma$, n). We are going to transform these data to the endf-6 format presentation.

***BNCT Therapy***

For that task some data for photo-neutron production (cross section and angular-energy distribution) for the Be-9 and Ta-181 target was obtained and used in the MCNP-calculation.

# Photonuclear data evaluations at Los Alamos

Mark B. Chadwick
Los Alamos National Laboratory
Los Alamos, U.S.A.

(October 22, 1999)

We have completed a number of new photonuclear evaluations for incident energies up to 150 MeV. These evaluations were based upon GNASH nuclear model calculations, and guided by available experimental data. To date, isotopes of C, Al, Ca, Fe, Cu, Ta, W, and Pb have been completed, and we plan to evaluate photonuclear reactions on O and Si shortly. The goal has been to provide a suite of evaluated libraries essential for simulations of photonuclear reactions on accelerator structural materials, bremsstrahlung conversion and spallation targets, and shielding materials. Certain photonuclear reactions are also important in astrophysical nucleosynthesis.

The GNASH calculations typically use absorption data as an input, and then predict secondary neutron, photon, and charged particle spectra, together with cross sections for (g,n), (g,2n), (g,3n) etc reactions. These calculated results were extensively checked against measurements, such as those compiled in Dietrich and Bermans compilation, or Varlamovs atlas. For a few rare case, such as reactions on carbon, and calcium, secondary double-differential emission spectra measurements exist for monochromatic photons. These data allowed us to validate our modeling of preequilibrium and equilibrium decay processes and our angular-distribution theory. Finally, the measurements of emitted neutron multiplicities from Saclay, by Lepretre et al, also provided a valuable test of the evaluated results.

Most of the evaluations use an ENDF MT5 format, representing the data for inclusive reactions in terms of the total nonelastic cross section (the absorption cross section), yields (or multiplicities) for secondary ejectiles and recoils, and spectra for these ejectiles. In the case of carbon, a slightly different approach was used where, in addition to MT5, the formats MT50 and MT600 were used to represent the important (g,n0) and (g,p0) reactions. These reactions were evaluated from experimental data, and included a Legendre-polynomial dipole description of the angular distributions.

In addition to evaluation work at Los Alamos, research has been undertaken by the MCNP group to expand the MCNP code to include a photonuclear capability, and to process the evaluated data for use by MCNP. This work has been led by Morgan White and Robert Little, with data processing work in an NJOY context by Robert MacFarlane. Great progress has been made and MCNP is now able to perform radiation transport with photonuclear reactions.

Morgan White has performed some MCNP calculations to simulate integral experiments of photoneutron production. Surprisingly, very few experiments seem to exist for neutron production from electron-bremsstrahlung reactions. One of the few careful experiments is that of Barber and George, from Stanford. Generally then MCNP calculations of neutron production per incident electron are in good agreement with the measurements.

We have also led the task of putting together various participant's contributions to the TECDOC. This is being done using LaTeX, and makes use of an extensive BiBTeX database of relevant citations. A large amount of editing and writing has been done. We expect to be able to complete this report in the coming year.

# JAERI Progress Report on Compilation and Evaluation of Photonuclear Data for Applications

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## 1. Evaluation and Compilation of the JENDL Photonuclear Data File

See summaries by Kishida and Murata in the Appendix 3 of the present report.

## 2. Production of the IAEA TECDOC Document

Draft manuscript of the IAEA-TECDOC on Photonuclear Data Library was written for:

Chapter 5: Evaluations
- 5.3 Methods used for producing evaluated libraries
- 5.3.2 JAERI library (JENDL-PDF)

Chapter 6: IAEA Photonuclear Data Library
- Table of status of evaluated photonuclear data libraries were revised.

## 3. Intercomparison of Results in Libraries

The status of evaluated photonuclear data files, BOFOD, CNDC, EPNDL, JENDL, KAERI and LANL was checked. Intercomparison plots were prepared as a part of the selection procedure. The following 129 reactions in the above libraries were compared with experimental data:

| | | | | |
|---|---|---|---|---|
| H-2(g,abs), | Be-9(g,abs), | Be-9(g,nx), | Be-9(g,1n), | Be-9(g,1nx), |
| Be-9(g,2nx), | Be-9(g,1p), | Be-9(g,1dx), | Be-9(g,1a), | C-12(g,abs), |
| C-12(g,nx), | C-12(g,px), | C-12(g,dx), | C-12(g,hx), | C-12(g,tx), |
| C-12(g,ax), | C-12(g,1n), | C-12(g,1nx), | C-12(g,1p), | C-12(g,np), |
| C-12(g,x+Li-6), | C-12(g,x+Li-7), | C-12(g,x+Be-7), | N-14(g,abs), | N-14(g,nx), |
| N-14(g,px), | N-14(g,dx), | N-14(g,hx), | N-14(g,ax), | N-14(g,np), |
| O-16(g,abs), | O-16(g,nx), | O-16(g,px), | O-16(g,dx), | O-16(g,tx), |
| O-16(g,hx), | O-16(g,ax), | O-16(g,1n), | O-16(g,np), | Al-27(g,abs), |
| Al-27(g,Tn), | Al-27(g,nx), | Al-27(g,px), | Al-27(g,1n), | Al-27(g,1nx), |
| Al-27(g,2n), | Al-27(g,2nx), | Al-27(g,np), | V-51(g,Tn), | V-51(g,nx), |
| V-51(g,n+np), | V-51(g,2n), | V-51(g,2nx), | Fe-54(g,nx), | Fe-54(g,1n), |
| Fe-54(g,1p), | Fe-56(g,abs), | Fe-56(g,nx), | Fe-56(g,1n), | Ni-58(g,abs), |
| Ni-58(g,Tn), | Ni-58(g,nx), | Ni-58(g,1n), | Ni-58(g,1nx), | Ni-58(g,2nx), |
| Cu-63(g,Tn), | Cu-63(g,nx), | Cu-63(g,1n), | Cu-63(g,1nx), | Cu-63(g,2n), |
| Cu-63(g,2nx), | Cu-63(g,1p), | Cu-63(g,np), | Cu-65(g,Tn), | Cu-65(g,nx), |
| Cu-65(g,1n), | Cu-65(g,1nx), | Cu-65(g,2nx), | Cu-65(g,1p), | Cu-65(g,np), |
| Zr-90(g,Tn), | Zr-90(g,nx), | Zr-90(g,1n), | Zr-90(g,1nx), | Zr-90(g,2n), |
| Zr-90(g,2nx), | W-182(g,abs), | W-182(g,Tn), | W-184(g,abs), | W-184(g,Tn), |
| W-186(g,abs), | W-186(g,Tn), | W-186(g,nx), | W-186(g,1nx), | W-186(g,2nx), |
| W-186(g,3n), | Pb-206(g,Tn), | Pb-206(g,nx), | Pb-206(g,1n), | Pb-206(g,1nx), |
| Pb-206(g,2nx), | Pb-207(g,Tn), | Pb-207(g,nx), | Pb-207(g,1n), | Pb-207(g,1nx), |
| Pb-207(g,2nx), | Pb-208(g,abs), | Pb-208(g,Tn), | Pb-208(g,nx), | Pb-208(g,1n), |
| Pb-208(g,1nx), | Pb-208(g,2n), | Pb-208(g,2nx), | Pb-208(g,3n), | Bi-209(g,abs), |
| Bi-209(g,Tn), | Bi-209(g,nx), | Bi-209(g,1n), | Bi-209(g,1nx), | Bi-209(g,2nx), |
| U-235(g,abs), | U-235(g,fis), | U-235(g,1nx), | U-235(g,2n), | U-238(g,abs), |
| U-238(g,fis), | U-238(g,1n), | U-238(g,1nx), | U-238(g,2n). | |

