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# EVALUATION AND IMPROVEMENT OF CROSS SECTION ACCURACY FOR MOST IMPORTANT DOSIMETRY REACTIONS 27Al(n,p), 56Fe(n,p) AND 237Np(n,f) INCLUDING COVARIANCE DATA

**K.I.Zolotarev**

Institute of Physics and Power Engineering, Obninsk, Russia

*Progress Report on Research Contract No 11372/RB/R1*

February 2004

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# EVALUATION AND IMPROVEMENT OF CROSS SECTION ACCURACY FOR MOST IMPORTANT DOSIMETRY REACTIONS 27Al(n,p), 56Fe(n,p) AND 237Np(n,f) INCLUDING COVARIANCE DATA

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## Abstract

New evaluations of cross sections and their uncertainties for dosimetry reactions $^{27}$Al(n,p), $^{56}$Fe(n,p) and $^{237}$Np(n,f) have been carried out in the frame work of IAEA Research Contract No. 11372/RB. Data files prepared for this reactions in the ENDF-6 format may be consider as candidates for the new International Reactor Dosimetry File: IRDF-2002.

February 2004

**Contents**

## 1. Introduction

The activation detectors on the basis of $^{27}Al(n,p)^{27}Mg$, $^{56}Fe(n,p)^{56}Mn$ and $^{237}Np(n,f)$ reactions are commonly used in the reactor dosimetry and neutron metrology. The Aluminium-27, Iron-56 and Neptunium-237 activation detectors are usually used for neutron spectrum determination in the critical assemblies and power reactors. In the neutron spectrum unfolding procedure measured reaction rates of $^{237}Np(n,f)$, $^{27}Al(n,p)^{27}Mg$, $^{56}Fe(n,p)^{56}Mn$ reactions giving information about the components of flux above 0.5 MeV, 1.9 MeV and 3.0 MeV, respectively. In addition to the reactor dosimetry application reactions $^{27}Al(n,p)^{27}Mg$ and $^{56}Fe(n,p)^{56}Mn$ are very often used in the experimental nuclear physic as the monitor reactions for measurements of unknown cross sections by means of activation method in the neurone energy interval (13 – 15) MeV.

Evaluated excitation functions for above mention dosimetry reactions up to 20 MeV are given in the International Reactor Dosimetry File (IRDF-90 ver.2) [1] and in the national dosimetry libraries.

Cross section data for $^{27}Al(n,p)^{27}Mg$ reaction in the IRDF-90 ver.2 file (MAT 1325) were evaluated by D.Hetric and C.Y.Fu in 1989. The similar cross section data in the Japanese Reactor Dosimetry File – JENDL/D-99 (MAT 1325) [2] were evaluated by K.Kobayashi and Y.Uno in March 1996. In the both evaluations were used only original experimental data - not corrected to the new recommended standards. Evaluation prepared by D.Hetric and C.Y.Fu was based on the experimental cross section data obtained up to 1989 year. In the dosimetry file JENDL/D-99 authors of evaluation didn't took into account the results of absolute precise measurements of Ikeda et al. in the energy range (13.32 – 14.90) MeV [3] as well as the results of new measurements of Filatenkov et al. [4], Csikai et al. [5] and Fessler [6] for the incident neutron energies (13.47 – 14.81) MeV, (7.57 – 14.70) MeV and (16.01 – 20.17) MeV, respectively.

Cross section data for $^{56}Fe(n,p)^{56}Mn$ reaction in the IRDF-90 ver.2 file (MAT 2631) were taken from ENDF/B-VI library. Evaluation was carried out by D.Hetric and C.Y.Fu in 1989. The similar cross section data in the Japanese Reactor Dosimetry File – JENDL/D-99 (MAT 2631) [2] were evaluated by S.Iijima and H.Yamakoshi in March 1987. In the process of evaluation D.Hetric and C.Y.Fu renormalized experimental data to the ENDF/B-VI standards. In the JENDL/D-99 evaluation authors used only original experimental data. In the both evaluations authors couldn't took into account experimental data of Mannhart and Boerker in the energy range (9.10 – 14.64) MeV [8], the results of absolute precise measurements of Ikeda et al. in the energy interval (13.57 – 14.91) MeV [3], experimental cross section data of Bao Zongyu et al. for the 14.57 MeV neutrons [9] and Lu Hanlin et al. for the (14.0 – 19.1) MeV neutrons [10] as well as the results of new measurements of Filatenkov et al. in the energy range (13.56 – 14.78) MeV [4] and Fessler in the energy range (16.04 – 20.36) [7]. It is necessary to note that the uncertainty information for the cross sections given in the JENDL/D-99 (MAT 2631) for $^{56}Fe(n,p)^{56}Mn$ reaction was taken from IRDF-85 dosimetry file.

Cross section data for $^{237}Np(n,f)$ reaction in the IRDF-90 ver.2 file were taken from ENDF/B-V library. Evaluation was carried out by F.Mann et al. in April 1978. The $^{237}Np$ fission cross sections in the Japanese Reactor Dosimetry File – JENDL/D-99 (MAT 9346) [2] were evaluated by K.Kobayashi in April 1996. The ENDF/B-V evaluation was carried out on the basis of experimental data obtained up to 1978. The JENDL/D-99 evaluation not take into account the experimental data of Lisowski et al. [11], Lisowski et al. [12], Carlson et al. [13] and Goverdovskij et al. [14] obtained for the incident neutron energies (1.00 –19.86) MeV, (1.00 - 1.99) MeV, (1.02 – 2.00) MeV and (3 – 360) eV, respectively. In the both evaluations were used only original experimental data.

This report devoted to the preparation of the new evaluations of cross sections data and related covariance matrixes of uncertainties for above mentioned dosimetry reactions.

Detailed description of all procedures evaluation is given in the report. New evaluations of cross sections and their uncertainties for dosimetry reactions $^{27}Al(n,p)^{27}Mg$, $^{56}Fe(n,p)^{56}Mn$ and $^{237}Np(n,f)$ have been carried out in the frame work of IAEA Research Contract No. 11372/RB/R1. Prepared for this reactions data files in the ENDF-6 format may be consider as candidates to the new International Reactor Dosimetry File: IRDF-2002.

## 2. Method of evaluation of dosimetry reactions excitation functions

### 2.1 The sources of information used in the evaluation

In the process of evaluations cross sections and their uncertainties two common information sources were used for dosimetry reactions $^{27}Al(n,p)^{27}Mg$, $^{56}Fe(n,p)^{56}Mn$ and $^{237}Np(n,f)$ : available differential and integral experimental data. In addition to this two sources for evaluation fission cross section for Np-237 results of the theoretical model calculations was used also. Resonance parameters used for calculation $^{237}Np(n,f)$ reaction excitation function in the resolved resonance region were evaluated on the basis the data given in the compilations of S.F.Mughabghab [1] and S.I.Sukhoruchkin [2].

Differential and integral experimental data were taken mainly from EXFOR Library (Version May 2002). In the cases then the data were absent in the EXFOR, information were taken from the original publications.

### 2.2 Analysis of experimental data

In the first step of evaluation all experimental data were analyzed. During this procedure all experimental data if it was possible were corrected to the new recommended cross section data for monitor reactions used in the measurements and to the new recommended decay data. Correction of experimental data to the new standards lead in generally to decreasing the discrepancies in the experimental data and thus to decreasing the uncertainty in the evaluated cross section values. The needed information about standards used for correction experimental data under investigation given in the Table 1. Recommended cross section data for monitor reactions and $^{237}Np(n,f)$ reaction at the neutron energy $E_n$=0.0253 eV were taken from recent compilation [20].

### 2.3 Theoretical model calculation cross section values for the dosimetry reactions

For theoretical description of excitation functions $^{237}Np(n,f)$ dosimetry reaction optical-statistical method was used with taking into account consistently the contribution of the direct, preequilibrium and statistical equilibrium processes into different outgoing channels.

The practical calculations of cross sections were made by means of modified version of the GNASH code [21]. Modified GNASH code differ in general from original GNASH code [22] with having a subroutine for calculations of width fluctuation correction.

The calculation of penetrability coefficients for neutrons was made on the basis of generalized optical model, which permits to estimate the cross sections for the direct excitations of collective low-lying levels. The ECIS coupled channel deformed optical model code [23] was used for this calculations. The optical coefficients of proton and alpha particles penetrabilities were determined by means of the SCAT2 code [24].

By means of the modified GNASH code cross sections for $^{237}Np(n,f)$ reaction were calculated in the neutron energies range 12 - 20 MeV.

## 3. The evaluation of the Al-27(n,p)Mg-27 reaction excitation function

The abundance of the $^{27}Al$ isotope in the natural aluminium is equal to 100 atom percent [86].

The half-live of $^{27}Mg$ is equal to (9.458±0.012) Minutes. Nucleus $^{27}Mg$ has 100% β- decay mode. For determination of $^{27}Al(n,p)^{27}Mg$ reaction rate it is usually measured the activity

**Table 1. THE DATA USED AS STANDARDS FOR CORRECTIONS OF MICROSCOPIC EXPERIMENTAL CROSS SECTIONS OF $^{27}$Al(n,p)$^{27}$Mg, $^{56}$Fe(n,p)$^{56}$Mn and $^{237}$Np(n,f) REACTIONS**

| Monitor Reaction | Cross sections used as standards | Half-life for residual nucleus | Radiation Mode and Energy | Emission Probability |
|---|---|---|---|---|
| $^{1}$H(n,n)$^{1}$H | ENDF/B-VI [3] | | | |
| $^{6}$Li(n,t)$^{4}$He | ENDF/B-VI [4] | | | |
| $^{27}$Al(n,p)$^{27}$Mg | Zolotarev+ 03 [5] | 9.458 (12) M | Gamma 843.7 keV<br>Gamma 1014.44 keV | 0.718 ( 4) [17]<br>0.280 ( 4) [17] |
| $^{27}$Al(n,α)$^{24}$Na | Zolotarev+ 03 [6] | 0.62356 (17) D | Gamma 1368.633 keV | 0.999926(15) [18] |
| $^{28}$Si(n,p)$^{28}$Al | JENDL-3.2 [7] | | | |
| $^{30}$Si(n,α)$^{27}$Mg | Janczyszyn [8] | 9.458 (12) M | Gamma 843.7 keV<br>Gamma 1014.44 keV | 0.718 ( 4) [17]<br>0.280 ( 4) [17] |
| $^{32}$S(n,p)$^{32}$P | IRDF-90v.2 [9] | 14.262 (14) D | Beta- 1710.6 keV | 1.000 [18] |
| $^{56}$Fe(n,p)$^{56}$Mn | Zolotarev+ 02 [10] | 2.5785 ( 2) H | Gamma 846.754 keV<br>Gamma 1810.72 keV | 0.9887 ( 3) [17]<br>0.2719 (79) [17] |
| $^{63}$Cu(n,2n)$^{62}$Cu | Ryves 89 [11] | 9.73 ( 2) M | Beta+ 2925.8 keV<br>Gamma 511 keV | 0.9720 ( 2) [18]<br>1.9486 ( 5) [18] |
| $^{65}$Cu(n,2n)$^{64}$Cu | Ryves 89 [11] | 12.700 ( 2) H | Gamma 511 keV<br>Beta+ 653.1 keV<br>Beta- 578.7 keV | 0.343 [19]<br>0.174 ( 2) [18]<br>0.390 ( 3) [18] |
| $^{93}$Nb(n,2n)$^{92m}$Nb | RRDF-98 [12] | 10.15 ( 2) D | Gamma 934.44 keV | 0.9907 ( 4) [17] |
| $^{115}$In(n,n')$^{115m}$ In | Zolotarev+ 03 [13] | 4.486 ( 4) H | Gamma 336.241 keV | 0.459 (1) [17] |
| $^{235}$U(n,f) | ENDF/B-VI [14] | | | |
| $^{238}$U(n,f) | ENDF/B-VI [15] | | | |
| $^{239}$Pu(n,f) | JENDL-3.2 [16] | | | |

For Beta- and Beta+ transitions the max. energies are given.

corresponding to the most intensive gamma-ray lines: 843.76-keV ($I_\gamma$=0.718 ± 0.004) and 1014.44 keV ($I_\gamma$=0.280 ± 0.004). Recommended values of $^{27}$Mg half-life and gamma-rays emission probability per decay -$I_\gamma$ were taken from [77].

Excitation function of the $^{27}$Al(n,p)$^{27}$Mg reaction was evaluated for the energies of incident neutrons from threshold ($E_{th}$=1.89637 MeV) to 23 MeV

It was analysed 76 works on measurement of the $^{27}$Al(n,p)$^{27}$Mg reaction cross sections, which were carried out in the period from 1952 to 2000 years. Brief description of these experiments is given in Table 2.

Microscopic experimental data [1-76] were analyzed in the process of preparation of input data base for the evaluation of cross sections and their uncertainty for the $^{27}$Al(n,p)$^{27}$Mg reaction. During this procedure all experimental data if it was possible were corrected to the new recommended cross section data for monitor reactions used in the measurements (Table 1.) and to the recommended decay data from ref. [77].

Data base for the evaluation Al-27(n,p)Mg-27 reaction excitation function in the energies region from threshold to 23.0 MeV was formed from microscopic experimental data [1-58].

Experimental data [4], [7], [9], [11], [13-14], [16-27], [29-30], [33-36], [38], [40-41], [46], [48-53], [55-56] and [58] were corrected to the new standards.

Special correction was done with experimental data [3], [8], [12], [13], [15], [17], [27], [28], [47] and [58].

Experimental data of Hudson and Morgan [3], Gabbard et al.[8], Ferguson and Albergotti [15], Cuzzocrea et al. [17], Csikai and Chimoe et al. [47] were renormalized to the results of precise absolute measurements of Ikeda et al.[53] in the overlapping energy ranges. Correction factors for the experimental data [3], [8], [15], [17] were Fc=0.87555, Fc=1.41467, Fc=1.60840, Fc=0.89474, respectively. Data of independent measurements of Csikai and Chimoe et al. [47] were multiplied to the coefficients Fc=0.89370 and Fc=0.92320, respectively. Original and corrected experimental data [3], [8], [15], [17], [47] in a comparison with results of precise absolute measurements of Ikeda et al. [53] are given in Fig.1a and Fig.1b, respectively.

Cross sections for the Al-27(n,p)Mg-27 reaction measured by Bass et al. [12] in the neutron energy range 6.00 - 9.00 MeV with 25 keV step were recalculated by averaging original experimental data over 100 keV energy intervals.

Experimental data of Calvi et al. [13] and Shimizu et al.[58] were corrected to the results of Smith and Meadows measurements [27] with Li-7(p,n)Be-7 neutron source in the overlapping energy intervals. Correction factors were Fc=0.96506 and Fc=1.47768, respectively. For the experimental data [58] value Fc=1.47768 is a total correction factor. At the first step of correction data of Shimizu et al. [58] were renormalized to the new evaluated cross sections for the monitor reaction In-115(n,n')In-115m [78].

Data of Smith and Meadows [27] measured with using neutrons from D(d,n)He3 reaction were renormalized to the results of this experiment obtained with Li-7(p,n)Be-7 neutron source in the overlapping interval 5.398 - 5.870 MeV. D(d,n)He3 data in the energy range 5.398 - 9.897 MeV were increased to the factor Fc=1.08300.

Data given in ref. [28] by Mostafa were renormalized to the absolute cross section value for $^{27}$Al(n,p)$^{27}$Mg reaction evaluated at 7.1 MeV with taking into account experimental data [12], [14] and [27].

The influence of above mentioned corrections applied to the experimental data [27] and [28] is demonstrated on Fig.2a and Fig.2b. Experimental data [13], [27], [28] and both data from ref. [47] plotted on Fig.2a are the original experimental data given by authors. Corrected experimental data [27] and [28] and renormalized to the new standards experimental data [13], [27] are given on Fig.2b. Experimental data of Bass et al. [12] are presented on the both Figs. in the form of the averaged cross sections recalculated from the original data given in the 120 energy points. Comparison of the cross sections given in Fig.1a, Fig.1b and Fig.2a, Fig.2b show that the discrepancies between experimental are significantly decrease after the applied correction and renormalization of the original experimental data.

## TABLE 2. SUMMARY OF EXPERIMENTS FOR THE REACTION Al27(n,p)Mg27

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference | | |
|---|---|---|---|---|---|---|
| 14.10 | 1 | Activation method, Beta | Al27(n,a)Na24 | Forbes | 52 | [ 1] |
| 14.50 | 1 | Activation method, Beta | Long boron counter | Paul+ | 53 | [59] |
| 2.74 - 5.18 | 37 | No information | No information | Henkel | 54 | [ 2] |
| 14.10 | 1 | Act. method, end window Geiger- Mueller counter, Beta | Associated alpha T(d,n) | Yasumi | 57 | [60] |
| 13.20 | 1 | Track det., det. of emitted protons | H-1(n,n)H-1 | Brown+ | 57 | [61] |
| 15.00 | 1 | Activation method | Al27(n,p)Mg27 norm. at 4.60 MeV | Hudson+ | 59 | [ 3] |
| 13.03 - 17.06 | 28 | Activation method | Al27(n,p)Mg27 norm. between 13.3 –15.4 MeV | Hudson+ | 59 | [ 3] |
| 13.30 - 15.40 | 3 | Activation method | No information | Hudson+ | 59 | [ 3] |
| 14.80 | 1 | Act. method, Beta | Cu63(n,2n)Cu62 | Poularikas+ | 59 | [62] |
| 15.00 | 1 | Act. method, prop. counter, Beta | Cu63(n,2n)Cu62 | Depraz+ | 60 | [ 4] |
| 11.92 - 20.72 | 17 | Act. method, NaI(Tl) det., Gamma | Al27(n,p)Mg27 norm. at 14.00 MeV | Mani+ | 60 | [ 5] |
| 14.00 | 1 | Act. method, Geiger-Mueller counter, Beta- | Fe56(n,p)Mn56 | Khurana+ | 60 | [63] |
| 14.10 | 1 | CsI(Tl) det., det. of emitted proton | H-1(n,n)H-1 | Storey+ | 60 | [64] |
| 14.10 | 1 | Act. method, Beta | Associated alpha particles | Sakisaka+ | 61 | [65] |
| 14.10 | 1 | Act. method, NaI(Tl) det., Gamma | Long counter | Pollehn+ | 61 | [ 6] |
| 14.80 | 1 | Act. method, end window Beta counter | Al27(n,a)Na24 | Mukherjee+ | 61 | [ 7] |
| 14.70 | 1 | Act. method, Beta and Gamma | Cu63(n,2n)Cu62 | Kantele+ | 62 | [66] |
| 13.40 - 14.20 | 3 | Act. method, Beta and Gamma | Cu63(n,2n)Cu62 | Kantele+ | 62 | [66] |
| 14.10 | 1 | Act. method, NaI(Tl) det., Gamma | No information | Langmann | 62 | [67] |
| 14.40 | 1 | Cross section obtained from integrated angular distribution | H-1(n,n)H-1 | Hassler+ | 62 | [68] |
| 12.40 - 17.70 | 13 | Act. method, NaI(Tl) det., Gamma | Al27(n,p)Mg27 norm. at 14.40 MeV | Gabbard+ | 62 | [ 8] |
| 14.60 | 1 | Act. method, Geiger-Mueller counter, Beta | Al27(n,a)Na24 | Csikai+ | 62 | [ 9] |
| 14.70 | 1 | Act. method, Geiger-Mueller counter, Beta | Associated alpha particles | Bonazzola+ | 64 | [10] |
| 14.70 | 1 | Act. method, NaI(Tl) det., Gamma | Al27(n,a)Na24 | Strain+ | 65 | [11] |
| 6.00 - 9.00 | 120 | Act. method, NaI(Tl) det., Beta and Gamma | H-1(n,n)H-1 | Bass+ | 66 | [12] |

**Table 2. SUMMARY OF EXPERIMENTS FOR THE REACTION Al27(n,p)Mg27 (continued)**

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference | | |
|---|---|---|---|---|---|---|
| 2.62 - 5.10 | 49 | Act. method, Geiger-Mueller counters, Beta | Al27(n,p)Mg27 norm. between 4.5 – 5.0 MeV | Calvi+ | 66 | [13] |
| 14.80 | 1 | Act. method, Beta and Gamma | Cu63(n,2n)Cu62 | Mitra+ | 66 | [69] |
| 2.44 - 14.10 | 12 | Act. method, Prop. gas counters, Beta | Al27(n,p)Mg27 U238(n,f)FP | Grundl | 67 | [14] |
| 12.35 - 13.89 | 40 | Act. method, NaI(Tl) det., Gamma | Al27(n,p)Mg27 norm. to integral between 12.35 – 13.89 MeV | Ferguson+ | 67 | [15] |
| 14.40 | 1 | Act. method, Gamma | Fe56(n,p)Mn56 | Ranakumar+ | 68 | [16] |
| 13.70 - 14.67 | 27 | Act. method, Geiger-Mueller counter, Beta | Cu63(n,2n)Cu62 norm. at 14.11 MeV | Cuzzocrea+ | 68 | [17] |
| 14.20 | 1 | Act. method, NaI(Tl) det., Gamma | Al27(n,a)Na24 | Tiwari+ | 68 | [18] |
| 14.20 | 1 | Act. method, NaI(Tl) det., Gamma | Al27(n,a)Na24 | Rama Prasad+ | 69 | [19] |
| 14.80 | 1 | Act. method, Ge(Li) det., Gamma | Fe56(n,p)Mn56 | Husain+ | 70 | [20] |
| 14.70 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Schantl | 70 | [21] |
| 14.80 | 1 | Act. method, Ge(Li) det., Gamma | Associated alpha particles | Salaita | 71 | [22] |
| 14.80 | 1 | Act. method, NaI(Tl) det., Gamma | Fe56(n,p)Mn56 | Prasad+ | 71 | [70] |
| 4.30 - 5.27 | 18 | Act. method, 4PI Beta-Gamma coincidence | H-1(n,n)H-1 | Robertson+ | 72 | [71] |
| 14.10 | 1 | Act. method, Prop. counter, Beta | Al27(n,a)Na24 norm. at 14.10 MeV | Mogharrab+ | 72 | [23] |
| 8.00 - 9.30 | 4 | Act. method, 4PI prop. counter, Beta | U238(n,f)FP | Nemilov+ | 72 | [24] |
| 14.60 | 1 | Act. method, NaI(Tl) det., Gamma | Fe56(n,p)Mn56 | Dresler+ | 73 | [25] |
| 14.78 | 1 | Act.method, 4PI Beta-Gamma coincidence | Fe56(n,p)Mn56 | Robertson+ | 73 | [26] |
| 2.81 – 3.96 | 24 | Act. method, Ge(Li) and NaI det., Gamma | U235(n,f)FP | Smith+ | 75 | [27] |
| 4.01 – 5.92 | 40 | Act. method, Ge(Li) and NaI det., Gamma | U238(n,f)FP | Smith+ | 75 | [27] |
| 5.44 – 9.96 | 18 | Act. method, Ge(Li) and NaI det., Gamma | U238(n,f)FP | Smith+ | 75 | [27] |
| 4.42 - 8.35 | 6 | Act. method, Geiger-Mueller counter, Beta | Al27(n,p)Mg27 norm. at 7.10 MeV | Mostafa | 76 | [28] |
| 14.60 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Sigg | 76 | [29] |
| 2.78 - 4.59 | 16 | Act. method, Ge(Li) det., Gamma | H-1(n,n)H-1 | Ai+ | 77 | [30] |
| 14.90 | 1 | Act. method, Ge(Li) det., Gamma | 1-H-1(n,n)1-H-1 | Andersson+ | 78 | [31] |

**Table 2. SUMMARY OF EXPERIMENTS FOR THE REACTION Al27(n,p)Mg27** (continued)

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference | | |
|---|---|---|---|---|---|---|
| 12.93 - 15.96 | 5 | Act. method, NaI(Tl) det., Gamma | Cu63(n,2n)Cu62 norm. at 14.70 MeV | Jarjis | 78 | [72] |
| 13.43 - 14.92 | 9 | Act. method, NaI(Tl) det., Gamma | Cu63(n,2n)Cu62 norm. at 14.70 MeV | Jarjis | 78 | [72] |
| 8.40 | 1 | Act. method, Gamma | Cu65(n,2n)Cu64 and Al27(n,p)Mg27 | Ghose | 78 | [32] |
| 14.20 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Lakshmana+ | 78 | [33] |
| 14.65 - 19.00 | 4 | Act. method, 4PI Beta-Gamma coincidence | Fe56(n,p)Mn56 | Ryves+ | 78 | [34] |
| 14.90 | 1 | Act. method, NaI(Tl) det., Gamma | Al27(n,a)Na24 norm. at 14.10 MeV | Melent'jev+ | 78 | [35] |
| 14.60 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Ngoc+ | 79 | [36] |
| 20.00 - 23.00 | 2 | Act. method, Ge(Li) det., Gamma | No information | Welch+ | 81 | [37] |
| 14.20 | 1 | Act. method, Ge(Li) det., Gamma-Gamma coincidences | Associated alpha particles | Harper+ | 82 | [38] |
| 13.50 - 14.78 | 6 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 norm. at 14.10 MeV | Csikai+ | 82 | [73] |
| 14.70 | 1 | Act. method | Al27(n,a)Na24 | Qaim | 82 | [39] |
| 14.93 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Chiadli+ | 82 | [40] |
| 14.90 | 1 | Act. method, Ge(Li) det., Gamma | Si30(n,a)Mg27 | Janczyszyn | 82 | [41] |
| 2.99 - 4.50 | 13 | Act. method, NaI(Tl) det., Gamma | Det. protons from D(d,p)H3 | Husain+ | 83 | [42] |
| 14.80 | 1 | Act. method, Scint. Gamma-spectrometer | Abs. measurements | Shchebolev+ | 83 | [43] |
| 8.60 - 12.10 | 3 | No information | No information | Bradley+ | 85 | [44] |
| 6.36 - 8.29 | 7 | Act. method, Ge(Li) det., Gamma | NE213 liquid scint. | Enz+ | 85 | [45] |
| 13.44 - 14.90 | 9 | Act. method, NaI(Tl) det., Gamma | Cu63(n,2n)Cu62 | Tahir | 85 | [74] |
| 14.8 | 1 | Act. method, Scint. Gamma-spectrometr | Fe56(n,p)Mn56 | Gupta+ | 85 | [75] |
| 14.80 | 1 | Act. method, Ge(Li) det, Gamma | U235(n,f)FP | Garlea+ | 85 | [46] |
| 14.10 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Kobayashi+ | 85 | [51] |
| 13.40 - 14.83 | 7 | Act. method, Ge(Li) and NaI(Tl) det.,Gamma | Al27(n,a)Na24 and U238(n,f) | Csikai+ | 86 | [47] |
| 13.84 - 14.71 | 5 | Act. method, Ge(Li) and NaI(Tl) det., Gamma | NE213 liquid scint., Al27(n,a)Na24 | Chimoye+ | 86 | [47] |
| 14.74 | 1 | Act. method, Ge(Li) det., Gamma | U235(n,f)FP | Meadows+ | 87 | [48] |
| 14.10 | 1 | EDE method | Abs. measurements | Klochkova+ | 87 | [76] |

**Table 2. SUMMARY OF EXPERIMENTS FOR THE REACTION Al27(n,p)Mg27** (continued)

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference | | |
|---|---|---|---|---|---|---|
| 13.33 - 14.93 | 6 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Ikeda+ | 88 | [49] |
| 14.05 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Kobayashi+ | 88 | [51] |
| 4.99 | 1 | Act. method, HP Ge detector, Gamma | 1-H-1(n,el)1-H-1 | Kudo+ | 88 | [50] |
| 14.60 | 1 | Act. method, 4PI Beta-Gamma coincidence | Al27(n,a)Na24 | Kudo+ | 88 | [50] |
| 15.21 - 19.87 | 5 | Act. method, 4PI Beta-Gamma coincidence | Al27(n,a)Na24 | Kudo+ | 88 | [50] |
| 14.10 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Kimura+ | 90 | [51] |
| 14.60 | 1 | Act. method, HP Ge detector, Gamma | Al27(n,a)Na24 | Ercan+ | 91 | [52] |
| 14.10 | 1 | EDE method | H-1(n,n)H-1 | Klochkova+ | 92 | [76] |
| 13.32 - 14.90 | 8 | Act. method, HP Ge det., Gamma | Associated alpha-part. | Ikeda+ | 93 | [53] |
| 14.90 | 1 | Lifetime correction method | No information | Zhou and Hongyu+ | 94 | [54] |
| 7.57 - 12.51 | 5 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Csikai+ | 98 | [55] |
| 14.70 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Csikai+ | 98 | [55] |
| 13.47 - 14.81 | 8 | Act. method, Ge(Li) det., Gamma | Nb93(n,2n)Nb92m | Filatenkov+ | 99 | [56] |
| 14.10 | 1 | Act. method, Ge(Li) det., Gamma | Nb93(n,2n)Nb92m and Al27(n,a)Na24 | Filatenkov+ | 99 | [56] |
| 16.01 - 20.17 | 5 | Act. method, HP Ge det., Gamma | Al27(n,a)Na24 and Nb93(n,2n)Nb92m | Fessler+ | 00 | [57] |
| 2.70 - 3.20 | 3 | Act. method, HP Ge det., Gamma | In115(n,n')In115m | Shimizu+ | 00 | [58] |

Experimental data [5], [8], [12] and [44] were used partialy. Data of Mani et al. [5] were taken into account only for the 9 neutron energies: 11.92, 13.82, 14.75, 16.20, 16.63, 17.83, 18.13, 20.15 and 21.72 MeV. Renormalized experimental data of Gabbard et al. [8] were used in the evaluation only for the 8 neutron energies: 12.90, 13.10, 13.70, 14.40, 14.90, 15.45, 16.80 and 17.40 MeV. Information obtained from Bass et al. experiment [12] was taken into account in the evaluation in the energy region 6.0 - 8.6 MeV. In the energy interval 8.6 - 9.0 MeV this experiment gives significantly over-estimated cross sections in a comparison with corrected experimental data [24], [27] and new experimental data [55]. Cross section measured by Bradley et al. [44] for the neutron energy 11 MeV was not input in the data base for evaluation due to a very big discrepancy with new experimental data of Csikai et al. [55].

Uncertainties for cross section data measured by Henkel. [2] were evaluated between ±(8-30)%. Total uncertainties were evaluated for the experimental data of Mani et al. [5], Gabbard et al.[8], Calvi et al. [13], Grundl [14] and Mostafa et al. [28].

Experimental cross section data [59-76] were rejected due to their discrepancy with the main bulk of experimental data [1-58]. In the rejected experiments [59-70] and [75-76] cross section values were measured only in a one energy point in the interval 14 - 15 MeV.

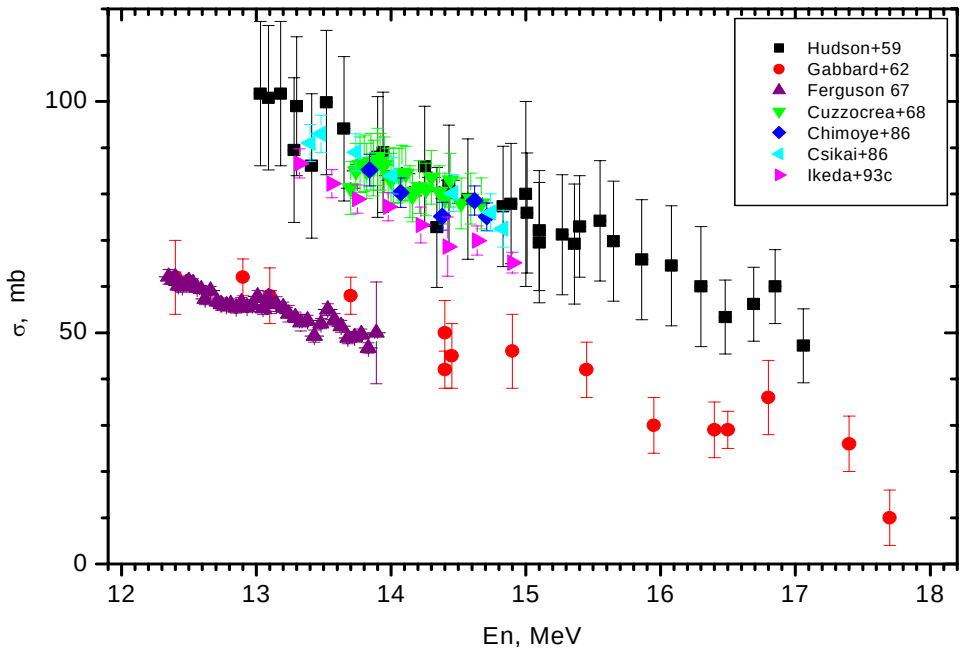


Fig. 1a Original experimental data [3], [8], [15], [17], [47] for the reaction Al-27(n,p)Mg-27 in comparison with results of precise measurements of Ikeda et al. [53].

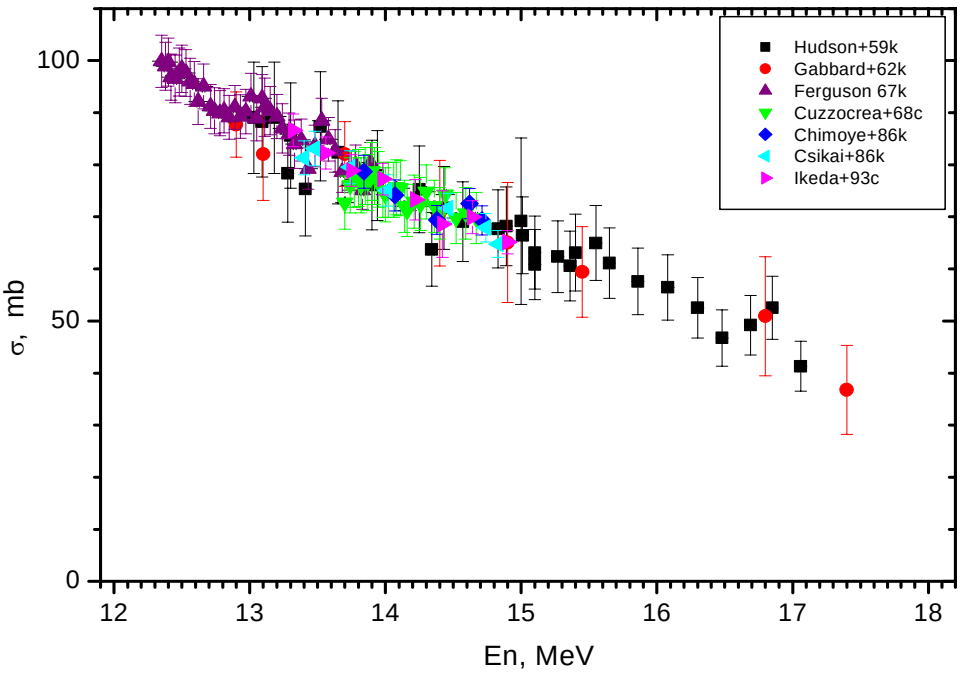


Fig. 1b Corrected experimental data [3], [8], [15], [17], [47] for the reaction Al-27(n,p)Mg-27 in comparison with results of precise measurements of Ikeda et al. [53].

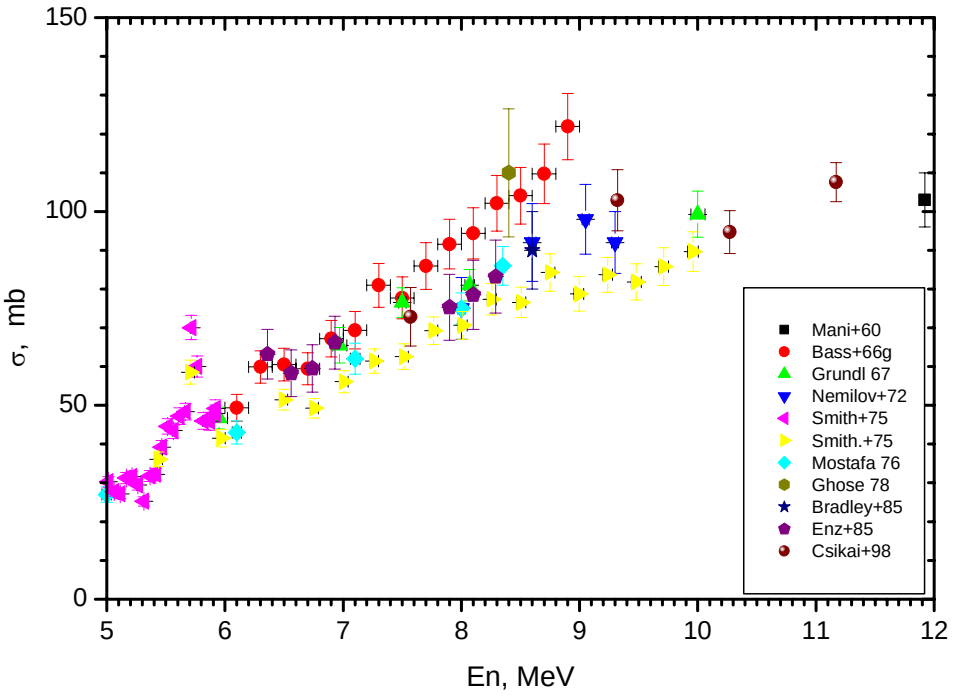


Fig. 2a Original experimental cross section for the Al-27(n,p)Mg-27 reaction in the neutron energy range 5 – 12 MeV.

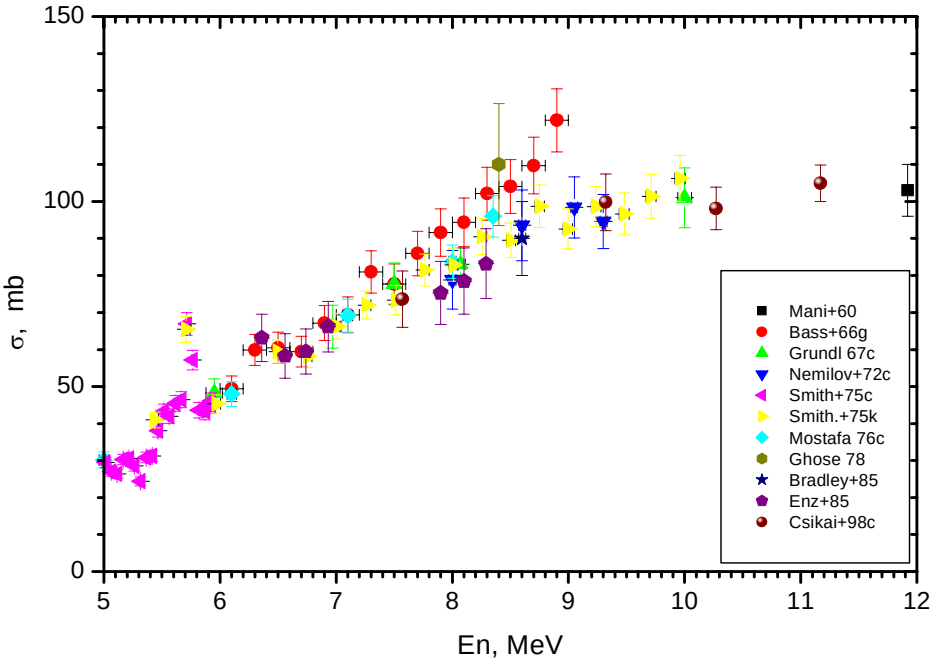


Fig. 2b Experimental cross section for the Al-27(n,p)Mg-27 reaction in the neutron energy range 5 – 12 MeV after carried out correction.