# KAERI Photonuclear Data Library

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## Status of the Library

KAERI is building a photonuclear data library in response to nuclear data needs from various R&Ds and applications. Currently, total 143 isotopes of 38 elements are included in the evaluated photonuclear data library as follows:

- Structural, Shielding and Bremsstrahlung Target Materials
  $^{24,25,26}$Mg, $^{27}$Al, $^{50,52,53,54}$Cr, $^{55}$Mn, $^{54,56,57,58}$Fe, $^{59}$Co, $^{58,60,61,62,64}$Ni, $^{63,65}$Cu, $^{64,66,67,68,70}$Zn, $^{90,91,92,94,96}$Zr, $^{92,94,95,96,97,98,100}$Mo, $^{112,114,115,116,117,118,119,120,122,124}$Sn, $^{120,122,123,124,125,126,128,130}$Te, $^{141}$Pr, $^{165}$Ho, $^{197}$Au, $^{209}$Bi.
- Biological Materials
  $^{12,13}$C, $^{14,15}$N, $^{16,17,18}$O, $^{23}$Na, $^{32,33,34,36}$S, $^{35,37}$Cl, $^{40,42,43,44,46,48}$Ca.
- Nuclear Waster Transmutation
  $^{84,86,87,88,90}$Sr, $^{93}$Zr, $^{93,94}$Nb, $^{102,104,105,106,107,108}$Pd, $^{107,108,109}$Ag, $^{127,129}$I, $^{133,135,137}$Cs, $^{144,147,148,149,150,151,152,154}$Sm, $^{158,159}$Tb.
- Actvation Analysis
  $^{28,29,30}$Si, $^{36,38,40}$Ar, $^{39,40,41}$K, $^{46,47,48,49,50}$Ti, $^{70,72,73,74,76}$Ge, $^{110}$Pd, $^{106,108,110,111,112,113,114,116}$Cd, $^{121,123}$Sb.
- Astrophysics
  Nuclei such as $^{27}$Si, for use as a cosmological chronometer.

## Theoretical Models and Evaluation Techniques

The Giant-Dipole Resonance (GDR) and the Quasi-Deuteron Model (QDM) are used to calculate the photoabsorption cross sections. The GDR parameters are adjusted by fitting the experimental data of photoabsorption cross sections or photoneutron cross sections. If experimental data exist for total photoabsorption cross section, it can be used to adjust the GDR parameters. For heavy nuclei, the total photoneutron cross section can be used to approximate the photoabsorption cross sections, since contributions from charged particle emissions are small. However, in light nuclei where the photoproton cross section is no longer small, the resonance parameters are adjusted in such a way that the decaying model calculation with the initial nuclear excitation reproduces available photonuclear reaction measurements. When the photoabsorption cross sections are established, the decay processes including neutron, proton, deuteron, triton and alpha particle emissions are calculated up to 140 MeV using GNASH code. Figure 1 shows some of our evaluation results of the photonuclear reaction for Mo, Zn, S and Cl isotopes, compared with available experimental data.

## Acknowledgements

This work was performed under the auspices of Korea Ministry of Science and Technology as one of the long-term nuclear R&D programs.

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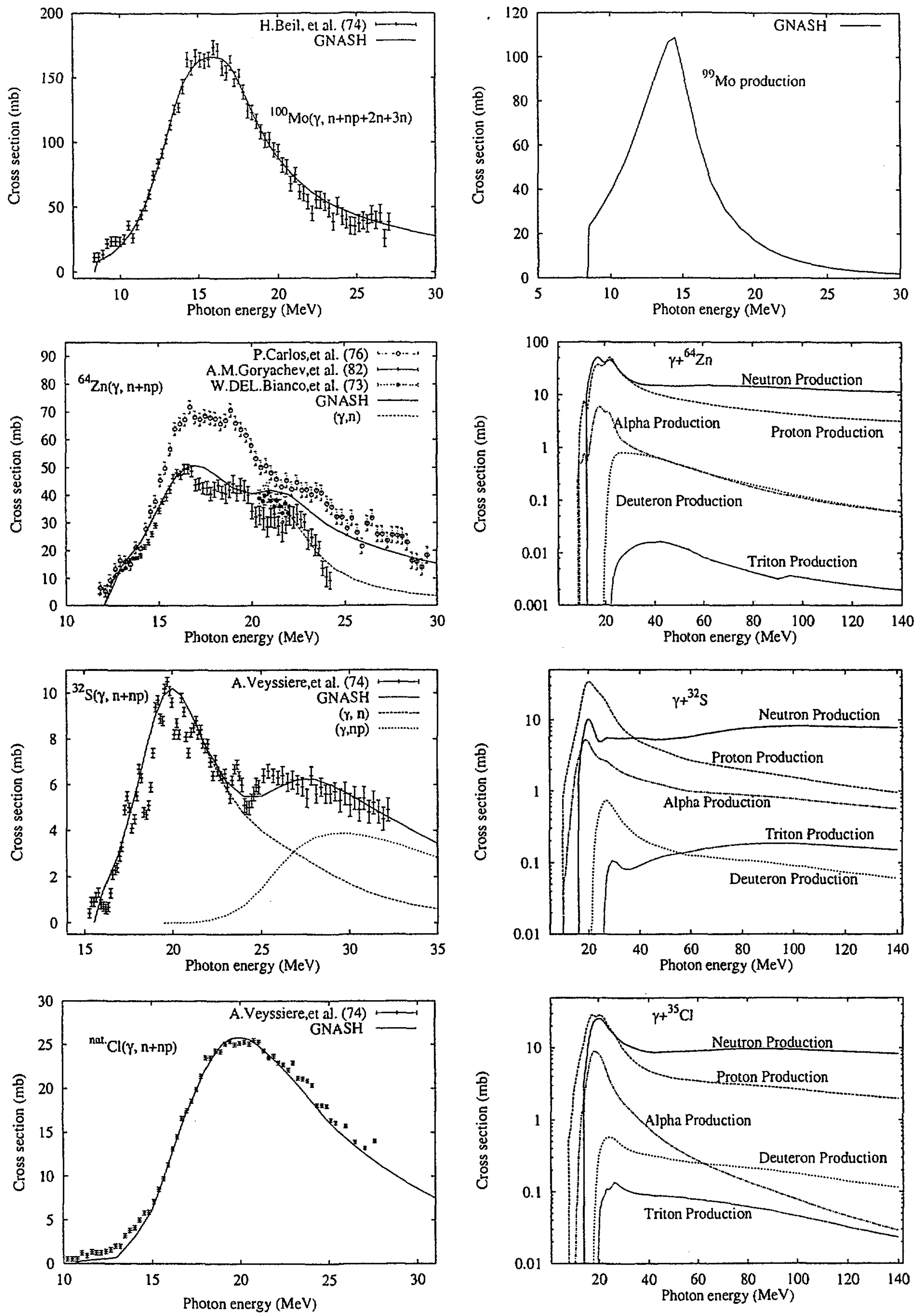