The prepared data base included information about the $^{27}Al(n,p)^{27}Mg$ reaction in the 404 points covered energy range from 2.44 MeV to 23 MeV.

Statistical analysis of input cross section data was carried out by means of PADE-2 code [79]. Rational function was used as the model function [80].

**Uncertainties in the evaluated $^{27}Al(n,p)^{27}Mg$ cross sections**

Uncertainties in the evaluated excitation function for the $^{27}Al(n,p)^{27}Mg$ reaction are given in the form of relative covariance matrix for the 49-neutron energy groups (LB=5). The relative covariance matrix was obtained with taking into account uncertainties in the experimental cross section data. Average correlation coefficients ($F_c$) corresponds to experimental data were taken into account also. The Covariance matrix of uncertainties was calculated simultaneously with recommended cross section data by means of PADE-2 code. The eigenvalues of the 6-th digits relative covariance matrix given in the 33-file are the following:

| | | | |
|---|---|---|---|
| 9.62022E-08 | 9.94230E-08 | 1.04190E-07 | 1.09967E-07 |
| 1.15699E-07 | 1.20174E-07 | 1.24951E-07 | 1.30570E-07 |
| 1.37068E-07 | 1.43716E-07 | 1.50173E-07 | 1.58001E-07 |
| 1.68205E-07 | 1.76372E-07 | 1.86739E-07 | 1.94590E-07 |
| 2.06816E-07 | 2.14527E-07 | 2.29525E-07 | 2.40453E-07 |
| 2.53581E-07 | 2.82127E-07 | 2.99422E-07 | 3.49389E-07 |
| 3.68505E-07 | 4.35939E-07 | 5.42544E-07 | 7.20462E-07 |
| 9.45090E-07 | 2.44284E-06 | 1.77944E-05 | 8.88268E-05 |
| 1.54306E-04 | 2.21515E-04 | 2.92421E-04 | 3.30954E-04 |
| 3.45302E-04 | 3.84750E-04 | 4.56266E-04 | 6.07458E-04 |
| 1.31442E-03 | 1.53210E-03 | 1.76053E-03 | 2.87076E-03 |
| 4.69639E-03 | 5.64972E-03 | 1.04479E-02 | 1.48842E-02 |
| 5.19587E-02 | | | |

It is necessary to note that all eigenvalues are positive.

**The main characteristics of the evaluated $^{27}Al(n,p)^{27}Mg$ reaction excitation function**

Group cross sections and their uncertainties for the evaluated $^{27}Al(n,p)^{27}Mg$ reaction excitation function are adduced in Table 4. Boundaries of groups are the same as in the File-33. One can see from Table 3 that the minimal of uncertainties in the evaluated cross sections – (1.45 – 1.88) % are observed in the neutron energy interval 13.0 – 15.5 MeV. Significant error 22.3 % in the cross sections in the energy interval from threshold to 3.0 MeV is due to a big uncertainties in the experimental data in this region and exist discrepancy between experimental data. Due to poor experimental information the $^{27}Al(n,p)^{27}Mg$ reaction cross section uncertainties increased in the neutron energy range 17 – 23 MeV from 3.22 % to 7.26 %. Evaluated $^{27}Al(n,p)^{27}Mg$ reaction excitation function in the energy range 13.0 – 15.0 MeV may be recommended as the reference cross section data for the activation measurements with short-lived resudal nuclei.

Evaluated excitation function for the reaction $^{27}Al(n,p)^{27}Mg$ is shown in Fig.3a (energy range 1.80 MeV – 6.00 MeV), Fig.3b (energy range 7.00 MeV – 13.00 MeV), Fig.3c (energy range 13.00 MeV – 15.00 MeV) and Fig.3d (energy range 15.00 MeV – 23.00 MeV) in comparison with the experimental data and IRDF90v.2 and JENDL/D-99 cross sections.

In the energy range 3 – 6 MeV (Fig.3a) new evaluation satisfactory reproduce the resonance structure in the $^{27}Al(n,p)^{27}Mg$ excitation function observed in the high resolution measurements of Smith and Meadows. JENDL/D-99 evaluation in this energy range gives the smoothed cross sections. Between 4.9 – 6.0 MeV IRDF-90v2 gives also the smoothed cross sections.

One can see from Fig.3b that in the energy range 6 – 13 MeV the present evaluation also agree satisfactory with experimental data. The IRDF-90v2 and JENDL/D-99 evaluations are systematically underestimated the $^{27}Al(n,p)^{27}Mg$ cross sections especially in the maximum of excitation function.

The energy dependence of cross section on the interval 13 – 15 MeV (Fig.3c) is correctly reproduced only in the present evaluation. New evaluation agree well with the main bulk of experimental data obtained in this region and first of all with absolute precise measurements of Ikeda et al. [75]. The IRDF-90v2 and JENDL/D-99 evaluations are systematically underestimated the $^{27}Al(n,p)^{27}Mg$ cross sections below 13.6 MeV.

Below 15 MeV (Fig.3d) the present evaluation agree satisfactory with the IRDF-90v2 and experimental data. The evaluated $^{27}Al(n,p)^{27}Mg$ reaction excitation function in the energy range 15 –20 MeV passed mainly through experimental data of Kudo et al.[71] and Fessler [79]. The JENDL/D-99 data in this energy region has the unphysical behavior.

Evaluated excitation function for the reaction Al27(n,p)Mg27 was tested with using integral experimental data [81-83] for U-235 thermal fission neutron spectrum and evaluated integral experimental data [83] for Cf-252 spontaneous fission neutron spectrum. Data for U-235 thermal fission neutron spectrum and Cf-252 spontaneous fission neutron spectrum were taken from ref.[84] and [85], respectively. The results of testing are given in Table 3, there C/E – is the ratio of calculated to experimental values.

**Table 3. Calculated and measured averaged cross sections for the $^{27}Al(n,p)^{27}Mg$ reaction in the U-235 thermal fission and Cf-252 spontaneous fission neutron spectra**

| Type of neutron field | Average cross section, mb | | C/E | 90% response range, MeV |
|---|---|---|---|---|
| | calculated | measured | | |
| **U-235 thermal fission neutron spectrum** | 4.0768 | 4.133 ± 0.074 [81] | 0.9864 | 3.50 – 9.50 |
| | | 3.914 ± 0.070 [82] | 1.0416 | |
| | | 3.902 ± 0.069 [83] | 1.0448 | |
| **Cf-252 spontaneous fission neutron spectrum** | 4.9070 | 4.880 ± 0.104 [83] | 1.0055 | 3.60 – 10.00 |

Calculated from the evaluated excitation function average cross section value for U-235 thermal fission neutron spectrum is agree more well with experimental data of Horibe et al. [81], than with evaluated experimental data of Mannhart [82], [83]. Calculated from the evaluated excitation function average cross section for Cf-252 spontaneous fission neutron spectrum is agree very well with evaluated experimental data of Mannhart [83]. The 90% response ranges of Al27(n,p)Mg27 reaction excitation function are practically the same as for U-235 thermal fission neutron spectrum and for Cf-252 spontaneous fission neutron spectrum: 3.50 – 9.50 MeV and 3.60 – 10.00 MeV, respectively. The results of testing are given in the Table 3 permit to say that evaluated microscopic cross sections for Al27(n,p)Mg27 reaction in the energy range 3.5 – 10.0 MeV agree satisfactory with differential and integral experimental data simultaneously.

**Table 4. GROUP CROSS-SECTIONS AND THEIR UNCERTAINTIES FOR THE EVALUATED $^{27}Al(n,p)^{27}Mg$ REACTION EXCITATION FUNCTION (boundaries of groups are the same as in the FILE-33)**

| Group number | Energy group [MeV] to [MeV] | Cross-section [mb] | Uncertainty [mb] | Uncertainty [%] |
|---|---|---|---|---|
| 1 | 1.90 - 3.00 | 0.13953 | 0.03110 | 22.29 |
| 2 | 3.00 - 3.50 | 2.69659 | 0.10652 | 3.95 |
| 3 | 3.50 - 3.75 | 6.19226 | 0.22602 | 3.65 |
| 4 | 3.75 - 4.00 | 6.26331 | 0.19103 | 3.05 |
| 5 | 4.00 - 4.25 | 6.68648 | 0.18856 | 2.82 |
| 6 | 4.25 - 4.50 | 11.58930 | 0.33493 | 2.89 |
| 7 | 4.50 - 4.75 | 17.94630 | 0.52762 | 2.94 |
| 8 | 4.75 - 5.00 | 18.80810 | 0.54920 | 2.92 |
| 9 | 5.00 - 5.25 | 27.91140 | 0.80385 | 2.88 |
| 10 | 5.25 - 5.50 | 30.96030 | 0.81116 | 2.62 |
| 11 | 5.50 - 5.75 | 48.85990 | 1.33388 | 2.73 |
| 12 | 5.75 - 6.00 | 45.52410 | 1.22460 | 2.69 |
| 13 | 6.00 - 6.25 | 50.31090 | 1.31311 | 2.61 |
| 14 | 6.25 - 6.50 | 56.36870 | 1.53887 | 2.73 |
| 15 | 6.50 - 6.75 | 60.86700 | 1.76514 | 2.90 |
| 16 | 6.75 - 7.00 | 65.08460 | 1.99810 | 3.07 |
| 17 | 7.00 - 7.25 | 69.18790 | 2.21401 | 3.20 |
| 18 | 7.25 - 7.50 | 73.15340 | 2.39943 | 3.28 |
| 19 | 7.50 - 7.75 | 76.99380 | 2.57159 | 3.34 |
| 20 | 7.75 - 8.00 | 80.71400 | 2.72006 | 3.37 |
| 21 | 8.00 - 8.25 | 84.31060 | 2.86656 | 3.40 |
| 22 | 8.25 - 8.50 | 87.77190 | 3.01058 | 3.43 |
| 23 | 8.50 - 8.75 | 91.07750 | 3.15128 | 3.46 |
| 24 | 8.75 - 9.00 | 94.19860 | 3.29695 | 3.50 |
| 25 | 9.00 - 9.25 | 97.09850 | 3.43729 | 3.54 |
| 26 | 9.25 - 9.50 | 99.73440 | 3.57049 | 3.58 |
| 27 | 9.50 - 9.75 | 102.05800 | 3.69450 | 3.62 |
| 28 | 9.75 - 10.00 | 104.02100 | 3.80717 | 3.66 |
| 29 | 10.00 - 10.50 | 106.12100 | 3.92648 | 3.70 |
| 30 | 10.50 - 11.00 | 107.31900 | 3.96007 | 3.69 |
| 31 | 11.00 - 11.50 | 106.44700 | 3.69371 | 3.47 |
| 32 | 11.50 - 12.00 | 103.55400 | 3.09626 | 2.99 |
| 33 | 12.00 - 12.50 | 98.93200 | 2.43373 | 2.46 |
| 34 | 12.50 - 13.00 | 93.04820 | 1.95401 | 2.10 |
| 35 | 13.00 - 13.50 | 86.43630 | 1.62500 | 1.88 |
| 36 | 13.50 - 14.00 | 79.58810 | 1.32116 | 1.66 |
| 37 | 14.00 - 14.20 | 74.85290 | 1.13776 | 1.52 |
| 38 | 14.20 - 14.40 | 72.22300 | 1.06168 | 1.47 |
| 39 | 14.40 - 14.60 | 69.66320 | 1.01012 | 1.45 |
| 40 | 14.60 - 14.80 | 67.18380 | 0.98088 | 1.46 |
| 41 | 14.80 - 15.00 | 64.79240 | 0.97189 | 1.50 |
| 42 | 15.00 - 15.50 | 60.92650 | 0.99919 | 1.64 |
| 43 | 15.50 - 16.00 | 55.93010 | 1.07945 | 1.93 |
| 44 | 16.00 - 16.50 | 51.59850 | 1.17129 | 2.27 |
| 45 | 16.50 - 17.00 | 47.81180 | 1.25745 | 2.63 |
| 46 | 17.00 - 18.00 | 42.99390 | 1.38440 | 3.22 |
| 47 | 18.00 - 19.00 | 37.68880 | 1.56032 | 4.14 |
| 48 | 19.00 - 20.00 | 33.41320 | 1.72746 | 5.17 |
| 49 | 20.00 - 23.00 | 27.16440 | 1.97214 | 7.26 |

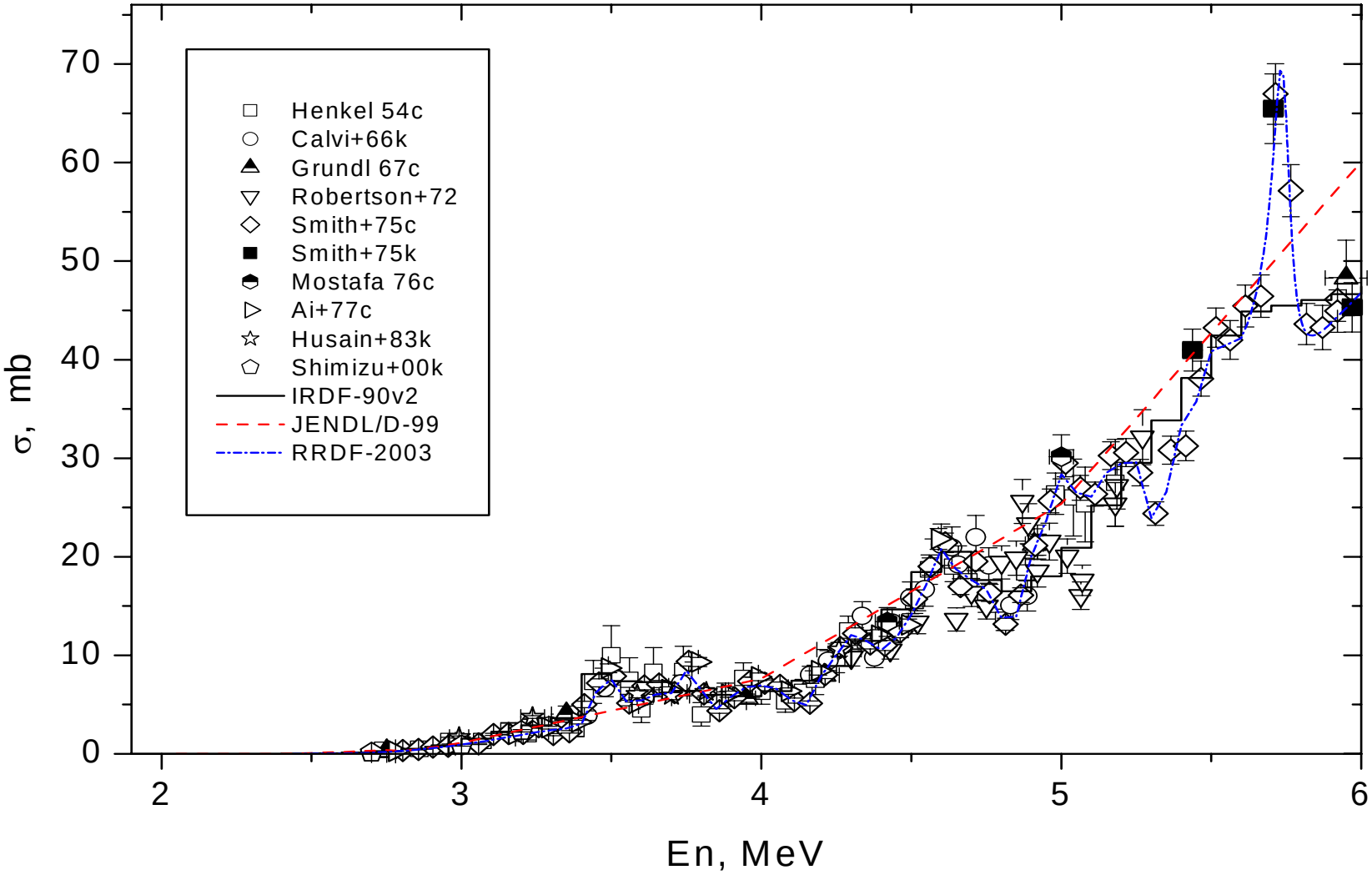


Fig. 3a Evaluated excitation function for the reaction Al-27(n,p)Mg-27 in the energy range 1.9 – 6.0 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

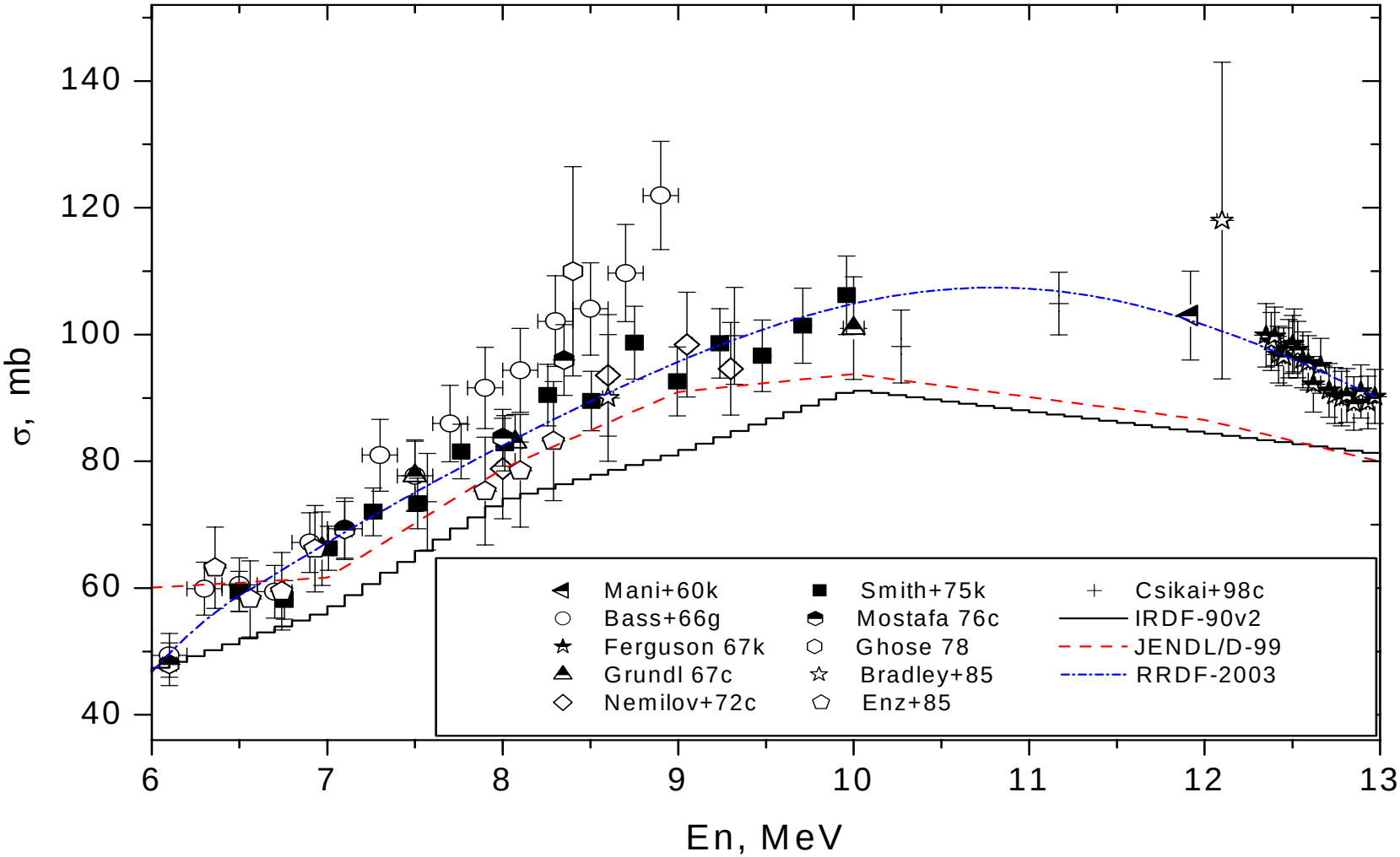


Fig. 3b Evaluated excitation function for the reaction Al-27(n,p)Mg-27 in the energy range 6 – 13 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

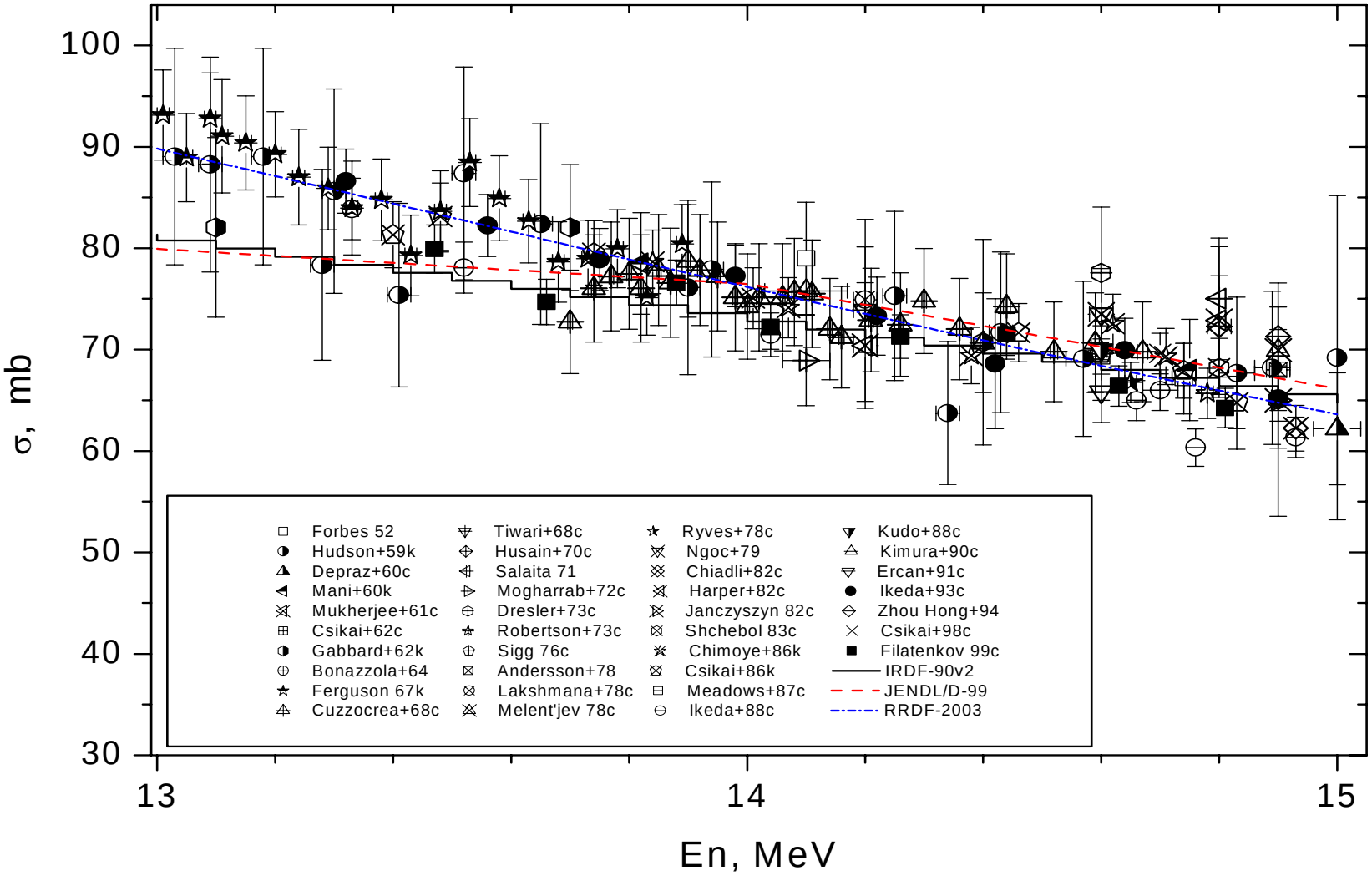


Fig. 3c Evaluated excitation function for the reaction Al-27(n,p)Mg-27 in the energy range 13 – 15 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

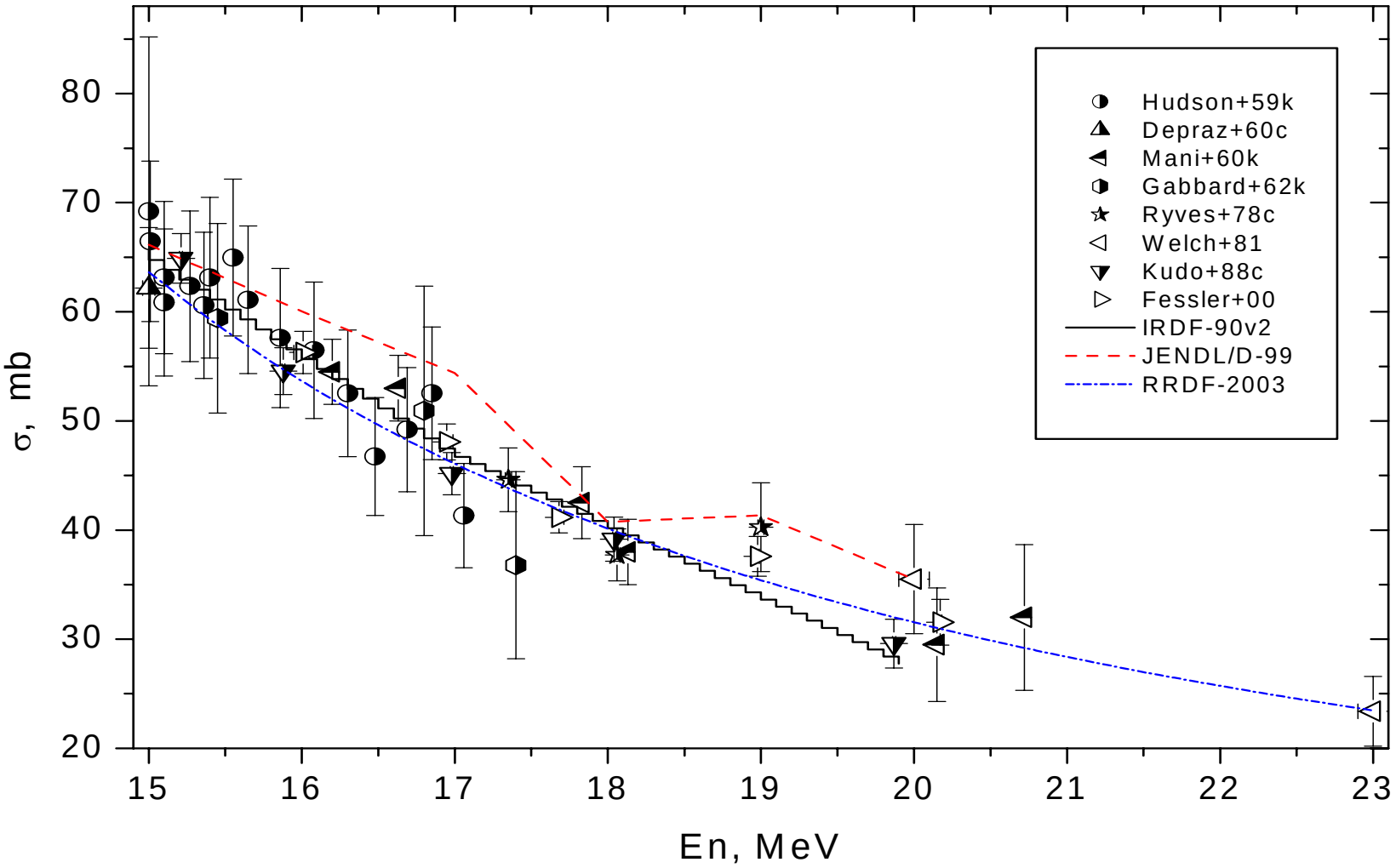


Fig. 3d Evaluated excitation function for the reaction Al-27(n,p)Mg-27 in the energy range 15 – 23 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

In the process of analysis of uncertainties in the evaluated $^{27}Al(n,p)^{27}Mg$ reaction excitation function it was mentioned that the minimal of uncertainties in the evaluated cross sections – (1.45 – 1.88) % are observed in the neutron energy interval 13.0 – 15.5 MeV. As it was said before in addition to the reactor dosimetry application reaction $^{27}Al(n,p)^{27}Mg$ is very often used in the experimental nuclear physic as the monitor reactions for measurements of unknown cross sections by means of activation method in the neutron energy range (13 – 15) MeV. Recommended cross section data and related uncertainties for the monitor reaction $^{27}Al(n,p)^{27}Mg$ from the present evaluation given in Table 5 in the column "Final data". In the 23 experimental works the $^{27}Al(n,p)^{27}Mg$ cross sections in the neuron energies range (13 – 15) MeV were measured relative the $^{27}Al(n,a)^{24}Na$ reaction cross sections. The $^{27}Al(n,p)^{27}Mg$ "Preliminary data" were obtained when for the monitor reaction were taken cross sections from ref. [87]. The thoroughly analysis of experimental cross section data for the $^{27}Al(n,a)^{24}Na$ reaction published up to March 2003 showed that the evaluated cross sections given in the ref. [87] are needed in the correction. The analysis of the components of systematic errors showed also that the total uncertainty of 0.3 – 0.8 % assigned to the the $^{27}Al(n,a)^{24}Na$ reaction cross sections between 13.40 – 14.95 MeV in this evaluation are rather small. Taking into account the above mentioned reasons new evaluation of the $^{27}Al(n,a)^{24}Na$ excitation function from threshold to 23 MeV were carried out in the process of this work. The $^{27}Al(n,p)^{27}Mg$ "Final data" were obtained with using for the $^{27}Al(n,a)^{24}Na$ monitor reaction the cross sections from new evaluation.

**Table 5. Recommended cross section data and their uncertainties for the monitor reaction $^{27}Al(n,p)^{27}Mg$ in the energy range 13-15 MeV**

| Neutron energy [MeV] | Preliminary data | | Final data | |
|---|---|---|---|---|
| | Cross-section [mb] | Uncertainty [%] | Cross-section [mb] | Uncertainty [%] |
| 13.00 | 89.022 | 1.68 | 89.821 | 1.99 |
| 13.10 | 87.676 | 1.65 | 88.482 | 1.88 |
| 13.20 | 86.326 | 1.60 | 87.128 | 1.88 |
| 13.30 | 84.975 | 1.55 | 85.763 | 1.88 |
| 13.40 | 83.627 | 1.50 | 84.391 | 1.88 |
| 13.50 | 82.282 | 1.46 | 83.015 | 1.77 |
| 13.60 | 80.944 | 1.43 | 81.639 | 1.66 |
| 13.70 | 79.615 | 1.40 | 80.266 | 1.66 |
| 13.80 | 78.296 | 1.37 | 78.898 | 1.66 |
| 13.90 | 76.988 | 1.34 | 77.537 | 1.66 |
| 14.00 | 75.694 | 1.32 | 76.187 | 1.59 |
| 14.10 | 74.414 | 1.31 | 74.849 | 1.52 |
| 14.20 | 73.150 | 1.30 | 73.526 | 1.50 |
| 14.30 | 71.903 | 1.28 | 72.219 | 1.47 |
| 14.40 | 70.673 | 1.28 | 70.929 | 1.46 |
| 14.50 | 69.462 | 1.27 | 69.658 | 1.45 |
| 14.60 | 68.269 | 1.28 | 68.408 | 1.46 |
| 14.70 | 67.095 | 1.29 | 67.178 | 1.46 |
| 14.80 | 65.941 | 1.30 | 65.971 | 1.48 |
| 14.90 | 64.807 | 1.31 | 64.787 | 1.50 |
| 15.00 | 63.693 | 1.32 | 63.626 | 1.57 |

## 4. The evaluation of the Fe-56(n,p)Mn-56 reaction excitation function

The abundance of the $^{56}$Fe isotope in the natural iron is equal to (91.754 ± 0.036**)** atom percent [83].

The half-live of $^{56}$Mn is equal to (2.5785 ± 0.012) Hours. Nucleus $^{56}$Mn has 100% β- decay mode. For determination of $^{56}$Fe(n,p)$^{56}$Mn reaction rate it is usually measured the activity corresponding to the most intensive gamma-ray lines: 846.754-keV ($I_\gamma$=0.9887 ± 0.0030) , 1810.72 keV ($I_\gamma$=0.27189 ± 0.00791) and 2113.05 keV ($I_\gamma$=0.14336 ± 0.00395). Recommended values of $^{56}$Mn half-life and gamma-rays emission probability per decay -$I_\gamma$ were taken from [84].

Excitation function of the $^{56}$Fe(n,p)$^{56}$Mn reaction was evaluated for the energies of incident neutrons from threshold ($E_{th}$=2.96554 mV) to 20 MeV.

It was analyzed 70 works on measurement of the $^{56}$Fe(n,p)$^{56}$Mn reaction cross sections, which were carried out in the period from 1952 to 2000 years. Brief description of these experiments is given in Table 6.

Microscopic experimental data [1-70] were analyzed in the process of preparation of input data base for the evaluation of cross sections and their uncertainty for the $^{56}$Fe(n,p)$^{56}$Mn reaction. During this procedure all experimental data if it was possible were corrected to the new recommended cross section data for monitor reactions used in the measurements (see table 1.) and to the recommended decay data from ref. [84].

Experimental data [14], [22-23], [25], [26], [31-32], [38], [46], [49], [51], [54], [65] and [67] were corrected to the new standards.

Data base for the evaluation $^{56}$Fe(n,p)$^{56}$Mn reaction excitation function in the energy region from threshold to 20.0 MeV was formed from microscopic experimental data [1-40].

Special correction was done with experimental data [2],[9-10] and [17].

Experimental data of Terrell and Holm [2] correspondent to neutron energies 6.54 MeV,7.41 MeV, 8.21 MeV were renormalized to the preliminary evaluated cross section value at En=8.2 MeV.

Data of Liskien and Paulsen [9] measured in the energy range 12.60 - 19.58 MeV were corrected to the preliminary evaluated integral of cross section in the energy interval 14-15 MeV. Data obtained by Liskien and Paulsen in the energy range 6.06-8.20 MeV [10] were renormalized to the preliminary evaluated cross section value at 8.0 MeV. The correction factors for the experimental data [2], [9] and [10] were Fc=1.23487, Fc=1.09674 and Fc=1.05835, respectively.

Data of Smith and Meadows [17] obtained in the experiment with neutrons from D(d,n)He3 reaction in the energy range 6.486 - 9.945 MeV were renormalized to the preliminary evaluated cross section value at 9.945 MeV. The correction factor for this data was Fc=1.14066 .

Experimental information about $^{56}$Fe(n,p)$^{56}$Mn reaction excitation function are given in the ref. [13],[21],[23] in the form of cross section ratios to monitor reactions.

The results of precise relative measurements of Vonach et al. [13] in the energy range 13.6-14.7 MeV were normalized to the preliminary evaluated absolute cross section value 107.13 mb for $^{56}$Fe(n,p)$^{56}$Mn reaction at 14.7 MeV point.

Raics et al. [21] and Antov et al. [23] measured ratios of $^{56}$Fe(n,p)$^{56}$Mn cross section to $^{238}$U(n,f) and $^{27}$Al(n,a)$^{24}$Na reactions cross section. Recommended absolute cross section data for $^{238}$U(n,f) and $^{27}$Al(n,a)$^{24}$Na reactions were taken from ref. [72] and [73], respectively.

Experimental data from refs.[5] and [11] were used partially. It were used only data obtained at 14.5 MeV [5] and in the energy range 3.95 - 10.0 MeV [11]. Cross et al. data [5] for the neutron energies 13.78 MeV, 14.07 MeV and 14.73 MeV were rejected due to their systematically underestimation $^{56}$Fe(n,p)$^{56}$Mn cross sections. The result of Grundl measurements [11] at 14.1 MeV was not taken into account due to a very overestimated cross section value obtained for this energy point.

**TABLE 6. SUMMARY OF EXPERIMENTS FOR THE REACTION Fe56(n,p)Mn56**

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference |
|---|---|---|---|---|
| 14.10 | 1 | Act. method, Beta | No information | Forbes 52 [41] |
| 14.50 | 1 | Act. method, Beta | Long Boron counter | Paul+ 53 [42] |
| 14.00 | 1 | Activation method | No information | McClure+ 55 [43] |
| 14.10 | 1 | Photo. plate track detector, protons | Cu65(n,2n)Cu64 | Allan 57 [44] |
| 14.10 | 1 | Act. method, end window Geiger- Mueller counter, Beta- | Associated alpha particles | Yasumi 57 [45] |
| 13.20 | 1 | Photo emulsion track det., protons | H-1(n,n)H-1 | Brown+ 57 [ 1] |
| 3.43 - 8.21 | 10 | Activation method, Beta | Fe56(n,p)Mn56 norm. at 14.30 MeV | Terrell+ 58 [ 2] |
| 12.43 17.89 | 8 | Activation method, Beta | Fe56(n,p)Mn56 norm. at 14.30 MeV | Terrell+ 58 [ 2] |
| 15.27 | 1 | Activation method, NaI(Tl) det., Gamma | Li6(n,t)He4 | Kern+ 59 [47] |
| 15.00 | 1 | Act. method, prop. Counter, Beta | Cu63(n,2n)Cu62 | Depraz+ 60 [48] |
| 14.10 | 1 | CsI(Tl) det., protons | H-1(n,n)H-1 | Storey+ 60 [49] |
| 14.80 | 1 | Act. method, 2PI prop. counter, Beta | Al27(n,a)Na24 and Cu63(n,2n)Cu62 | Chittenden+ 61 [50] |
| 14.10 | 1 | Act. method, NaI(Tl) det., Gamma | Long counter | Pollehn+ 61 [ 3] |
| 14.40 | 1 | Act. method, NaI(Tl) det., Gamma | No information | Gabbard+ 62 [ 4] |
| 13.20 - 19.60 | 5 | Act. method, Boric acid counter, Gamma | Fe56(n,p)Mn56 norm. at 14.10 MeV | Bormann+ 62 [51] |
| 14.50 | 1 | Activation method | Al27(n,a)Na24 | Cross+ 63 [ 5] |
| 13.78 - 14.73 | 3 | Activation method | Al27(n,a)Na24 norm. at 14.50 MeV | Cross+ 63 [ 5] |
| 4.57 - 5.02 | 3 | Act. method, Beta prop. counter | S32(n,p)P32 | Santry+ 64 [ 6] |
| 5.30 - 13.58 | 30 | Act. method, Beta prop. counter | S32(n,p)P32 | Santry+ 64 [ 6] |
| 12.53 - 20.30 | 14 | Act. method, Beta prop. counter | S32(n,p)P32 norm. at 14.50 MeV | Santry+ 64 [ 6] |
| 14.70 | 1 | Act. method, Geiger-Mueller counter, Beta- | Associated alpha particals | Bonazzola+ 64 [ 7] |
| 14.70 | 1 | Act. method, NaI(Tl) det., Gamma | Al27(n,a)Na24 + 2 monit. reactions | Strain+ 65 [52] |
| 12.60 - 19.58 | 28 | Act. method, NaI detector, Gamma | 1-H-1(n,n)1-H-1 norm. at 14.80 MeV | Liskien+ 65 [ 9] |
| 14.80 | 1 | Act. method, 2PI Geiger-Mueller count., Beta | Li6(n,t)He4 | Bormann+ 65 [ 8] |
| 6.06 - 8.20 | 17 | Act. method, NaI detector, Gamma | 1-H-1(n,n)1-H-1 | Liskien+ 66 [10] |