Figure 1: Comparison of calculated results with experimental data for Mo, Zn, S, and Cl photonuclear reaction cross sections

# Some photonuclear cross sections relevant for shielding purposes

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This paper presents some experimental results of photonuclear cross sections which are relevant for shielding materials. Iron is a very important material in construction, largely used in structures, and nevertheless poorly studied in terms of its photonuclear properties. Below is presented a measurement of the photoproton cross section $^{56}$Fe(γ,xp) (Fig. 1). These results were generated by the virtual photon analysis of electro- and electro-plus-photodisintegration data [1]. Also presented is a spectrum of the protons emitted at 90°, when the target was bombarded by 30 MeV electrons (Fig. 2).

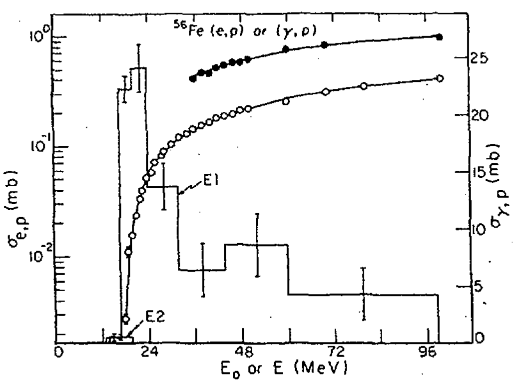


Figure 1 — Electrodisintegration cross section (open circles) and electro-plus-photodisintegration yield (full circles) of $^{56}$Fe with the emission of at least one proton (left hand scale). $^{56}$Fe(γ,xp) cross section (histogram, right hand scale). From Ref. [1].

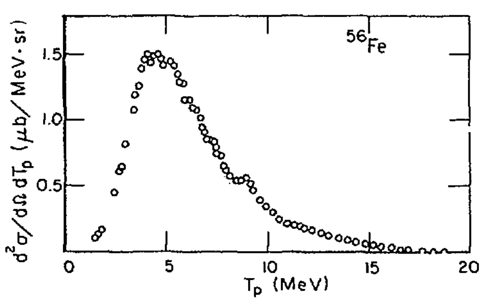


Figure 2 — Spectrum of protons emitted at 90°, when the target is bombarded by 30 MeV electrons. From Ref. [1].

Another important material in construction is Silicon, present in concrete, which is used for both structural and shielding purposes. As in most light nuclei, the photoproton cross section can be as important as the photoneutron cross sections in Silicon. As in the case of Iron, the photoproton cross sections were obtained from the virtual photon analysis of electro and electro-plus-photodisintegration data. In this case the measurement was done by detecting the residual activity of the final nucleus, so that the reaction channel is perfectly determined. Below are presented the (γ,1p) cross sections for both $^{29}$Si and $^{30}$Si (Figs. 3 and 4, respectively). The relative importance of the neutron and proton channels in the photodisintegration of the Silicon isotopes can be evaluated in the figures presented below, which show a comparison between photoneutron and photoproton cross section for $^{29}Si$ and $^{30}Si$.

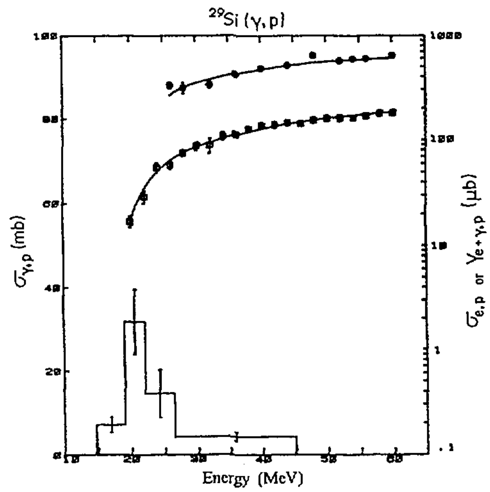


Figure 3 — $^{29}Si$ electrodisintegration by one proton emission (squares, right hand scale), electro-plus-photodisintegration yield (circles, right hand scale), $^{29}Si(\gamma,1p)$ cross section (histogram, left hand scale). From Ref. [2].

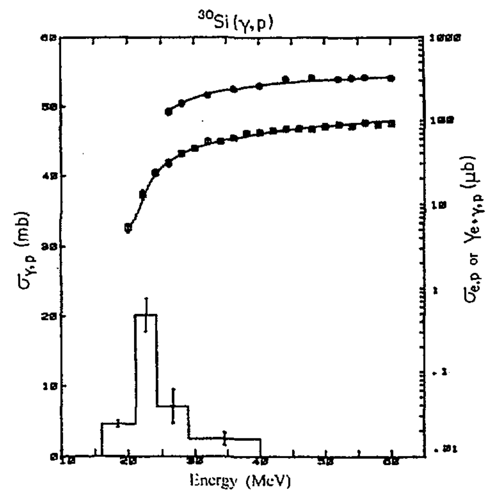


Figure 4 — Results for $^{30}Si$, please see caption of Fig. 3. From Ref. [2].

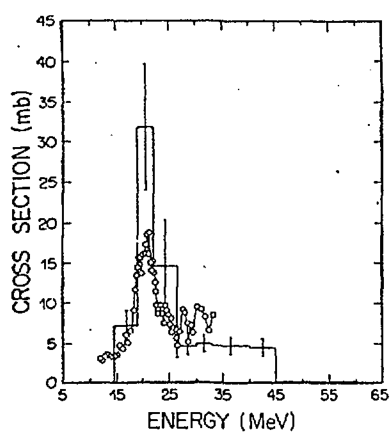


Figure 5 — Comparison between (γ,xn) (circles) and (γ,xp) (histogram) cross sections for $^{29}Si$. From Ref. [2].

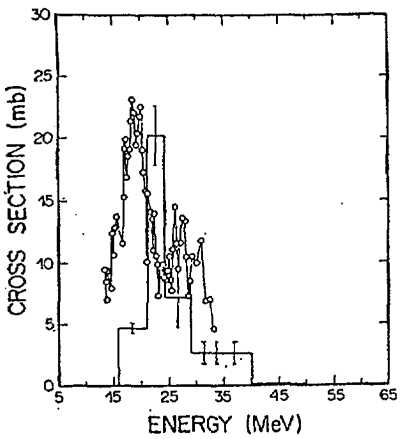


Figure 6 — Comparison between (γ,xn) (circles) and (γ,xp) (histogram) cross sections for $^{30}$Si. From Ref. [2].

Table 1 shows a comparison between the integrated cross sections (up to 30 MeV) of the different channels for both $^{29}$Si and $^{30}$Si.