**Table 6. SUMMARY OF EXPERIMENTS FOR THE REACTION Fe56(n,p)Mn56** (continued)

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference |
|---|---|---|---|---|
| 13.50 - 14.80 | 2 | Act. method, Beta-Gamma coincidence counter | Associated alpha particles | Hemingway + 66 [53] |
| 3.95 - 4.91 | 3 | Act. method, Prop. gas counter, Gamma, Beta | Fe56(n,p)Mn56 and U238(n,f)FP | Grundl 67 [11] |
| 5.95 - 10.00 | 5 | Act. method, Prop. gas counter, Gamma, Beta | Fe56(n,p)Mn56 and U238(n,f)FP | Grundl 67 [11] |
| 14.10 | 1 | Act. method, Prop. gas counter, Gamma, Beta | Fe56(n,p)Mn56 and U238(n,f)FP | Grundl 67 [11] |
| 14.70 | 1 | Act. method, NaI(Tl) det., Gamma | Al27(n,a)Na24 | Vonach+ 68 [13] |
| 13.60 – 14.60 | 11 | Act. method, NaI(Tl) det., Gamma | Fe56(n,p)Mn56 norm. at 14.70 MeV | Vonach+ 68 [13] |
| 13.70 14.67 | 23 | Act. method, Geiger-Mueller counter, Beta- | Cu65(n,2n)Cu64 norm. at 14.11 MeV | Cuzzocrea+ 68 [54] |
| 14.80 | 1 | Act. method, End-window counter, Beta | Cu65(n,2n)Cu64 | Levkovskij+ 68 [12] |
| 14.60 | 1 | Act. method, NaI(Tl) det., Gamma | Al27(n,a)Na24 | Barrall+ 69 [14] |
| 14.80 | 1 | Act. method, NaI(Tl) det., Gamma | H-1(n,tot) | Barrall+ 69 [14] |
| 15.10 | 1 | Act. method, Ge(Li) det., Gamma | C12(n,n'g)C12 | Joensson+ 69 [55] |
| 14.70 | 1 | Act. method, Ge(Li) det, Gamma | Al27(n,p)Mg27 + 3 monit. reactions | Qaim+ 71 [56] |
| 14.40 | 1 | Act. method, NaI(Tl) det., Gamma | Si28(n,p)Al28 | Dyer+ 72 [15] |
| 14.50 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Singh 72 [57] |
| 14.78 | 1 | Act. method, 4PI Beta-Gamma coincidence | 1-H-1(n,n)1-H-1 | Robertson+ 73 [16] |
| 3.98 | 1 | Act. method, Ge(Li) and NaI(Tl) det., Gamma | U235(n,f)FP | Smith+ 75 [17] |
| 4.08 - 5.94 | 22 | Act. method, Ge(Li) and NaI(Tl) det., Gamma | U238(n,f)FP | Smith+ 75 [17] |
| 6.49 - 9.94 | 6 | Act. method, Ge(Li) and NaI(Tl) det., Gamma | U238(n,f)FP | Smith+ 75 [17] |
| 14.10 | 1 | Act. method, NaI(Tl) det., Gamma | Al27(n,a)Na24 | Spangler+ 75 [58] |
| 5.20 - 8.35 | 5 | Act. method, Geiger-Mueller counter, Beta- | Fe56(n,p)Mn56 norm. at 8.35 MeV | Mostafa 76 [59] |
| 14.80 | 1 | Act. method, 4PI Beta-Gamma coincidence | Associated alpha particles | Kudo 77 [18] |
| 14.80 | 1 | Act. method, Beta- | 1-H-1(n,n)1-H-1 | Ramendik+ 77 [60] |
| 14.80 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,p)Mg27 | Sothras 78 [61] |
| 14.67 - 18.95 | 6 | Act. method, 4PI Beta-Gamma coincidence | 1-H-1(n,n)1-H-1 | Ryves+ 78 [19] |

**Table 6. SUMMARY OF EXPERIMENTS FOR THE REACTION Fe56(n,p)Mn56** (continued)

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference | | |
|---|---|---|---|---|---|---|
| 14.70 | 1 | Act. method, 4PI-Beta prop. counter | Abs. measurements | Sharma+ | 78 | [62] |
| 7.70 - 9.30 | 3 | Act. method, 4PI counter, Beta-, NaI(Tl) det.,Gamma | Abs. measurements | Nemilov+ | 78 | [20] |
| 6.78 - 10.50 | 8 | Act. method, Ge(Li) det., Gamma | U238(n,f)FP | Raics+ | 80 | [21] |
| 14.60 | 1 | Act. method, 4PI Beta-Gamma coincidence | Associated alpha particles | Kudo | 82 | [22] |
| 14.54 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Antov+ | 83 | [23] |
| 13.55 - 14.71 | 6 | Act. method, Ge(Li) det., Gamma | No information | Ngoc+ | 83 | [63] |
| 14.80 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Ngoc+ | 83 | [64] |
| 14.00 - 19.87 | 8 | Act. method, 4PI Beta-Gamma coincidence | Associated alpha part., 1-H-1(n,n)1-H-1 | Kudo | 84 | [24] |
| 14.70 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Bahal+ | 84 | [25] |
| 14.75 | 1 | Act. method, Ge(Li) det., Gamma | U235(n,f) | Garlea+ | 84 | [65] |
| 14.80 | 1 | Act. method, Scintil. det., Gamma | Fe56(n,p)Mn56 | Gupta+ | 85 | [66] |
| 14.80 | 1 | Act. method, Ge(Li) det., Gamma | U238(n,f) | Garlea+ | 85 | [26] |
| 14.60 | 1 | Act. method, Ge(Li) and NaI(Tl) det., Gamma | Associated alpha particles | Zhou Muyao+ | 87 | [27] |
| 13.33 - 14.92 | 8 | Act. method, Ge(Li) det., Gamma | Nb93(n,2n)Nb92m | Ikeda+ | 88 | [28] |
| 14.58 | 1 | Act. method, NaI(Tl) det., Gamma | Associated alpha particles | Li Chichou+ | 89 | [29] |
| 12.79 - 18.26 | 24 | Act. method, NaI(Tl) det., Gamma | Fe56(n,p)Mn56 norm. at 14.58 MeV | Li Chichou+ | 89 | [29] |
| 10.43 - 13.79 | 3 | Act. method, Gamma | Al27(n,a)Na24 | Cabral+ | 90 | [30] |
| 14.10 | 1 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Kimura+ | 90 | [31] |
| 8.00 | 1 | E - delta E method | 1-H-1(n,n)1-H-1 | Saraf+ | 91 | [32] |
| 13.77 - 14.83 | 7 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Viennot+ | 91 | [67] |
| 14.62 | 1 | Act. method, NaI(Tl) det., Gamma | Associated alpha particals | Fuga | 91 | [33] |
| 12.80 - 18.26 | 23 | Act. method, NaI(Tl) det., Gamma | Fe56(n,p)Mn56 | Fuga | 91 | [33] |
| 14.60 | 1 | Act. method, HP Ge detector, Gamma | Al27(n,a)Na24 | Ercan+ | 91 | [68] |
| 14.80 | 1 | Act. method, Ge(Li) det., Gamma | Nb93(n,2n)Nb92 | Garlea+ | 92 | [69] |

**Table 6. SUMMARY OF EXPERIMENTS FOR THE REACTION Fe56(n,p)Mn56** (continued)

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference | | |
|---|---|---|---|---|---|---|
| 9.10 - 11.10 | 2 | Act. method, HPGe det., Gamma | Al27(n,a)Na24 | Ikeda+ | 92 | [34] |
| 14.10 | 1 | EDE method | 1-H-1(n,n)1-H-1 | Klochkova+ | 92 | [70] |
| 9.10 - 14.64 | 13 | Act. method, Ge(Li) det., Gamma | Al27(n,a)Na24 | Mannhart+ | 92 | [35] |
| 14.57 | 1 | Act. method, 4PI-Beta-Gamma coincide | Associated alpha particles | Bao Zongyu+ | 93 | [36] |
| 13.57 - 14.91 | 7 | Act. method, HPGe det., Gamma | Associated alpha particles | Ikeda+ | 93 | [37] |
| 14.00 - 19.10 | 4 | Act. method, Ge(Li) or HPGE det., Gamma | Al27(n,a)Na24 and Nb93(n,2n)Nb92m | Lu Hanlin+ | 98 | [38] |
| 13.56 - 14.78 | 7 | Act. method, Ge(Li) det., Gamma | Nb93(n,2n)Nb92m | Filatenkov+ | 99 | [39] |
| 14.10 | 1 | Act. method, Ge(Li) det., Gamma | Nb93(n,2n)Nb92m | Filatenkov+ | 99 | [39] |
| 16.04 - 20.26 | 4 | Act. method, HPGe detector, Gamma | Al27(n,a)Na24 + 2 monit. reactions | Fessler+ | 00 | [40] |

Experimental cross section data [41-70] were rejected due to their discrepancy with the main bulk of experimental data [1-40]. In the rejected experiments [41-50], [52], [55-58], [60-62], [64-67] and [69] the cross section values were measured only in a one neutron energy point in the interval 14 - 15 MeV.

The prepared data base included information about the $^{56}Fe(n,p)^{56}Mn$ reaction cross sections in the 203 points covered energy range from 3.8 MeV to 20.3 MeV. The energy dependence of cross-section from 4.0 MeV to the threshold was extrapolated with L=0 penetrability function for the outgoing p + Mn-56 channel [71].

Statistical analysis of input cross section data was carried out by means of PADE-2 code [74]. Rational function was used as the model function [75].

## Uncertainties in the evaluated $^{56}Fe(n,p)^{56}Mn$ cross sections

Uncertainties in the evaluated excitation function for the $^{56}Fe(n,p)^{56}Mn$ reaction are given in the form of relative covariance matrix for the 25-neutron energy groups (LB=5). The relative covariance matrix was obtained with taking into account uncertainties in the experimental cross section data. Average correlation coefficients ($F_c$) corresponds to experimental data were taken into account also. The Covariance matrix of uncertainties was calculated simultaneously with recommended cross section data by means of PADE-2 code. The eigenvalues of the 6-th digits relative covariance matrix given in the 33-file are the following:

| | | | |
|---|---|---|---|
| 4.35195E-09 | 4.49367E-09 | 4.76919E-09 | 5.19445E-09 |
| 5.64595E-09 | 6.15408E-09 | 7.11594E-09 | 7.89561E-09 |
| 9.40785E-09 | 1.19394E-08 | 1.48739E-08 | 1.86574E-08 |
| 2.18905E-08 | 1.32640E-06 | 2.77587E-04 | 3.86559E-04 |
| 6.52483E-04 | 1.02062E-03 | 1.26078E-03 | 1.33119E-03 |
| 1.81407E-03 | 2.05264E-03 | 3.00443E-03 | 4.57086E-03 |
| 8.12954E-03 | | | |

It is necessary to note that all eigenvalues are positive.

**The main characteristics of the evaluated $^{56}$Fe(n,p)$^{56}$Mn reaction excitation function**

Group cross sections and their uncertainties for the evaluated $^{56}$Fe(n,p)$^{56}$Mn reaction excitation function are adduced in Table 7. Boundaries of groups are the same as in the File-33. Relatively big error 8.21 % in the cross sections in the energy interval from threshold to 5 MeV are due to a big uncertainties in the experimental data in this region..

**Table 7. GROUP CROSS-SECTIONS AND THEIR UNCERTAINTIES FOR THE EVALUATED $^{56}$Fe(n,p)$^{56}$Mn REACTION EXCITATION FUNCTION (boundaries of groups are the same as in the FILE-33)**

| Group number | Energy group [MeV] to [MeV] | Cross-section [mb] | Uncertainty [mb] | Uncertainty [%] |
|---|---|---|---|---|
| 1 | 2.97 - 5.00 | 0.128 | 0.011 | 8.21 |
| 2 | 5.00 - 6.00 | 5.584 | 0.278 | 4.97 |
| 3 | 6.00 - 7.00 | 22.515 | 1.029 | 4.57 |
| 4 | 7.00 - 8.00 | 37.982 | 1.831 | 4.82 |
| 5 | 8.00 - 9.00 | 53.842 | 1.954 | 3.63 |
| 6 | 9.00 - 10.00 | 66.735 | 2.062 | 3.09 |
| 7 | 10.00 - 11.00 | 80.165 | 2.301 | 2.87 |
| 8 | 11.00 - 11.50 | 91.881 | 2.554 | 2.78 |
| 9 | 11.50 - 12.00 | 99.947 | 2.509 | 2.51 |
| 10 | 12.00 - 12.50 | 107.232 | 2.316 | 2.16 |
| 11 | 12.50 - 13.00 | 112.742 | 2.019 | 1.79 |
| 12 | 13.00 - 13.50 | 115.594 | 1.699 | 1.47 |
| 13 | 13.50 - 14.00 | 115.323 | 1.407 | 1.22 |
| 14 | 14.00 - 14.50 | 112.052 | 1.199 | 1.07 |
| 15 | 14.50 - 15.00 | 106.409 | 1.149 | 1.08 |
| 16 | 15.00 - 15.50 | 99.270 | 1.211 | 1.22 |
| 17 | 15.50 - 16.00 | 91.485 | 1.247 | 1.36 |
| 18 | 16.00 - 16.50 | 83.716 | 1.247 | 1.49 |
| 19 | 16.50 - 17.00 | 76.390 | 1.222 | 1.60 |
| 20 | 17.00 - 17.50 | 69.737 | 1.213 | 1.74 |
| 21 | 17.50 - 18.00 | 63.845 | 1.207 | 1.89 |
| 22 | 18.00 - 18.50 | 58.719 | 1.204 | 2.05 |
| 23 | 18.50 - 19.00 | 54.317 | 1.222 | 2.25 |
| 24 | 19.00 - 19.50 | 50.580 | 1.386 | 2.74 |
| 25 | 19.50 - 20.00 | 47.444 | 1.903 | 4.01 |

Evaluated excitation function for the reaction $^{56}$Fe(n,p)$^{56}$Mn is shown in Fig.4a (energy range 3.0 MeV – 12.0 MeV), Fig.4b (energy range 12.0 MeV – 15.0 MeV) and Fig.4c (energy range 15.0 MeV – 20.0 MeV) in comparison with the experimental data and IRDF90v.2 and JENDL/D-99 cross sections.

In the energy range 3 – 13 MeV (Fig.4a) the present evaluation agree well with experimental data. The JENDL/D-99 in the interval 6.4 – 7.2 MeV gives slightly underestimated cross sections in comparison with experimental data. Between 7.5 – 11.5 MeV JENDL/D-99 and present evaluation are well agree. The IRDF-90v2 significantly underestimated the $^{56}$Fe(n,p)$^{56}$Mn cross sections for the incident neutron energies 7.5 – 11.5 MeV. The IRDF-90v2 curve was passed through the noncorrected Smith and Meadows measurements with D(d,n)He3 neuron source [17].

In the energy range 12 – 15 MeV shown in Fig.4b excitation functions from present evaluation and IRDF-90v2 file are differs negligible and agree well with all precise measurements. JENDL/D-99 cross sections in the interval 12 – 13 MeV are slightly underestimated. From new evaluation the$^{56}$Fe(n,p)$^{56}$Mn cross sections in the interval 13 – 15 MeV are determined with uncertainty (1.07 – 1.47) %. This permit to use this data as the reference cross sections.

Above 15 MeV (Fig.4d) the $^{56}Fe(n,p)^{56}Mn$ reaction excitation function agree well with the main bulk of experimental data up to 20 MeV and higher. The present and IRDF-90v.2 evaluations are practically similar up to 19 MeV. JENDL/D-99 evaluation gives in the neutron energy interval 16 – 18.5 MeV slightly underestimated cross sections in a comparison with new evaluation and IRDF-90v.2 data.

Evaluated excitation function for the reaction $^{56}Fe(n,p)^{56}Mn$ was tested with using integral experimental data [78-80], [82] for U-235 thermal fission neutron spectrum and evaluated integral experimental data [81-82] for Cf-252 spontaneous fission neutron spectrum. Data for U-235 thermal fission neutron spectrum and Cf-252 spontaneous fission neutron spectrum were taken from ref.[76] and [76], respectively. The results of testing are given in Table 8.

**Table 8. Calculated and measured averaged cross sections for the $^{56}Fe(n,p)^{56}Mn$ reaction in the U-235 thermal fission and Cf-252 spontaneous fission neutron spectra**

| Type of neutron field | Average cross section, mb | | C/E | 90% response range, MeV |
|---|---|---|---|---|
| | Calculated | measured | | |
| **U-235 thermal fission neutron spectrum** | 1.1085 | 1.090 ± 0.040 [78] | 1.0170 | 5.50 – 11.30 |
| | | 1.130 ± 0.070 [79] | 0.9810 | |
| | | 1.083 ± 0.017 [80] | 1.0235 | |
| | | 1.079 ± 0.017 [82] | 1.0273 | |
| **Cf-252 spontaneous fission neutron spectrum** | 1.4730 | 1.471 ± 0.025 [81] | 1.0014 | 5.50 – 11.80 |
| | | 1.465 ± 0.026 [82] | 1.0055 | |

Calculated from the evaluated excitation function average cross section values for U-235 thermal fission neutron spectrum and Cf-252 spontaneous fission neutron spectrum are agree well with relevant experimental data.

The 90% response ranges of $^{56}Fe(n,p)^{56}Mn$ reaction excitation function are practically the same as for U-235 thermal fission neutron spectrum and for Cf-252 spontaneous fission neutron spectrum: 5.50 – 11.30 MeV and 5.50 – 11.80 MeV, respectively. The results of testing are given in the Table 8 permit to say that evaluated microscopic cross sections for $^{56}Fe(n,p)^{56}Mn$ reaction in the energy range 5.5 – 11.8 MeV agree satisfactory with differential and integral experimental data simultaneously.