Table 1 — Comparison between $^{29,30}$Si integrated photonuclear cross sections

| Reaction | Threshold (MeV) | $\int \sigma dE$ (MeVmb) |
|---|---|---|
| $^{29}$Si(γ,*p*) | 12.3 | 269(40) |
| $^{29}$Si(γ,2*p*) | 21.9 | 8.4(24) |
| $^{29}$Si(γ,*n*) | 8.50 | 183.0 |
| $^{29}$Si(γ,*n*+γ,*np*+γ,*p*+γ,*2p*) integrated x-section: 460.4 MeVmb | | |
| $^{30}$Si(γ,*p*) | 13.5 | 151(17) |
| $^{30}$Si(γ,2*p*) | 24.0 | 1.5(5) |
| $^{30}$Si(γ,*n*) | 10.6 | 181.0 |
| $^{30}$Si(γ,*2n*) | 19.1 | 67.0 |
| $^{30}$Si(γ,*n*+γ,*np*+γ,*2n*+γ,*p*+γ,*2p*) integrated x-section: 400.5 MeVmb | | |

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# Evaluation of (γ,n), (γ,p), and (γ,np) Reaction Cross Sections for $^{20,22}Ne$

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Report
to the 3-rd Research Co-ordination Meeting (25 - 29 October 1999, JAERI, Tokai, Japan)
of the IAEA Co-ordinated Research Programme on Compilation and Evaluation of Photonuclear Data for Applications

The high energy (above 17 MeV) $^{20}$Ne(γ,n)19Ne reaction is a concern to several scientific both basic and applied problems. From the point of view of interesting application there are the needs for this reaction cross section data for the energies of incident photons higher than reaction threshold 16.9 MeV because its competition to the reaction $^{20}$Ne(n,2n)$^{19}$Ne which is the one of several threshold neutron reactions widely used for the problems of DT plasma diagnostics solving. At the same time the pair of nuclei $^{20}$Ne (Z = N = 10) and $^{22}$Ne (Z = 10, N = 12) is very interesting from the point of view of basic research of Giant Dipole Resonance excitation and decay mechanisms investigation.

Unfortunately the experimental photonuclear reaction cross section data available for both nuclei under discussion are very poor (Table 1).

Table 1.

Published Ne photoneutron and photoproton reaction cross section data

| Isotope | Reaction | Energy region (MeV) | Upper limit of integration (MeV) | Интегр. сечение (MeV*mb) | First author | Reference | Comment |
|---|---|---|---|---|---|---|---|
| $^{nat.}$Ne | (γ,n) + (γ,np)<br><br>(γ,2n) | 16 - 26<br><br>16 - 26 | 20.6<br>26.7 | 15.8<br>42 ± 3 | Veyssiere | /1/ | * |
| | (γ, $n_0$+$n_1$+$n_2$) | 17 - 31 | 31.0 | 55 - 77 | Woodworth | /2/ | ** |
| $^{20}$Ne | (γ,n) + (γ,np) | 16 - 28 | 20.6<br>26.7<br>28.5 | 20 ± 2<br>49 ± 5<br>58 ± 6 | Allen | /3/ | |
| | (γ, p) + (γ, np) | 16 - 28 | 32.5 | 61 ± 11 | Hoffman | /4/ | *** |
| $^{22}$Ne | (γ,2n) | 16 - 26 | | | Veyssiere | /1/ | * |
| | (γ,p) + (γ,np) | 18 - 30 | 32.5 | 45 ± 8 | Hoffman | /4/ | *** |

*) up to the threshold energy ($E_{thr.}$ = 28.5 MeV) of reaction $^{20}$Ne(γ,2n) the cross sections of reactions $^{nat.}$Ne(γ,2n) и $^{22}$Ne(γ,2n) are identical ($^{21}$Ne abundance is 0.27 %);
**) differentiall reaction cross section obtained from the 90-degree photoneutron energy spectra multiplied to 4π;
***) differentiall reaction cross section obtained from the 90-degree photoproton energy spectra multiplied to 4π;

The evaluation of the $^{22}$Ne[(γ,n + (γ,np)] reaction cross section has been done /5 – 8/ on the base of $^{nat}$Ne[(γ,n + (γ,np)] /1/ and $^{20}$Ne[(γ,n + (γ,np)] /3/ reaction cross sections using the data on the isotopes $^{20}Ne$ and $^{22}Ne$ abundances (90.51 and 9.22 % correspondingly), the contribution of $^{21}Ne$ isotope with abundance 0.27 % has been neglected

The following formulae has been applied:

$$\sigma^{V} = 90.51\sigma^{A\text{-}n} + 9.22\sigma^{X},$$

where $\sigma^{X} = \sigma\{^{22}Ne\ (\gamma,np)\}$ is the evaluated cross section,

$\sigma^{A\text{-}n.} = \sigma^{A} \cdot N(E_\gamma)$ is the Allen's /3/ cross section $\sigma^{A}$, normalized to the Veyssiere's /1/ cross section $\sigma^{V} = \{^{nat}Ne[(\gamma,n) + (\gamma,np)]\}$,

$N(E_\gamma) = 0.048387 \cdot E_\gamma - 0.3016$ is the empirical function obtained using the integrated cross section data for 5 different energy ranges.

The (γ,n) and (γ,np) reaction cross sections for $^{20}Ne$ and $^{22}Ne$ have been evaluated for energies till about 28.0 MeV using the gaussian line separation of the $^{20,22}Ne[(\gamma,n)+(\gamma,np)]$ reaction cross sections into corresponding parts below and above the (γ,np) reaction threshold energy values ($E_{thr.}$ = 23.3 and 23.4 MeV correspondingly for $^{20}Ne$ and $^{22}Ne$ isotopes). The appropriate subtraction procedures have been applied.

The $^{20,22}Ne(\gamma,n)^{19,21}Ne$ reactions cross sections have been evaluated for photon energy range $E_\gamma$ = 16.0 – 28.0 MeV, the $^{20}Ne(\gamma,np)^{18}F$ reaction cross section - for photon energy range $E_\gamma$ = 23.3 – 28.0 MeV. There was no obtained enough information for evaluation of $^{22}Ne(\gamma,np)^{20}F$ reaction cross section.

The data for $^{20,22}Ne(\gamma,Xp)$ reaction cross sections /4/ have been used for separation of the (γ,p) and (γ,pn) reactions contributions. The $^{20,22}Ne(\gamma,p)^{19,21}F$ reaction cross sections have been evaluated for incident photon energies from 15.3 to 28.0 MeV.

The evaluated $^{20,22}Ne(\gamma,n)^{19,21}Ne$, $^{20,22}Ne(\gamma,p)^{19,21}F$, and $^{20}Ne(\gamma,np)^{18}F$ reaction cross sections /7, 8/ have been included into the preliminary version of the CDFE EPNDL3 library.

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# The IAEA Photonuclear Data Co-ordinated Research Programme CDFE Activities

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Progress Report
to the 3-rd Research Co-ordination Meeting (25 - 29 October 1999, JAERI, Tokai, Japan)
of the IAEA Co-ordinated Research Programme on Compilation and Evaluation of Photonuclear Data for Applications

The following works have been carried out by the CDFE in accordance to the scientific CRP Scope and Programme Goals /1/ and the corresponding CDFE /2/ tasks and the results have been obtained in 1998 - 1999 period of time.