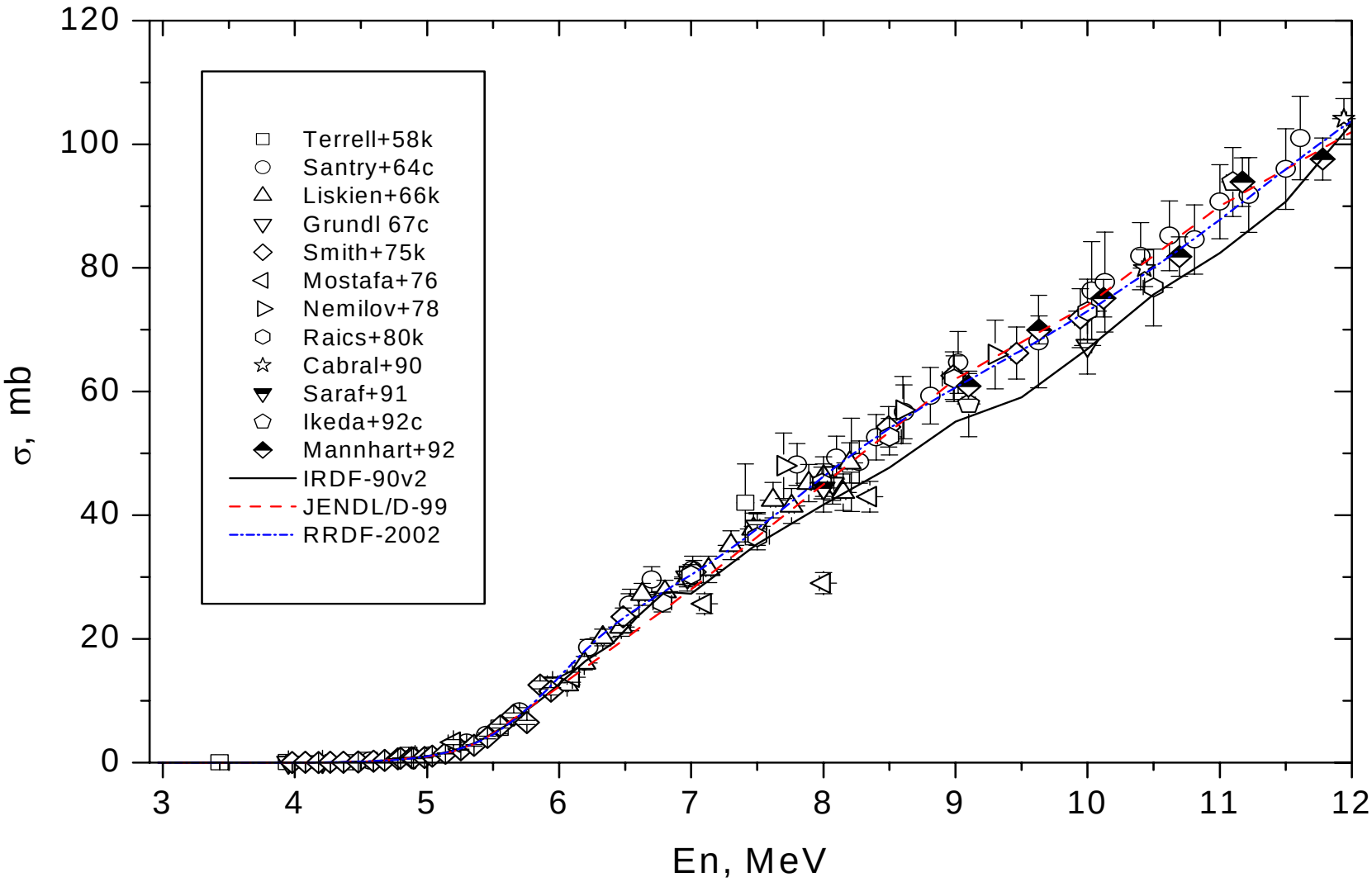


Fig. 4a Evaluated excitation function for the reaction Fe-56(n,p)Mn-56 in the energy range 3 – 12 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

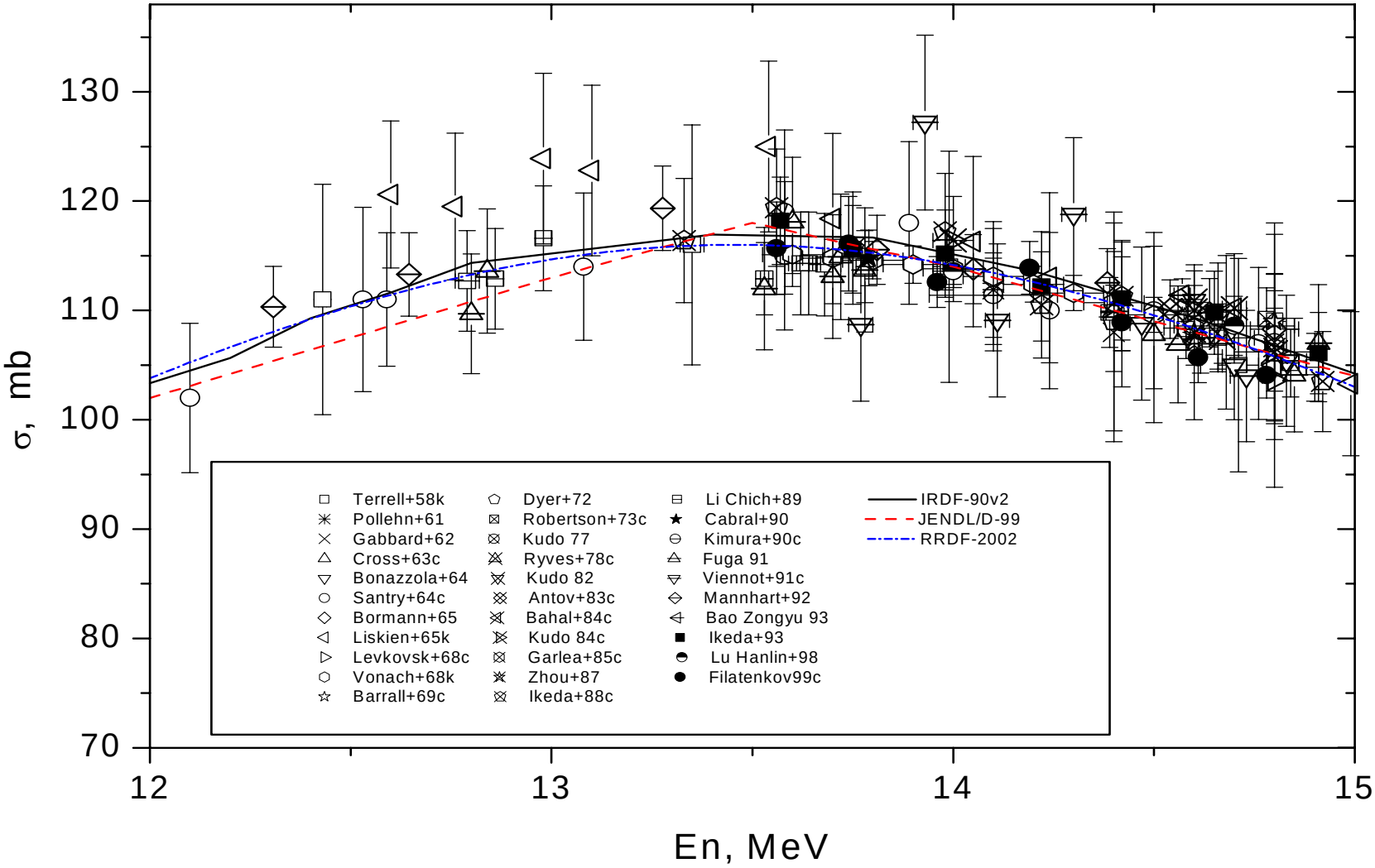


Fig. 4b Evaluated excitation function for the reaction Fe-56(n,p)Mn-56 in the energy range 12 – 15 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

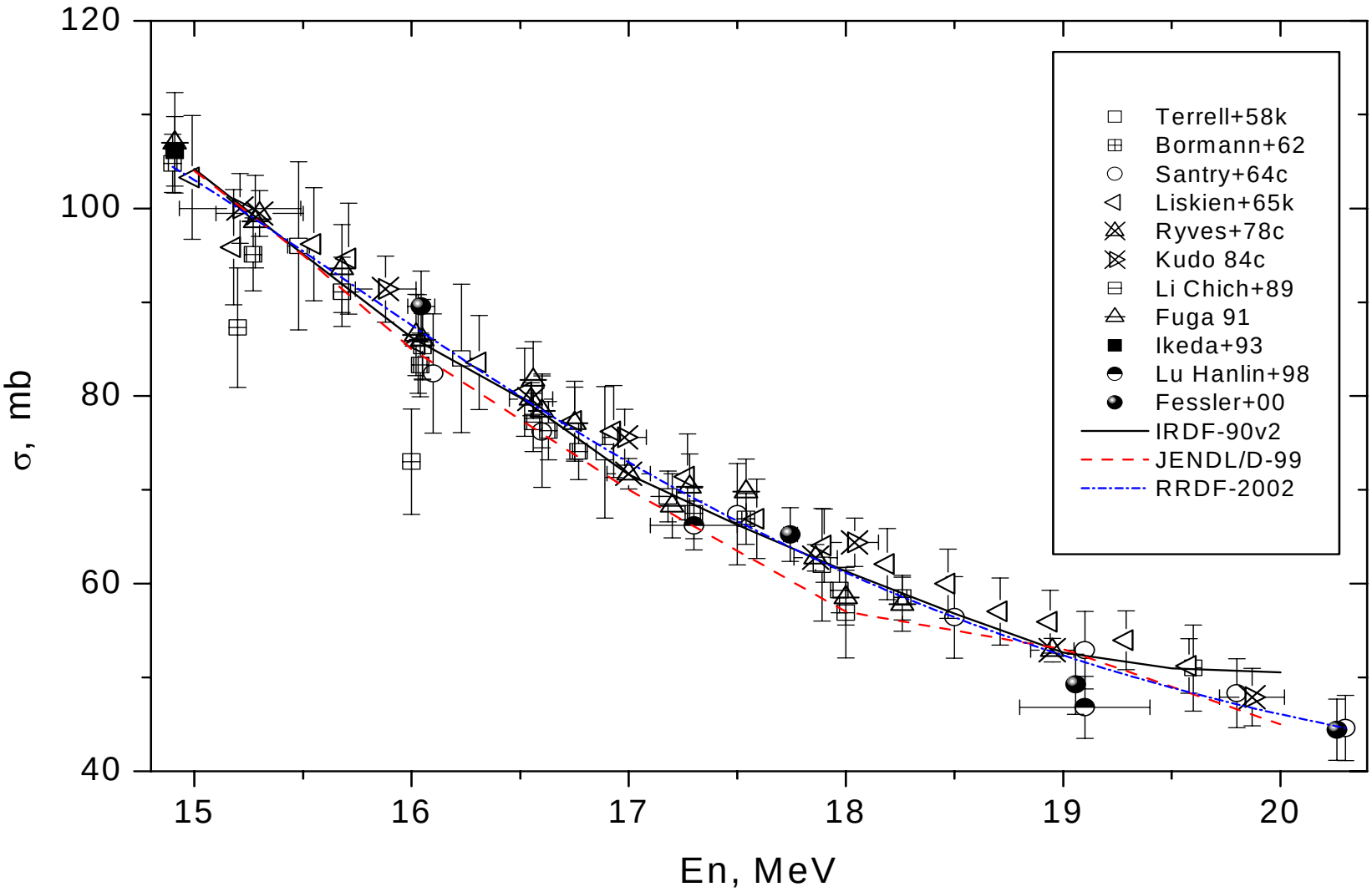


Fig. 4c Evaluated excitation function for the reaction Fe-56(n,p)Mn-56 in the energy range 15 – 20 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

## 5. The evaluation of the Np-237(n,f) reaction excitation function

For determination of $^{237}$Np(n,f) reaction rate by means of activation method it is usually measured activity corresponds to the fission products. About 11 fission products may be proposed to characterize the fission process. In measurements on critical assembles and power reactors for neutron spectrum unfolding it is usually measured activity induced by $^{140}$Ba $\Rightarrow$ $^{140}$La radioactive chain. The cumulative yield of 140 mass chain $^{140}$Ba $\Rightarrow$ $^{140}$La in $^{237}$Np fission depend of average neutron energy and lies between (5.5 – 6.5) %.

Decay data for $^{140}$La residual nucleus are suitable for measurements of neutron induced activity. The half-live of $^{140}$La is equal to (1.6781±0.0003) Days. Nucleus $^{140}$La has 100% β-decay mode. For determination of $^{237}$Np(n,f) reaction rate it is usually measured the activity corresponding to the most intensive gamma-ray lines of $^{140}$La: 328.76 keV ($I_\gamma$=0.203 ± 0.003), 487.02 keV ($I_\gamma$=0.455 ± 0.006), 815.77 keV ($I_\gamma$=0.233 ± 0.002), 1596.21-keV ($I_\gamma$=0.954 ± 0.0008). corresponding to the most intensive gamma-ray line: 1596.21-keV ($I_\gamma$=0.9540 ± 0.014). Recommended values of $^{140}$La half-life and gamma-rays emission probability per decay -$I_\gamma$ were taken from [59].

Excitation function of the $^{237}$Np(n,f) reaction was evaluated for the energies of incident neutrons from 1.000E-05 eV to 20 MeV.

It were analyzed 44 works on measurement of the $^{237}$Np(n,f) reaction cross sections, which were carried out in the period between 1947 and 1999 years. Summary of these experiments is given in Table 9.

### Resolved resonance region

The region of resolved resonances (RRR) was restricted by 130 eV in the ENDF/B-V evaluation (IRDF-90v.2) and by 150 eV in the ENDF/B-VI evaluation [46]. The resolved resonance parameters in the JENDL-3.2 [47] and in the JENDL/D-99 [48] are given up to 130 eV.

In this evaluation the analysis of the resonance parameters available for Np-237 was performed in the energy region up to 600 eV [49]. A statistical method of the resonance analysis was developed which allows to restore the average parameters of the weak missed resonances. The carried out analyze show that missing of the resonances becomes essential above the energy of 150 eV. However only weak resonances are missed with the neutron widths less than the average width by the factor 5-10. The resonances with widths close to average or above it were identified without the noticeable missing up to the energy of 600 eV. So as these resonances give dominant contribution into the neutron cross sections the resolved resonances region in the new evaluation was expanded up to 600 eV and average contribution of the missed weak resonances was taken into account by addition of relevant cross section background in the file MF=3.

The following values are obtained as a result of the analysis taking into account the missed resonances correction: the average resonance spacing $D_0$ = 0.57 ± 0.03 eV, the neutron strength function $S_0$ = (0.97 ± 0.07) $10^4$, the average radiation width $\Gamma_\gamma$ = 40.0 ± 1.2 meV. These values of the average neutron resonances parameters were used for the optical-statistical calculation of the cross sections in the unresolved resonance region.

Considerable attention was paid to the analysis of fission widths and elimination of contradictions in the description of intermediate structure of averaged fission cross sections for the neutron energies above 100 eV. The new experimental data on fission cross sections were included in the analysis. They were obtained by LANL physicists on their neutron spectrometer [40,45] and by Dubna-Obninsk collaboration on the pulsed reactor of JINR [41].

**TABLE 9. SUMMARY OF EXPERIMENTS FOR THE REACTION Np237(n,f)**

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference | | |
|---|---|---|---|---|---|---|
| 0.25 - 3.00 | 16 | Back-to-Back fission counter | U235(n,f) | Klema | 47 | [ 1] |
| 0.46 - 7.45 | 52 | No information | No information | Henkel | 57 | [ 2] |
| 14.60 | 1 | Act. method, Ionization chamber | Associated alpha particles T(d,n) | Protopopov+ | 58 | [ 3] |
| 1.64 - 7.43 | 47 | Back-to-back fission counter | U238(n,f) | Schmitt+ | 59 | [ 4] |
| 0.91 - 2.82 | 29 | Back-to-back fission counter | Np237(n,f) norm. at 1.64 MeV | Schmitt+ | 59 | [ 4] |
| 1.20 - 3.82 | 14 | Scintillation crystal | Li6(n,t)He4 | Murray+ | 59 | [ 5] |
| 3.60 - 7.96 | 10 | Scintillation crystal | Li6(n,t)He4 | Murray+ | 59 | [ 5] |
| 0.01 - 1.50 | 25 | Fission ionization chamber | No information | Gokhberg+ | 59 | [ 6] |
| 9.60 – 21.80 | 17 | TOF method, gas. scint. fiss.chamber | Absolute measurement | Pankratov+ | 60 | [ 7] |
| 2.50 | 1 | TOF method, gas. scint. fiss.chamber | Absolute measurement | Pankratov+ | 63 | [ 8] |
| 6.20 - 9.00 | 5 | TOF method, gas. scint. fiss.chamber | Absolute measurement | Pankratov+ | 63 | [ 8] |
| 9.80 - 21.70 | 17 | TOF method, gas. scint. fiss.chamber | Absolute measurement | Pankratov+ | 63 | [ 8] |
| 22.60 - 26.40 | 5 | TOF method, gas. scint. fiss.chamber | Absolute measurement | Pankratov+ | 63 | [ 8] |
| 1.07 - 1.68 | 3 | Act. method, Prop.gas counter, Beta, Gamma | U235(n,f) | Grundl | 67 | [ 9] |
| 2.19 - 4.21 | 4 | Act. method, Prop.gas counter, Beta, Gamma | U238(n,f) | Grundl | 67 | [ 9] |
| 2.18 - 4.91 | 6 | Act. method, Prop.gas counter, Beta, Gamma | U238(n,f) | Grundl | 67 | [ 9] |
| 5.95 - 8.07 | 4 | Act. method, Prop.gas counter, Beta, Gamma | U238(n,f) | Grundl | 67 | [ 9] |
| 1.00 – 2.25 | 2 | Detection of Fission Products | U235(n,f) | White+ | 67 | [ 10] |
| 5.40 | 1 | Detection of Fission Products | U235(n,f) | White+ | 67 | [ 10] |
| 14.10 | 1 | Detection of Fission Products | U235(n,f) | White+ | 67 | [ 10] |
| 1.00 - 4.50 | 12 | TOF method | U235(n,f) | Stein+ | 68 | [ 11] |
| 14.10 | 1 | Plastic track detector method | U238(n,f) | Iyer+ | 69 | [ 12] |
| 0.10 - 2.85 | 161 | TOF method, 215.7-m flight path | U235(n,f) | Brown+ | 70 | [ 13] |
| 0.20 - 7.66 | 102 | TOF method, solid-state detector | U235(n,f) | Jiacoletti | 72 | [ 14] |
| 2.00 - 3.00 | 3 | Glass method | Pu239(n,f) | Kuprijanov+ | 78 | [ 15] |
| 0.13 - 0.28 | 4 | Doubled fission chamber | Pu239(n,f) | Kuprijanov+ | 78 | [ 15] |
| 0.35 - 3.00 | 39 | Doubled fission chamber | Pu239(n,f) | Kuprijanov+ | 78 | [ 15] |
| 3.60 - 7.00 | 18 | Doubled fission chamber | Pu239(n,f) | Kuprijanov+ | 78 | [ 15] |
| 0.77 - 0.96 | 2 | Manganese bath method, track detector | Ref. Cf-252 source | Grady+ | 79 | [ 16] |

**Table 9. SUMMARY OF EXPERIMENTS FOR THE REACTION Np237(n,f)** (continued)

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference | | |
|---|---|---|---|---|---|---|
| 14.70 | 1 | Time-corr. assoc. particles method | Absolute measurement | Arlt+ | 80 | [ 17] |
| 0.11 - 18.89 | 115 | TOF method, ioniz. fission chamber | U235(n,f) | Behrens | 82 | [18] |
| 2.47 | 1 | 2PI fiss.ion chamber, TOF PRR telesc | 1-H-1(n,n)1-H-1 | Cance+ | 82 | [ 19] |
| 2.47 | 1 | 2PI fiss.ion chamber, TOF BF3 counct | BF3 long counter | Cance+ | 82 | [ 19] |
| 13.52 - 14.80 | 5 | Solid-state track detect., fission chamber | U235(n,f) | Varnagy+ | 82 | [ 20] |
| 13.52- 14.80 | 6 | Solid-state track detect., fission chamber | U238(n,f) | Varnagy+ | 82 | [ 20] |
| 0.13 - 4.53 | 47 | TOF method,Double ionization chamber | U235(n,f) | Meadows | 83 | [ 21] |
| 4.61 - 9.37 | 19 | TOF method,Double ionization chamber | U235(n,f) | Meadows | 83 | [ 21] |
| 8.40 | 1 | Associated particles method | Absolute measurement | Alkhazov+ | 83 | [ 22] |
| 14.70 | 1 | Associated particles method | Absolute measurement | Alkhazov+ | 83 | [ 22] |
| 14.62 | 1 | Act. method, polyest. track det. for fission fr. | Fe56(n,p)Mn56 | Zasadny+ | 84 | [ 23] |
| 4.00 - 5.50 | 4 | Fiss. ioniz. chamber, P-recoil telesc. | 1-H-1(n,n)1-H-1 | Wu Jingxia+ | 84 | [ 24] |
| 14.75 | 1 | Fission rate measur. by fiss. chamber | U235(n,f) | Garlea+ | 84 | [ 25] |
| 5.66 – 10.06 | 16 | TOF method, flight base 60 cm | U235(n,f) | Goverdovskij+ | 84 | [ 26] |
| 7.34 | 1 | Isotope impurities method | U235(n,f) | Goverdovskij+ | 84 | [ 27] |
| 16.40 | 1 | Isotope impurities method | U235(n,f) | Goverdovskij+ | 84 | [ 27] |
| 0.51 - 2.92 | 11 | TOF FP=14 m, fission ionization chamber | U235(n,f) | Kanda | 85 | [ 28] |
| 4.16 – 7.01 | 8 | TOF FP=14 m, fission ionization chamber | U235(n,f) | Kanda | 85 | [ 28] |
| 13.49 – 15.01 | 3 | TOF FP=14 m, fission ionization chamber | U235(n,f) | Kanda | 85 | [ 28] |
| 8.70 | 1 | Time-corr. assoc.particles method | Absolute measurement | Arlt+ | 85 | [ 29] |
| 6.55 - 7.75 | 4 | Ioniz. chamb. (fiss. frag.), scint. det. (neut.) | U235(n,f) | Goverdovskij+ | 85 | [ 30] |
| 4.44 - 10.69 | 35 | Ioniz. chamb. (fiss. frag.), scint. det. (neut.) | U235(n,f) | Goverdovskij+ | 85 | [ 30] |
| 0.70 - 2.99 | 11 | TOF FP=14 m, fission ionization chamber | U235(n,f) | Terayama+ | 86 | [ 31] |

**Table 9. SUMMARY OF EXPERIMENTS FOR THE REACTION Np237(n,f)** (continued)

| Energy range [MeV] | The number of points | Measurement method | Monitor | Reference | | |
|---|---|---|---|---|---|---|
| 4.19 - 6.99 | 10 | TOF FP=14 m, fission ionization chamber | U235(n,f) | Terayama+ | 86 | [ 31] |
| 1.90 | 1 | Time-corr. assoc.particles method | Absolute measurement | Alkhazov+ | 86 | [ 32] |
| 1.90 | 1 | Time-corr. assoc.particles method | Absolute measurement | Kalinin+ | 87 | [ 33] |
| 1.00 - 19.86 | 73 | TOF method, fission ionization chamber | U235(n,f) | Lisowski+ | 88 | [ 34] |
| 14.74 | 1 | Low mass double ionization chamber | U235(n,f) | Meadows | 88 | [ 35] |
| 2.15 - 2.45 | 2 | Low mass double ionization chamber | U238(n,f) | Meadows+ | 89 | [ 36] |
| 1.92 - 2.56 | 42 | No information | U238(n,f) | Meadows+ | 89 | [ 36] |
| 13.75 - 14.80 | 5 | FISCT, low-mass double ioniz. chamber | U235(n,f) | Desdin+ | 89 | [ 37] |
| 1.00 - 1.99 | 24 | TOF method, fission ionization chamber | U235(n,f) | Lisowski+ | 89 | [ 38] |
| 4.90 - 8.40 | 2 | Time-corr. assoc.particles method | Absolute measurement | Merla+ | 91 | [ 39] |
| 18.50 | 1 | Time-corr. assoc.particles method | Absolute measurement | Merla+ | 91 | [ 38] |
| 14.70 | 1 | Time-corr. assoc.particles method | Absolute measurement | Merla+ | 91 | [ 39] |
| 1.02 - 2.00 | 11 | TOF meth, fission ionization chamber | U235(n,f) | Carlson+ | 94 | [ 40] |
| (3 – 360)E-6 | 24 | TOF meth, fission ionization chamber | U235(n,f) | Goverdovskij+ | 95 | [41] |
| 5.157E-9 | 1 | No information | No information | Alfimenkov+ | 95 | [42] |
| 4.65E-7 – 2.15E-2 | 15 | Lead slowing-down spectrometer | U235(n,f) | Gerasimov+ | 97 | [43] |
| (8.4 –87.0)E-3 | 5 | TOF meth, fission ionization chamber | U235(n,f) | Iwasaki | 99 | [44] |

The resulting set of resonance parameters reproduces well the observed intermediate structure of fission cross sections. Corresponding group fission cross sections are 30-50% lower than JENDL-3.2 and JENDL/D-99 evaluations but approximately twice higher than ENDF/B-VI ones. Corrected fission widths of the neutron resonances below 100 eV also result in fission cross sections which are lower than JENDL-3.2 values and JENDL/D-99. It is necessary to note that new experimental cross section data of Gerasimov et al.[43] obtained in the energy interval 0.465 eV – 21.5 keV were not used in the evaluation of resonance parameters due to their very big discrepancy with experimental data [40], [41], [45]. For the incident neutron energies 0.465 – 1.000 eV Gerasimov et al. obtained very overestimated value of $^{237}$Np fission cross section of 465 barn.

**Unresolved resonance region**

Unresolved resonance parameters in the region 600 eV – 6 keV were prepared with using EVPAR code. Average resolved resonance parameters described above were used in the calculation.

**Region of smoothed cross sections**

From the calculation of 90% Response function of the $^{237}$Np(n,f) reaction for a different types of reactors it is evidence that for reactor dosimetry application of the $^{237}$Np(n,f) reaction it is very important to evaluate with more available accuracy cross section data for the neutron energies above 0.01 MeV. First of all the reliable cross section data are needed for the incident neutron energies 0.1 – 5 MeV.

Experimental data [1-40], [44] were analyzed for the evaluation of the $^{237}$Np(n,f) excitation function in the neutron energy region of 6 keV - 20 MeV. The top priority was given to absolute measurements where no reference cross sections were used to determine the neutron flux and to time-of-flight experiments with simultaneous registration of the fission and monitoring reaction events.

In a very many experiments the $^{237}$Np(n,f) cross sections were measured relatively to the fission of U-235. The use as the standard of the U-235 fission cross section from ENDF/B-VI library [50] instead of the old one (ENDF/B-V) results in decrease of the $^{237}$Np(n,f) cross sections in average by 2 percent in 0.1-2.0 MeV range and by 1.5 percent in 2.0-3.0 MeV range.

In the work by V.M.Kupriyanov et al. [15] the $^{237}$Np(n,f) cross sections were measured against the fission cross sections of $^{239}$Pu. At the present time there are no recommended $^{239}$Pu(n,f) cross sections as a standard data. The data from two libraries were used to get absolute values: ENDF/B-VI [51] and JENDL- 3.2. [52] Below 1.6 MeV the results of Ref. [15] disagree with the integral experiments no matter which data are used for $^{239}$Pu(n,f). The analysis of Kupriyanov et al. data demonstrated that the good agreement with the rest of data may be obtained for the energy region of 1.6-7.0 MeV if $^{239}$Pu(n,f) monitoring data are taken from JENDL-3.2.[52].

The ratio of $^{237}$Np to $^{235}$U fission cross sections measured by Behrens [18] in 0.11-18.89 MeV energy range was multiplied by factor of 1.051. This normalization factor was obtained from the values of the functional $<\sigma_{Np237(n,f)}>/ <\sigma_{U235(n,f)}>$ in the 1-5 MeV energy range evaluated before. There is a lot of experimental data which are in good agreement in this interval. The ratio of the $^{237}$Np(n,f) evaluated averaged cross section for the neutron spectrum of Cf-252 spontaneous fission, known from many works, to the averaged data of Behrens [18] is equal to 1.055 that confirms our renormalization of these data. The analysis of experimental data on the ratio of $^{237}$Np and $^{235}$U fission cross sections indicates that the relative energy trends of $<\sigma_{Np237(n,f)}>/ <\sigma_{U235(n,f)}>$ measured by Terayama et al. [30] in the energy range of 4.19-6.99 MeV and by Goverdovskiy et al in the 5.66-10.06 MeV energy range [26] coincides with the results of other authors. To make them agree in absolute values Terayama and Goverdovskiy results were multiplied by 0.96 and 1.079 respectively. The data on the $^{237}$Np fission cross sections obtained by Terayama et al on T(p,n)He-3 neutron source for the 0.70- 2.99 energy range are in good agreement with the results of Refs. [33-34], [36], [38], [40]. So they were corrected only according to the new cross section data on the monitoring reaction U-235(n,f) [46].

Experimental data of Meadows et al [21] as well as that of Kupriyanov et al [15] are systematically too low below 1 MeV that contradicts to the evaluated integral experiments available. Above 1 MeV Meadows data well agree with the results of other authors so they were included in the final evaluation only above this energy.

Due to a big discrepancies in the experimental cross sections in the energy range above 12 MeV data from GNASH were used for testing experimental data. As a result of this test experimental data of Protopopov et al. [3] and Pankratov et al. [7,8] were rejected.

The prepared data base for the evaluation $^{237}$Np(n,f) reaction excitation function included information about fission cross sections in the neutron energy range from 8.7 keV to 20 MeV. The evaluation $^{237}$Np(n,f) excitation function in the energy range 8.7 keV – 20 MeV has been carried out within the framework of generalized least squares method. Rational function was used as a model function [53]. Procedure of calculation recommended cross section data was performed by means of PADE-2 code [54].

**Uncertainties in the evaluated Np-237(n,f) cross sections**

Uncertainties in the evaluated excitation function for the $^{237}$Np(n,f) reaction are given by means of the two block matrixes. The first block matrixes is used for description of the cross sections uncertainty in the resolved and unresolved resonance regions and in the smooth cross sections up to 0.1 MeV.

In the energy range 1.000E-05 – 0.1 MeV uncertainties are given in the form of diagonal matrix of uncertainties for 6-th neutron energy intervals (LB=1). Uncertainties in the resolved resonance parameters were recalculated to the uncertainties in fission cross sections.

In the energy range 0.1 - 20 MeV uncertainties are presented in the form of relative covariance matrix for the 48-neutron energy groups (LB=5). The relative covariance matrix was obtained with taking into account uncertainties in the experimental cross section data.. Average correlation coefficients ($F_c$) corresponds to experimental data was taken into account.

The second block of the matrix was prepared with using PADE-2 code. Eigenvalues test carried out by PADE-2 code show that all eigenvalues of 6-th digits relative covariance matrix are the positive:

| | | | |
|---|---|---|---|
| 1.49939E-07 | 1.52531E-07 | 1.53109E-07 | 1.53318E-07 |
| 1.54049E-07 | 1.55336E-07 | 1.56641E-07 | 1.58051E-07 |
| 1.58347E-07 | 1.60763E-07 | 1.63743E-07 | 1.64776E-07 |
| 1.67513E-07 | 1.69820E-07 | 1.73330E-07 | 1.75751E-07 |
| 1.77557E-07 | 2.05370E-07 | 2.66364E-07 | 2.70615E-07 |
| 2.75409E-07 | 2.80956E-07 | 2.93138E-07 | 3.15582E-07 |
| 3.35128E-07 | 4.86134E-07 | 7.89097E-07 | 3.07453E-06 |
| 1.65989E-05 | 9.67332E-05 | 1.24983E-04 | 1.51845E-04 |
| 4.05040E-04 | 4.14092E-04 | 5.11273E-04 | 5.63190E-04 |
| 7.24776E-04 | 8.29295E-04 | 9.68770E-04 | 9.77438E-04 |
| 1.07709E-03 | 1.13969E-03 | 1.57856E-03 | 1.84372E-03 |
| 2.04068E-03 | 2.65362E-03 | 3.89983E-03 | 1.60049E-02 |

**The main characteristics of the evaluated $^{237}$Np(n,f) reaction excitation function**

Fission cross sections from 1.000E-5 eV to 6 keV are reconstructed from evaluated MLBW resolved and unresolved resonance parameters. Evaluated by means of PADE-2 code the $^{237}$Np(n,f) reaction cross sections in the energy range 6 keV – 20 MeV are given in the pointwise form in the File-3. No background fission cross sections are given in the File-3 below 6 keV.

Total, fission, capture thermal cross sections and resonance integrals obtained from the present evaluation for $^{237}$Np are adduced below in Table 10. The adopted resonance parameters give the thermal cross sections and resonance integrals which reproduce the recommended experimental data from compilations [49] rather well. Fission cross section at the neutron energy 0.025 eV from the present evaluation is agree exactly with recommended value (0.0215±0.0024) barn.

**Table 10. Thermal cross sections and resonance integrals obtained from the present evaluation for the $^{237}$Np**

| Parameters | This evaluation, barn | Experimental data [49], barn |
|---|---|---|
| $\sigma_{tot}$ | 190.23 | - |
| $\sigma_f$ | 0.0215 | 0.0215±0.0024 |
| $\sigma_\gamma$ | 176.04 | 175.9±2.9 |
| $I_f$ | 6.930 | 6.9±1.0 |
| $I_\gamma$ | 642.30 | 640±50 |

Evaluated excitation function for the reaction $^{237}$Np(n,p) is shown in Fig.5a (energy range 0.01 – 0.5 MeV), Fig.5b (energy range 0.5 – 2 MeV), Fig.5c (energy range 2 – 7 MeV) and Fig.5d (energy range 7 – 20 MeV) in comparison with the experimental data and IRDF90v.2 and JENDL/D-99 cross sections.

One can see from Fig.5a that between 0.1 and 0.5 MeV the present evaluation passed over corrected experimental data of Jiacoletti et al. [14] and Behrens [18] and not contradicted the tendency of cross section behavior predicted in the Meadows measurements [21].In the interval 0.28 – 0.50 MeV the present and JENDL/D-99 evaluations are practically the similar. Below 0.28 MeV JENDL/D-99 evaluation pass through experimental data of Brown et al. [13]. ENDF/B-V evaluation (IRDF-90v.2) leads to the Brown et al. experimental data [13] from 0.1 to 0.5 MeV. Below 0.28 MeV fission cross sections from present evaluation in the limit of uncertainty agree with experimental data of Hoffman.

In energy range 0.5 – 2.0 MeV (Fig.5b) new evaluation agree well with experimental data [18], [21], [28], [31], [33-36], [38], [40]. The existent discrepancies between evaluated data are not significant.

The above mentioned situation is repeated in the neutron energy range 2 – 7 MeV (Fig.5c). The ENDF/B-V (IRDF-90v2) evaluation in the interval 6.5 – 7.0 MeV gives overestimated fission cross sections in comparison with present and JENDL/D-99 evaluations.

The $^{237}$Np fission cross sections from new evaluation in the energy interval 7 – 20 MeV agree satisfactory with the main bulk of experimental data. The ENDF/B-V (IRDF-90v2) evaluation was obtained on the basis of the old experimental data of Protopopov [3] and Pankratov et al. [8] and gives the significantly overestimated fission cross sections for $^{237}$Np above 9 MeV in comparison with present and JENDL/D-99 evaluations. The $^{237}$Np fission cross section for the incident neutron energies 14.50 – 14.75 MeV evaluated in this work with accuracy of 1.57 %.

The prepared new evaluation of $^{237}$Np(n,f) reaction excitation function was tested by using integral experimental data for four reference neutron fields.

The results of the testing of the evaluated excitation function for the $^{237}$Np(n,f) reaction using the integral experiments with various neutron spectra are given in Table 11.

The present evaluated fission cross section is in a good agreement with the integral experimental data both for U-235 thermal neutron spectrum and for Cf-252 spontaneous fission neutron spectrum. The evaluated fission cross section agrees within the accuracy with integral experimental data for SIGMA-SIGMA facility. The fission cross sections measured in CFRMF neutron field are lower than calculated ones for any fission cross section evaluations: ENDF/B-V (IRDF-90v2), ENDF/B-VI, JENDL/D-99 and present $^{237}$Np(n,f) data. This apparently indicates the necessity of more detailed and careful analysis of the CFRMF experimental data accuracy.

New measurements of the $^{237}$Np(n,f) reaction cross section for the neutron spectrum of CFRMF facility will be useful also.

**Table 11. Calculated and measured averaged cross sections for the $^{237}$Np(n,f) reaction for four reference neutron fields**

| Type of neutron field | Average cross section, mb | | C/E | 90% response range, MeV |
|---|---|---|---|---|
| | Calculated | measured | | |
| **U-235 thermal fission neutron spectrum** | 1356.2 | 1359.0 ± 28.5 [55]<br>1353.0 ± 24.0 [56]<br>1350.0 ± 24.0 [57] | 1.0021<br>1.0024<br>1.0046 | 0.690 – 5.600 |
| **Cf-252 spontaneous fission neutron spectrum** | 1359.9 | 1356.0 ± 22.0 [58]<br>1361.0 ± 21.6 [57] | 1.0029<br>0.9992 | 0.690 – 6.000 |
| **CFRMF = coupled fast reactivity measurement facility (idaho)** | 585.46 | 548.0 ± 18.1 [59] | 1.0684 | 0.425 – 4.500 |
| **SIGMA-SIGMA = coupled thermal/fast uranium + boron carbide facility** | 613.39 | 634.0 ± 22.2 [60] | 0.9674 | 0.450 – 4.200 |

Group cross sections and their uncertainties for the evaluated $^{237}$Np(n,f) reaction excitation function are adduced in Table 12. Boundaries of groups are the same as in the File-33. Big uncertainties of (30 – 60) % in fission cross sections in resolved and unresolved resonance region and up to 0.1 MeV are to the significant discrepancy exist between experimental data [40], [45] and [41].