**Atlas of Photonuclear Reaction Cross Sections.** The Atlas of Giant Dipole Resonances (GDR) prepared by the MSU INP CDFE for previous CRP meeting /3/ has been added and improved and published as the IAEA NDS Technical document /4/. The Atlas includes 1317 entries described the GDR parameters and 846 cross sections in graphical form of various photonuclear reactions produced using the international EXFOR nuclear reaction data library. The data for almost all more than 400 various photoneutron cross section entries from well known Atlas of Photoneutron Cross Sections Obtained with Monoenergetic Photons /5/ are also included. All data under duscussion are presented upon the CDFE Web-site (**http:\\depni.npi.msu.su**

**Index of Photonuclear Data.** The complete photonuclear data Index for period of time 1955 - 1996 has been produced on the base of two CDFE /6/ and JAERI /7/ indexes with addition of the appropriate CDFE data file for 1996 /8/. The CDFE Photonuclear Data Informational files containing the data included into the indexes "PHOTONUCLEAR DATA - 1997" and "PHOTONUCLEAR DATA - 1998" have been prepared for publishing and including into the complete Index put upon the CDFE Web-site. The complete Index has been put upon the CDFE Web-site using hypertext presentation.

**New EXFOR TRANSes of Photonuclear Data.** 5 new CDFE EXFOR TRANSes have been produced and transmitted to the IAEA NDS.

| TRANS | 1-st ENTRY's number | Last ENTRY's Number | Amount of ENTRYs | Amount of DATA TABLES |
|---|---|---|---|---|
| M023 | M0533 | M0536 | 4 | 9 |
| M025 | M0537 | M0550 | 14 | 72 |
| M026 | M0551 | M0565 | 15 | 61 |
| M027 | M0566 | M0580 | 15 | 76 |
| M028 | M0581 | M0595 | 15 | 81 |
| | | | **Total: 63** | **Total: 299** |

In accordance with the Individual CDFE tasks specified in /2/ the several photoabsorption cross sections for Fe, Al, and Cu have been compiled and included into the new CDFE EXFOR TRANSes :

| REACTION | EXFOR SUBENT number |
|---|---|
| (13-AL-27(G,ABS),,SIG) | M0590 4 |
| (13-AL-27(G,XN),,SIG,,BRS,EXP) | M0538 2 |
| (13-AL-27(G,XN),,SIG,,BRS,EXP) | M0539 2 |
| (26-FE-0(G,ABS),,SIG,,BRS,EXP) | M0540 2 |
| (29-CU-0(G,ABS),,SIG) | M0590 5 |
| (29-CU-0(G,XN),,SIG,,BRS,EXP) | M0537 2 |
| (29-CU-0(G,XN),UNW,SIG,,BRS,EXP) | M0537 5 |
| (29-CU-0(G,XN),,SIG,,BRS,EXP) | M0541 6 |
| (29-CU-0(G,XN),,SIG,,,EXP) | M0542 2 |

**New EXFOR TRANS of Retransmitted Photonuclear Data.** CDFE TRANS M024 included pending retransmission of the number of ENTRYs from the CDFE old TRANSes M011 - M014 (TRANSes M0003 – M0340) has been produced and transmitted to the IAEA NDS. The corrections and modifications (60 DATA TABLES from 246 of 29 ENTRYs) have been done in accordance with the IAEA NDS (Dr. O.Schwerer) remarks and comments specified in the Memos CP-D/224 and CP-D/297.

**EPNDL–Evaluated PhotoNuclear Data Library.** All published data for $^{nat.,20}$Ne(γ,Xn) and $^{20,22}$Ne(γ,Xp) reactions /9 – 11/ have been analyzed and used for evaluation /12 -14/ of pure one-neutron and one-proton reactrion cross sections for both isotopes and the $^{20}$Ne(γ,np) $^{18}$F reaction cross section. The data for reactions thresholds and appropriate subtraction procedures have been used. The evaluated cross sections for $^{20,22}$Ne have been included into the preliminary version of the EPNDL3.

**Photoabsorption Reaction Cross Sections Data Collection for Future Evaluations.** The photoabsorption (or total photoneutron (γ,Xn) or (γ,Sn)) reaction cross section data collection for several highest priority elements (Be, Al, Fe, Ni, Cu, W, Pb) has been produced (about 70 data sets) for future evaluations using the available international EXFOR library and the Atlas /4/ data.

**Handbook on Photonuclear Data.** The revised CDFE contributions to the IAEA Handbook on Photonuclear Data specified in /2/ have been prepared.

The following handbook parts have been corrected and improved:
- Part 3.2. "Compiled Data";
- Part 5.1. "Evaluations Based on Experimental Data";
- Handbook Annex (the TEX version of the improved Table "Giant Dipole Resonance Parameters" of the Atlas of Photonuclear Reaction Cross Sections /4/).

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13. ***V.V.Varlamov, M.E.Stepanov***. The giant dipole resonance decay main channels analysis and photoneutron and photoproton reaction cross sections evaluation for $^{20,22}$Ne. MSU INP Preprint -99-40/598, Moscow, 1999.
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# Compilation and Evaluation of Photonuclear Data for Applications – Contract N0. 8833

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( CNDC, China Institute of Atomic Energy)

The main goals of the Coordinated Research Program are producing an IAEA Technical Document (TECDOC) on Photonuclear Data for Application and developing an IAEA Photonuclear Data Library. According to the main goals mentioned above, CNDC joined the CRP program. In this project China group has engaged in the study on the method used for producing evaluated libraries in terns of the evaluations of experimental data and theoretical calculations.

## 1 Status of activities for the CRP in CNDC

According to the contract N0.8833, the evaluation of photonuclear neutron data up to 30 MeV for $^{54,56,57,58}$Fe, $^{63,65}$Cu and $^{209}$Bi nuclides and developing code GUNF were performed, and reported in first CRP meeting in 1996.

According to the CNDC commitments, in the second period the improvement of the code GUNF and methods used for producing evaluated libraries have been performed, the recommended data for $^{180,182,183,184,186}$W , $^{90,91,92,94,96}$Zr and $^{51}$V in ENDF/B-VI format were carried out, and sent to IAEA. The comparisons with other evaluated data were given in the second CRP meeting in 1998.

The undertaken works of evaluations of $^{9}$Be,$^{27}$Al and $^{50,52,53,54}$Cr and the code GLUNF for $\gamma + {}^{9}$Be data calculation were performed in 1999. Based on the comparison in the second CRP Meeting, the re-evaluation for $^{54,56,57,58}$Fe, $^{63,65}$Cu and $^{209}$Bi have been revised and the new recommended data were issued.

The nuclides evaluated photonuclear data in CNDC under the contract N0.8833 during 3 year are as following:

$^{9}$Be, $^{27}$Al, $^{51}$V, $^{50,52,53,54}$Cr, $^{54,56,57,58}$Fe, $^{63,65}$Cu, $^{90,91,92,94,96}$Zr, $^{180,182,183,184,186}$W, $^{209}$Bi

The evaluated phptonuclear data files include ($\gamma$, n ), ($\gamma$, p ), ($\gamma$, $\alpha$ ), ($\gamma$, $^{3}$He ), ($\gamma$, d ), ($\gamma$, t ), ($\gamma$, 2n ), ($\gamma$, np ), ($\gamma$, n$\alpha$ ), ($\gamma$, pn ), ($\gamma$, 2p ), ($\gamma$, $\alpha$n ),($\gamma$, 3n ) and the outgoing particle spectra.

### 2 Analysis of Experimental Data and Theoretical Calculation

The experimental data stored in CNDC were obtained from EXFOR master file of IAEA, which was revised each half year. The various available measured data of photonuclear reaction were retrieved, collected and analyzed. These measured photonuclear reaction data are from threshold to 30 MeV for CNDC group.

In the calculation the photonuclear data, the giant dipole resonance parameters are obtained by fitting the experimental of the photoabsorption cross section in code

GUNF . Meanwhile, the neutron optical potential parameters can be obtained fitting ( $\gamma$ ,n) cross section. The optical potential parameters for particle p, $\alpha$ , $^3$He, d and t were taken from concerned references.

Using the code DREAM, a set of discrete level, pair correction parameter and level density parameters and concerned ground state mass and J $\pi$ of the levels used for theoretical calculation can be formed from Chinese Evaluated Nuclear Parameter Library (CENPL). Then the photonuclear reaction data can be calculated by the code GUNF.

The total photonuclear reaction cross section is given by the summation over every reaction channels. Since the calculated results for many channels are in pretty agreement with existed experimental data, therefore the cross sections without experimental data have been predicted.

# 3 Recommenced Photonuclear Data in ENDF/B-VI Format

At low energies (< 30 MeV), the giant-dipole resonance is the dominant excitation Mechanism, in this energy region a simple approximation of isotropy is used to the angular distribution for outgoing particles.

Beside MF=1,3,4, the MF=6 is also given by Chine group, but only spectra. Taking $\gamma+^9$Be as an example, in file-6 there are

MF=16 for ($\gamma$,2n) reaction, the spectra of neutron and $^7$Be are given;

MF=28 for ($\gamma$,np) reaction, the spectra of neutron, proton $^7$Li and gamma as well as the gamma-Multiplicity are given;

MF-29 for ($\gamma$,n2$\alpha$) reaction, the spectra of neutron and alpha-particles are given.

The check and test of the recommended data were carried out with computer programs in CNDC, including format, the consistence between the total and partial cross sections, the physics characterization and the energy balance.

# 4. Conclusion

Under Research Contract N0.8833 during 3 year, the research program was finished on time. Beside the recommended data, evaluation method, the codes GUNF for structure material nuclei. In particular a new model has been developed for light nuclei, which has been employed in the calculation of neutron and gamma induced reactions.

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# $\gamma +^9 Be$ Reactions Below 30 MeV

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# 1 Reaction Mechanism of $\gamma +^9 Be$ Reaction

At low energies below 30 MeV, the Giant-Dipole Resonance (GDR) is the dominant excitation mechanism, in this energy region a simple approximation of isotropy is used to the angular distributions for outgoing particle. Semiclassical pre-equilibrium exciton model has been proved to be powerful tool for predicting particle emission spectra. For the light nucleus, like $^9Be$ the recoil effect in multi-stage emission processes are included. The pre-equilibrium exciton model is implemented using a master equation approach, and generalized to include angular momentum and parity conservation, which allows a unified treatment of pre-equilibrium and equilibrium emission. The pick-up mechanism for cluster emissions are also included.

In view of $\gamma +^9 Be$ reactions for $E_\gamma \leq 30\ MeV$ the reaction channels are listed as the follows

$$\gamma +^9 Be = \begin{cases} \gamma +^9 Be & \text{Q= 0.0 MeV} \\ n' +^8 Be & \text{Q=-1.665 MeV} \\ p +^8 Li & \text{Q=-16.886 MeV} \\ \alpha +^5 He & \text{Q=-2.467 MeV} \\ ^3He +^6 He & \text{Q=-21.175 MeV} \\ d +^7 Li & \text{Q=-16.695 MeV} \\ t +^6 Li & \text{Q=-17.688 MeV} \\ 2n +^7 Be & \text{Q=-20.563 MeV} \\ n, p +^7 Li & \text{Q=-18.919 MeV} \\ n, \alpha + \alpha & \text{Q=-1.523 MeV} \\ p, n +^7 Li & \text{Q=18,919 MeV} \end{cases}$$

The $(\gamma,^3 He)$ reaction is caused by emitting a $^3He$ to the ground state of $^6He$, while the excited levels of $^6He$ will decay into $n + n + \alpha$ by three body break-up process. Reaction mechanism in the $\gamma +^9 Be$ system leading to decay into one neutron and two $\alpha$ particles may proceed via a number of different reaction channels, as two body break-up process or three body break-up process, the different approach strongly differs each other in their respective neutron and $\alpha$ particle energy spectra. The reaction channels to $^9Be(\gamma, n)2\alpha$ channel involved in the calculation are as follows:

(a) $\gamma +^9 Be \rightarrow n +^8 Be^* \ (\alpha + \alpha)$
(b) $\gamma +^9 Be \rightarrow \alpha +^5 He^* \ \ (n + \alpha)$
(c) $\gamma +^9 Be \rightarrow n, \alpha$

The discrete level scheme of every reaction channels at $E_\gamma \leq 30$ MeV are taken from the "Table of Isotopes" 1996[1].

The neutron production reaction channels include $\gamma +^9 Be$ at $E_\gamma \leq 30$ MeV include $(\gamma, n2\alpha)$, $(\gamma, 2n\alpha)^3He$, $(\gamma, 2np)^6Li$, $(\gamma, nd)^6Li$ channels and output in ENDF-BVI format.

The reaction situation from the compound nucleus $^9Be^*$ to the discrete levels of the residual nuclei up to $E_\gamma = 30\ MeV$ is presented In Table I. $E_{th}$ refers to the threshold energy to open the $k_2$ level of the residual nucleus via $k_1$ level.

From Table I one can see that all of the excited levels of $^9Be$ can emit secondary particles, therefore $(\gamma, n\gamma)$ reaction channel is always small enough to be omitted.

Following the first proton emission the residual nucleus is $^8Li$. The ground state of $^8Li$ becomes into $^8Be$ through $\beta^-$ decay, while the excited states of $^8Li$ can emit neutron and becomes into $^7Li$. The $^3He$ emission results the residual nucleus $^6He$, the ground state of which becomes to be $^6Li$ through $\beta^-$ decay, while the excited state of $^6He$ undergoes the three-body breakup process to $n + n + \alpha$. The residual nucleus of $(\gamma, 2n)$ reaction channel is $^7Be$, which becomes $^7Li$ through EC with $T_{\frac{1}{2}} = 53.29\ d$. The residual nucleus $^5He$ of $(\gamma, \alpha)$ reaction channel is separated spontaneously into $n + \alpha$.

Table I. The reaction situation from the compound nucleus $^{9}Be^{*}$ to the discrete levels of the residual nuclei from $(\gamma, 2n)$, $(\gamma, np)$, $(\gamma, n\alpha)$, and $(\gamma, pn)$ reactions up to $E_\gamma = 30\ MeV$

| | $E_{th}^{a}$ | $k_1$ | $k_2$ | | $E_{th}$ | $k_1$ | $k_2$ |
|---|---|---|---|---|---|---|---|
| $(\gamma, 2n)$ | 20.58 | 7 | gs[b] | $(\gamma, 2n)$ | 20.74 | 8 | gs |
| $(\gamma, 2n)$ | 20.91 | 9 | gs | $(\gamma, 2n)$ | 21.07 | 10 | gs |
| $(\gamma, 2n)$ | 21.53 | 11 | gs | $(\gamma, 2n)$ | 21.77 | 12 | gs |
| $(\gamma, 2n)$ | 21.87 | 13 | gs | $(\gamma, 2n)$ | 22.57 | 14 | gs |
| $(\gamma, 2n)$ | 23.37 | 15 | gs | $(\gamma, 2n)$ | 23.67 | 16 | gs |
| $(\gamma, 2n)$ | 23.72 | 17 | gs | | | | |
| $(\gamma, np)$ | 19.31 | 5 | gs | $(\gamma, np)$ | 19.82 | 6 | gs - 1 |
| $(\gamma, np)$ | 20.58 | 7 | gs - 1 | $(\gamma, np)$ | 20.74 | 8 | gs - 1 |
| $(\gamma, np)$ | 20.91 | 9 | gs - 1 | $(\gamma, np)$ | 21.07 | 10 | gs - 1 |
| $(\gamma, np)$ | 21.53 | 11 | gs - 1 | $(\gamma, np)$ | 21.77 | 12 | gs - 1 |
| $(\gamma, np)$ | 21.87 | 13 | gs - 1 | $(\gamma, np)$ | 22.57 | 14 | gs - 1 |
| $(\gamma, np)$ | 23.37 | 15 | gs - 1 | $(\gamma, np)$ | 23.67 | 16 | gs - 2 |
| $(\gamma, np)$ | 23.72 | 17 | gs - 2 | | | | |
| $(\gamma, n\alpha)$ | 4.705 | 1 | gs | $(\gamma, n\alpha)$ | 13.07 | 2 | gs |
| $(\gamma, n\alpha)$ | 13.07 | 3 | gs | $(\gamma, n\alpha)$ | 18.29 | 4 | gs |
| $(\gamma, n\alpha)$ | 19.31 | 5 | gs | $(\gamma, n\alpha)$ | 19.82 | 6 | gs |
| $(\gamma, n\alpha)$ | 20.58 | 7 | gs | $(\gamma, n\alpha)$ | 20.74 | 8 | gs |
| $(\gamma, n\alpha)$ | 20.91 | 9 | gs | $(\gamma, n\alpha)$ | 21.07 | 10 | gs |
| $(\gamma, n\alpha)$ | 21.53 | 11 | gs | $(\gamma, n\alpha)$ | 21.77 | 12 | gs |
| $(\gamma, n\alpha)$ | 21.87 | 13 | gs | $(\gamma, n\alpha)$ | 22.57 | 14 | gs |
| $(\gamma, n\alpha)$ | 23.37 | 15 | gs | $(\gamma, n\alpha)$ | 23.67 | 16 | gs |
| $(\gamma, n\alpha)$ | 23.72 | 17 | gs | | | | |
| $(\gamma, pn)$ | 19.16 | 2 | gs | $(\gamma, pn)$ | 20.12 | 3 | gs - 1 |
| $(\gamma, pn)$ | 22.31 | 4 | gs - 1 | $(\gamma, pn)$ | 23.01 | 5 | gs - 1 |
| $(\gamma, pn)$ | 23.45 | 6 | gs - 1 | $(\gamma, pn)$ | 24.91 | 7 | gs - 1 |

[a] The term $E_{th}$ refers to the threshold energy needed to open the $k_2$ level of the residual nucleus via $k_1$ level.
[b] The acronym $gs$ refers to ground state.

The formulation of the double differential cross sections from discrete levels to discrete levels of sequential two-body reactions, three-body breakup process and the double differential cross section of cluster separation can be found in Refs 2 and 3.

The residual nuclei $^8Be$ and $^5He$ are unstable and separated into two clusters spontaneously. For instance $^8Be \rightarrow \alpha + \alpha$, with $Q$=0.092 $MeV$, $^5He \rightarrow \gamma + \alpha$, with $Q$=0.894 $MeV$, respectively.

## 2 Results and Summary

The GLUNF code is developed for calculating the interrelated data below 30 MeV. The physical quantities calculated numerically by GLUNF code contain:

1. photoabsorption cross sections;
2. all kinds of reaction cross sections with different reaction mechanism and energy spectra of outgoing particles, like neutron, proton, $\alpha$ particle, triton and deuteron;
3. the energy spectra of outgoing particles from each reaction channel.
4. the total neutron spectrum of the emitted neutron.
5. outputting the data in ENDF/B-VI format.

The model has been used for calculating the cross sections of $\gamma +^9 Be$ reactions. The plotting of the $(\gamma, abs)$, $(\gamma, 2n)$ and $(\gamma, n + np + 2n)$ evaluated cross sections are shown through Fig.1 to 4, the experimental data are taken from Refs. 4 through 9. All of the comparisons between the experimental data and the calculated results are in good fitting. The plotting of every reaction channels is shown in Fig.5.

Lack of the experimental data on energy spectrum, so that this kind of plotting is not given.

In this model the sequential two-body emisions, two-body separation reactions and three-body breakup process are included, from which the different respective energy spectra are obtained as the components of the total energy spectrum of the outgoing particles.

The $E_1$, $M_1$ and $E_2$ mechanism are taken into account for $\gamma$ emission in pre-equilibrium and equilibrium processes. For light nucleus the direct emissions are not included, due to very small contribution at low energies.

The equilibrium mechanism and pre-equilibrium mechanism are involved in the model calculations. The pre-equilibrium mechanism plays important role in $\gamma +^9 Be$ reactions.

The new model for photonuclear light nucleus reactions has been proposed. The initial nuclear excitation can be understood in terms of particle-hole excitations (1p1h) for GDR. The key point in this model is the description of the particle emissions between discrete levels in both equilibrium state and pre-equilibrium state. The pre-equilibrium emission mechanism dominates the reaction processes.

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# The Present Status of JENDL Photonuclear Data File

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Evaluation task of photonuclear reaction cross sections is in progress as an activity under JNDC Photonuclear Data File Compilation Sub-Working Group which was organized in 1991. The goal of this working group is to construct an evaluated photonuclear reaction data file. The evaluated data is stored using ENDF6 high-energy format. The data file contains absorption, particle production and nuclide production cross sections up to 140 MeV, which is approximately corresponding to the threshold energy of $(\gamma,\pi)$ reactions. In addition, energy-angle double differential cross sections of emitted particles are stored.

The photoabsorption and photoneutron cross sections in the giant dipole resonance(GDR) energy region are evaluated using measured data. Since there exists great difference in absolute values as well as resonance shapes between the measured cross sections using the quasi mono-energetic photons and those using the bremsstrahlung photons, most evaluators of the group mainly adopts the former cross sections. The photoabsorption cross sections in energy above the GDR region are theoretically evaluated by employing a quasi-deuteron model cross sections.

From the viewpoint of a microscopical nuclear theory, the excitation process of GDR through photoabsorption is considered as production process of a particle–hole excited state. The quasi-deuteron model assumes that the incident photon excites one neutron and one proton above the Fermi energy and leaves two holes. It is therefore thought that the exciton plus evaporation model can describe the de-excitation process of the photonuclear reaction. Thus the energy spectra and nuclide production cross sections can be obtained from exciton-evaporation theoretical model codes if we have evaluated photoabsorption cross sections. However, we can scarcely obtained those cross sections for the lack of the measured data. On the other hand, since there exists many measured photoneuton cross sections, the evaluated photoneutron data can be determined comparatively easy. Hence, we derived photoabsorption cross sections from evaluated photoneutron crossections and reaction branching ratios to be caculated with some exciton-evaporation model codes. Enery-angle double differential cross sections of emission particles were evaluated using Chadwick's systematics.

At present, we have evaluated the cross sections for D, $^{9}$Be, $^{12}$C, $^{14}$N, $^{16}$O, $^{23}$Na, $^{24,\,25,\,26}$Mg, $^{27}$Al, $^{28,\,29,\,30}$Si, $^{40,\,48}$Ca, $^{46,\,48}$Ti, $^{51}$V, $^{52}$Cr, $^{55}$Mn, $^{54,\,56}$Fe, $^{59}$Co, $^{58,\,60}$Ni, $^{63,\,65}$Cu, $^{64}$Zn, $^{90}$Zr, $^{92,\,94,\,96,\,98,\,100}$Mo, $^{93}$Nb, $^{133}$Cs, $^{181}$Ta, $^{182,184,186}$W, $^{197}$Au, $^{206,\,207,\,208}$Pb, $^{209}$Bi and $^{235,\,238}$U.

# Photo-reaction Evaluation Methodology for Light Nuclei in JENDL*
# ( $^{2}D$,$^{9}Be$,$^{12}C$,$^{14}N$ and $^{16}O$ )

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Abstract

Photo-reaction nuclear data for $^{2}D$,$^{9}Be$,$^{12}C$,$^{14}N$ and $^{16}O$ have been evaluated in the incident photon energy range from particle emission threshold to 140 MeV, by analyzing experimental data with theoretical models.

For $^{2}D$, theoretical model given by Marshal and Guth /1/ was applied in the low energy region below 10 MeV. In the high energy region, results of theoretical calculation by Partovi /2/ were adopted.

For $^{12}C$,$^{14}N$ and $^{16}O$, experimental cross sections of photo-absorption, photo-neutrons, photo-protons and so on were analyzed with a resonance formula /3/ plus the quasi-deuteron model /4/. Resonance parameters were determined to reproduce the experimental cross section in some consistent manner. For the cross sections which experimental data were not available, systematic estimation was made among cross sections of these nuclides. Energy spectra and angular distributions of emitted particles (n,p,d,t,$^{3}$He and alpha-particle) were calculated with a statistical multi-step code EXIFON /5/ modified to include photo-reaction and d,t, $^{3}$He emission /6/.

For $^{9}Be$, emission cross sections of 1n,2n,3n,1p,1d,1a and p.n were evaluated with the almost same method for that of $^{12}C$,$^{14}N$ and $^{16}O$. But, triton,$^{3}$He and alpha particles were assumed to be emitted by the break-up reaction of the nuclides produced by the first chance reactions. The latter emission cross sections were estimated with the branching ratios and the first chance emission cross sections. The branching ratios were calculated with a simple statistical model.

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( *Work performed as a part of JNDC Photo-Reaction Evaluation Working Group )

# High-resolution Spectroscopy for Photo-absorption Cross Sections using HHS and LCP

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Fine structures in photonuclear reactions are important quantities for the investigation of the innovative applications of photonuclear reactions because the photonuclear cross sections of some special states are expected to have huge values that are comparable to the photo-atomic cross sections. However, very little is known about the fine structures neither experimentally nor theoretically.

Nuclear photoabsorption (NPA) spectroscopic method is an ideal tool to investigate photonuclear reactions. The measurement gives the cross section of the total photonuclear reaction that is the sum of all the at-induced reaction channels. The NaI scintillation spectrometer, $LD_2$/TOF spectrometer or the magnetic spectrometer has been applied for the photon absorption measurements.[1,2,3] However, the energy resolving power of these spectrometers were about a few percent, and were not enough to investigate fine structures in photonuclear reactions.

Recent progress on Ge detector fabrication technologies makes it possible to develop a high-resolution high-energy photon spectrometer (HHS)[4] (Fig. 1) with an excellent energy resolution of about 0.1% for high-energy photons, typically 10-30 MeV, with which NPA method can achieve a high resolution. As a result the fine structure in photonuclear reaction can be studied up to about 30 MeV.

The beam of laser Compton photon (LCP)[5] is now strong enough to be used in NPA experiments. The use of LCP overcomes the inherent disadvantage of the use of bremsstrahlung, that is, its high background, especially at the low energy side. The low energy tail of the LCP beam is cut off with a collimator since the energy of LCP is determined by LCP's scattering angle.

The experimental technique of NPA using HHS and LCP has been developed for several years,[6] and recently the energy resolving power of 0.1% has been successfully demonstrated.[7] The progress of the new spectroscopic method was briefly reviewed.

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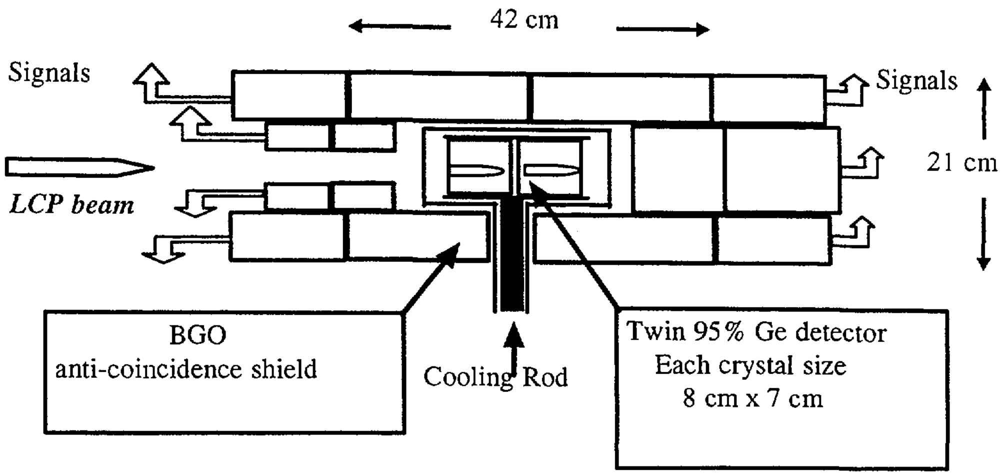


**Fig. 1** A schematic representation of the High-energy Photon Spectrometer.

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