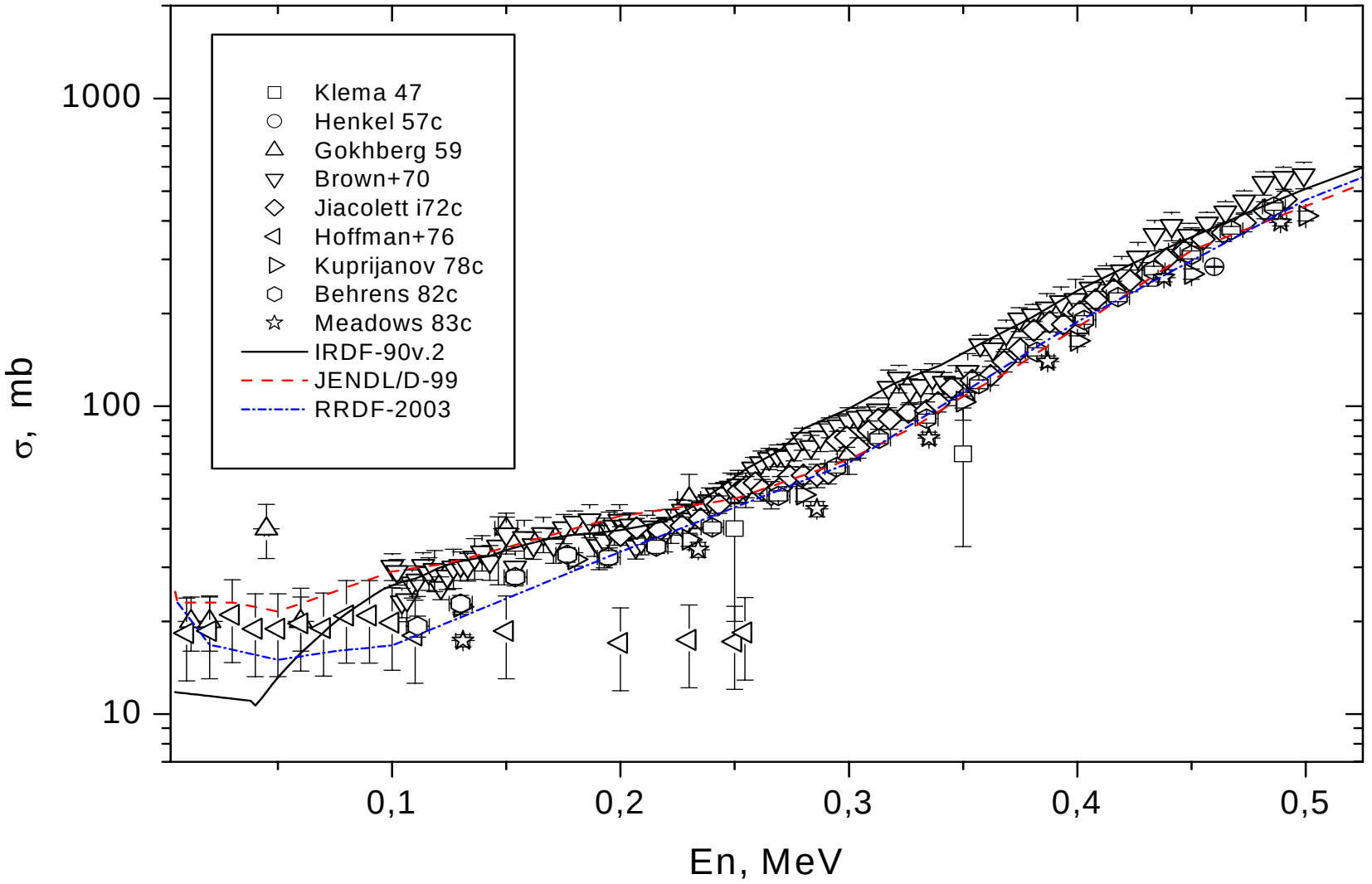


Fig. 5a Evaluated excitation function for the reaction Np-237(n,f) in the energy range 0.01 – 0.5 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

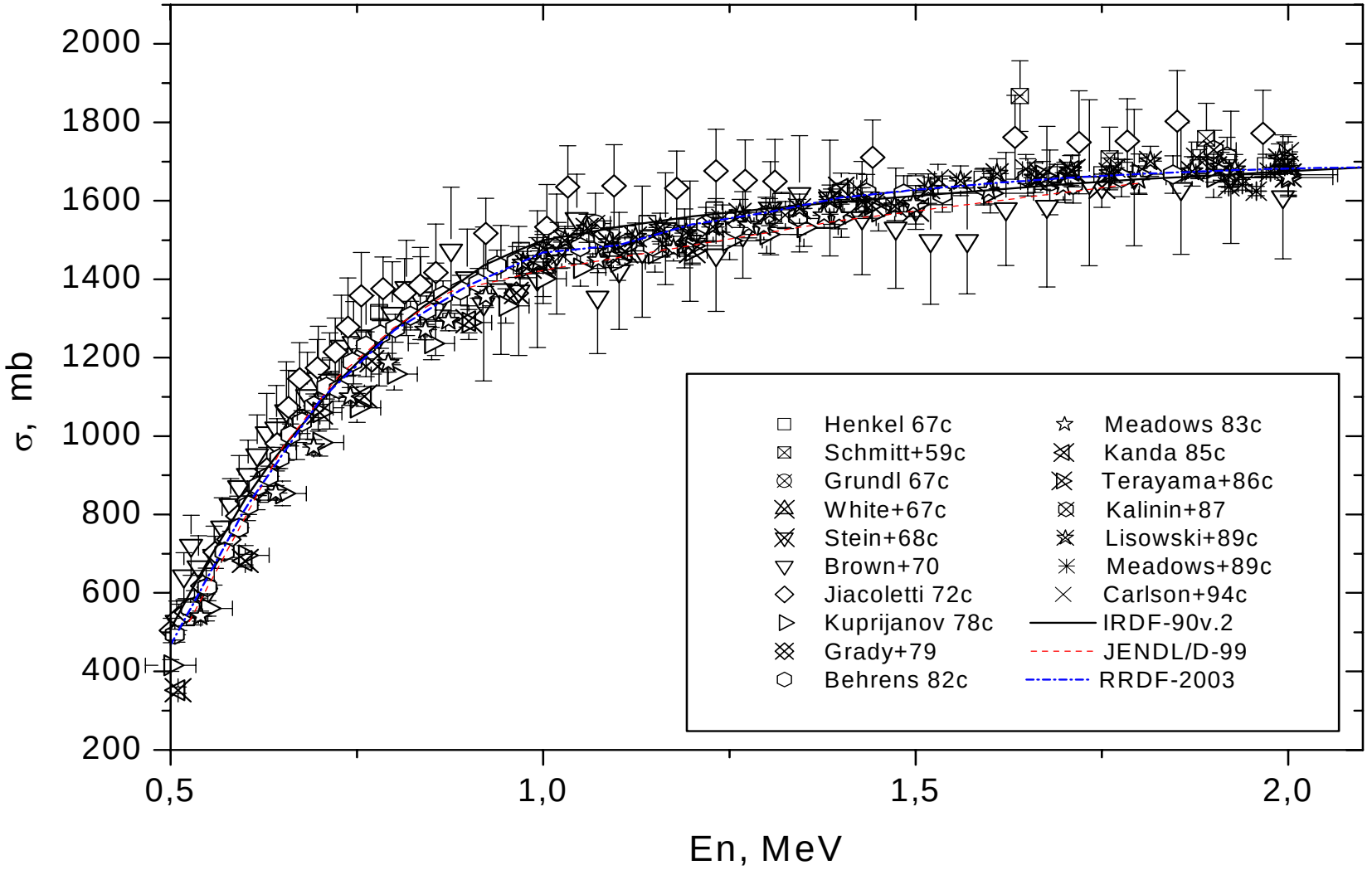


Fig. 5b Evaluated excitation function for the reaction Np-237(n,f) in the energy range 0.5 – 2.0 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

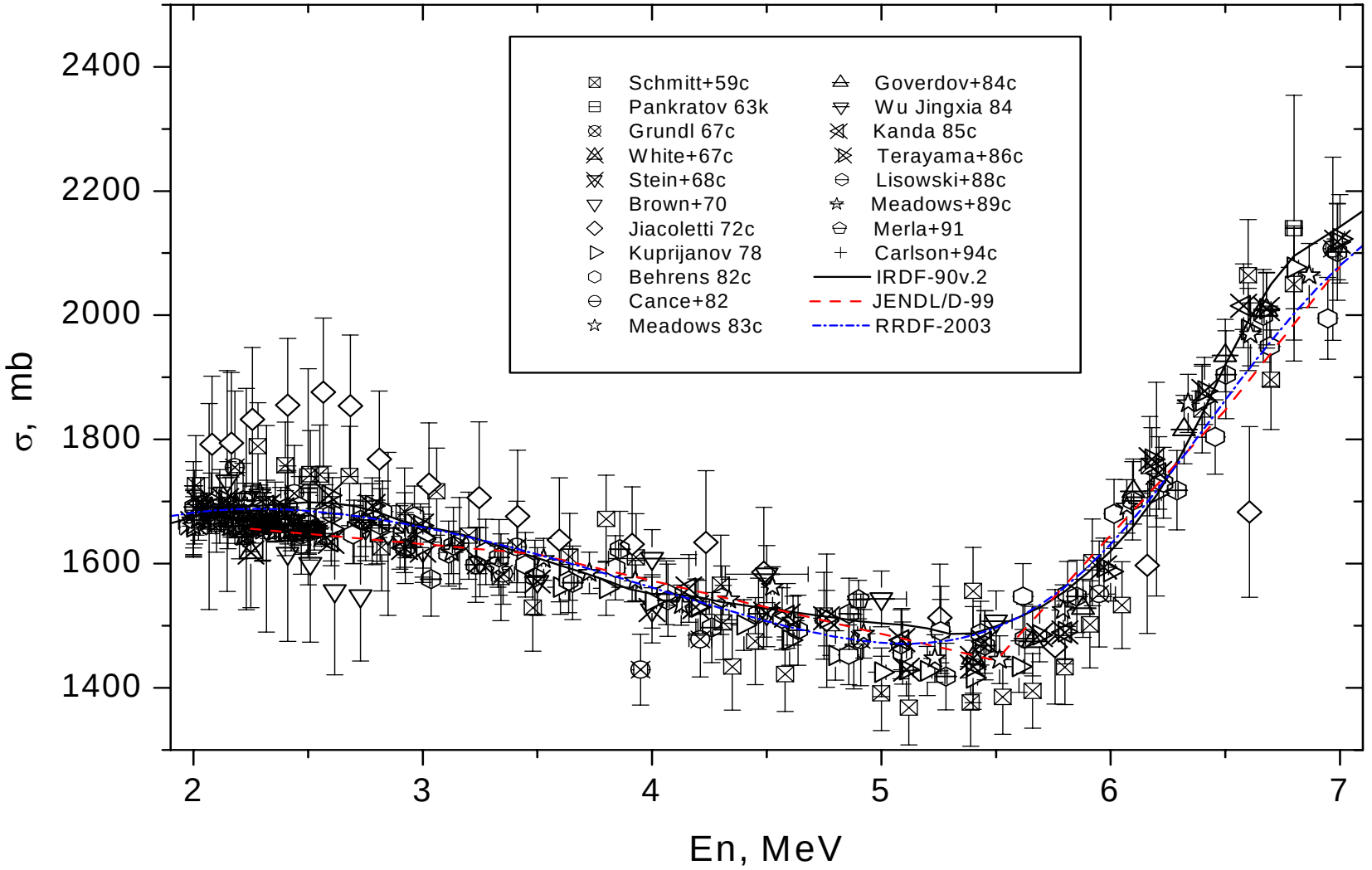


Fig. 5c Evaluated excitation function for the reaction Np-237(n,f) in the energy range 2 – 7 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

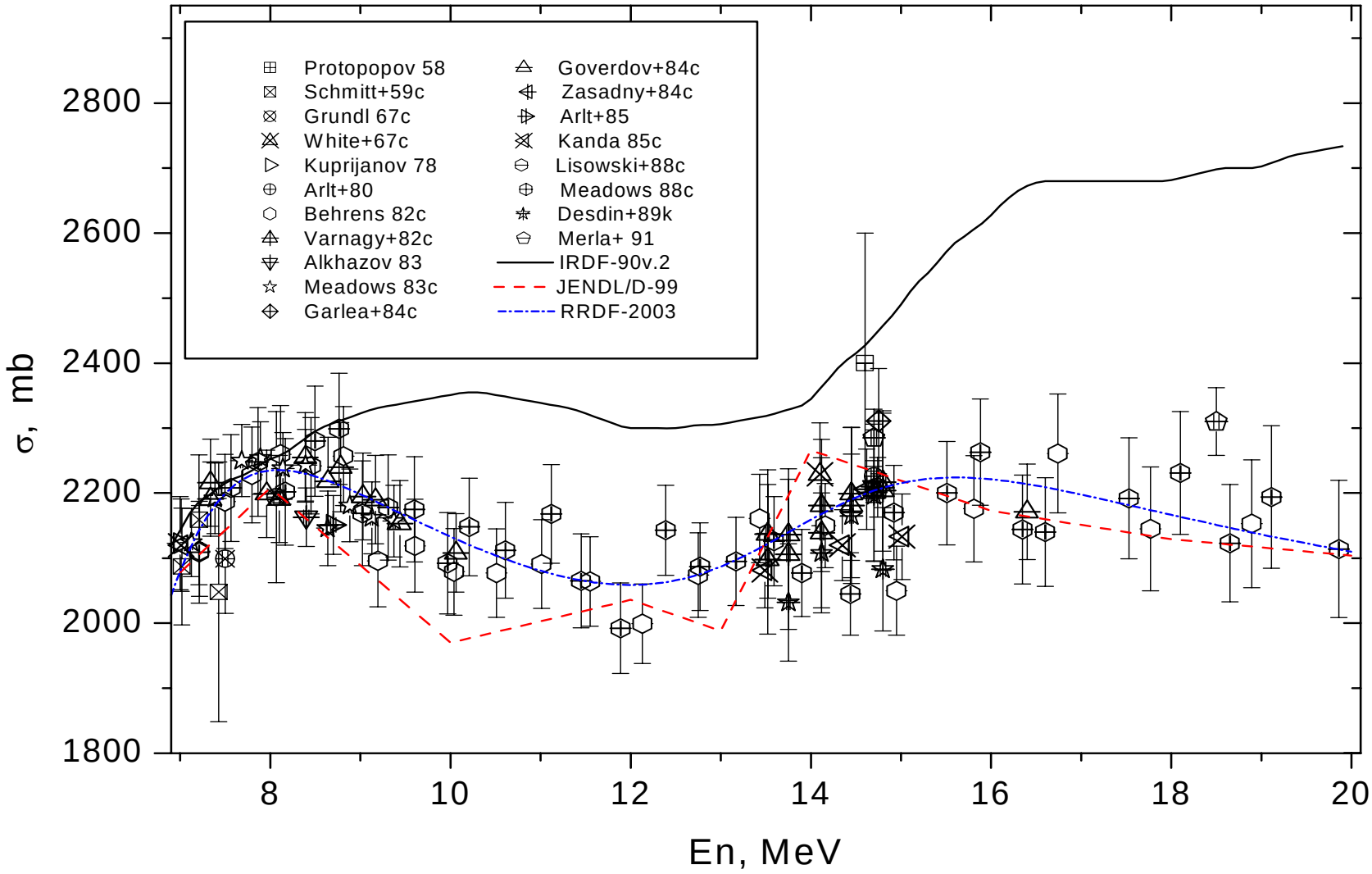


Fig. 5d Evaluated excitation function for the reaction Np-237(n,f) in the energy range 7 – 20 MeV in a comparison with IRDF-90v.2 , JENDL/D-99 and experimental data.

**Table 12. GROUP CROSS-SECTION AND THEIR UNCERTAINTIES FOR THE EVALUATED $^{237}$Np(n,f) REACTION FUNCTION (boundaries of groups are the same as in the FILE-33)**

| Group number | Energy group [MeV] to [MeV] | Cross-section [mb] | Uncertainty [mb] | Uncertainty [%] |
|---|---|---|---|---|
| 1 | 1.000E-11 - 1.000E-05 | 16.53 | 1.65 | 10.00 |
| 2 | 1.000E-05 - 7.000E-05 | 211.62 | 63.49 | 30.00 |
| 3 | 7.000E-05 - 4.000E-04 | 75.07 | 45.04 | 60.00 |
| 4 | 4.000E-04 - 5.000E-03 | 34.36 | 17.18 | 50.00 |
| 5 | 5.000E-03 - 5.000E-02 | 17.32 | 6.93 | 40.00 |
| 6 | 5.000E-02 - 1.000E-01 | 15.99 | 4.80 | 30.00 |
| 7 | 1.000E-01 - 2.000E-01 | 26.42 | 1.43 | 5.43 |
| 8 | 2.000E-01 - 3.000E-01 | 47.87 | 1.82 | 3.80 |
| 9 | 3.000E-01 - 4.000E-01 | 120.39 | 3.42 | 2.84 |
| 10 | 4.000E-01 - 5.000E-01 | 321.56 | 7.62 | 2.37 |
| 11 | 5.000E-01 - 6.000E-01 | 641.99 | 13.87 | 2.16 |
| 12 | 6.000E-01 - 7.000E-01 | 958.51 | 19.36 | 2.02 |
| 13 | 7.000E-01 - 8.000E-01 | 1188.92 | 23.78 | 2.00 |
| 14 | 8.000E-01 - 9.000E-01 | 1338.78 | 27.04 | 2.02 |
| 15 | 9.000E-01 - 1.000E+00 | 1438.40 | 28.91 | 2.01 |
| 16 | 1.000E+00 - 1.200E+00 | 1503.09 | 29.16 | 1.94 |
| 17 | 1.200E+00 - 1.400E+00 | 1572.28 | 30.03 | 1.91 |
| 18 | 1.400E+00 - 1.600E+00 | 1627.19 | 29.13 | 1.79 |
| 19 | 1.600E+00 - 1.800E+00 | 1657.41 | 29.34 | 1.77 |
| 20 | 1.800E+00 - 2.000E+00 | 1675.97 | 29.66 | 1.77 |
| 21 | 2.000E+00 – 2.500E+00 | 1686.44 | 30.52 | 1.81 |
| 22 | 2.500E+00 – 3.000E+00 | 1673.36 | 33.63 | 2.01 |
| 23 | 3.000E+00 – 3.500E+00 | 1637.74 | 36.03 | 2.20 |
| 24 | 3.500E+00 – 4.000E+00 | 1588.56 | 37.49 | 2.36 |
| 25 | 4.000E+00 – 4.500E+00 | 1533.74 | 38.96 | 2.54 |
| 26 | 4.500E+00 – 5.000E+00 | 1487.00 | 39.55 | 2.66 |
| 27 | 5.000E+00 – 5.500E+00 | 1477.59 | 39.16 | 2.65 |
| 28 | 5.500E+00 – 6.000E+00 | 1553.80 | 43.04 | 2.77 |
| 29 | 6.000E+00 – 6.500E+00 | 1742.76 | 49.84 | 2.86 |
| 30 | 6.500E+00 – 7.000E+00 | 1977.51 | 56.95 | 2.88 |
| 31 | 7.000E+00 – 7.500E+00 | 2147.83 | 58.85 | 2.74 |
| 32 | 7.500E+00 – 8.000E+00 | 2222.28 | 56.00 | 2.52 |
| 33 | 8.000E+00 – 8.500E+00 | 2232.70 | 52.69 | 2.36 |
| 34 | 8.500E+00 – 9.000E+00 | 2212.87 | 50.45 | 2.28 |
| 35 | 9.000E+00 – 9.500E+00 | 2181.97 | 50.84 | 2.33 |
| 36 | 9.500E+00 – 1.000E+01 | 2149.02 | 53.30 | 2.48 |
| 37 | 1.000E+01 – 1.050E+01 | 2118.21 | 56.13 | 2.65 |
| 38 | 1.050E+01 – 1.100E+01 | 2091.86 | 58.36 | 2.79 |
| 39 | 1.100E+01 – 1.150E+01 | 2071.96 | 61.12 | 2.95 |
| 40 | 1.150E+01 – 1.200E+01 | 2060.82 | 63.89 | 3.10 |
| 41 | 1.200E+01 – 1.250E+01 | 2061.14 | 64.51 | 3.13 |
| 42 | 1.250E+01 – 1.300E+01 | 2075.22 | 61.84 | 2.98 |
| 43 | 1.300E+01 – 1.350E+01 | 2102.99 | 56.99 | 2.71 |
| 44 | 1.350E+01 – 1.400E+01 | 2139.83 | 49.00 | 2.29 |
| 45 | 1.400E+01 – 1.450E+01 | 2176.92 | 38.10 | 1.75 |
| 46 | 1.450E+01 – 1.500E+01 | 2205.33 | 33.96 | 1.54 |
| 47 | 1.500E+01 – 1.550E+01 | 2220.58 | 41.52 | 1.87 |
| 48 | 1.550E+01 – 1.600E+01 | 2223.31 | 51.58 | 2.32 |
| 49 | 1.600E+01 – 1.650E+01 | 2216.87 | 58.97 | 2.66 |
| 50 | 1.650E+01 – 1.700E+01 | 2204.90 | 64.16 | 2.91 |
| 51 | 1.700E+01 – 1.750E+01 | 2190.17 | 69.43 | 3.17 |
| 52 | 1.750E+01 – 1.800E+01 | 2174.45 | 76.32 | 3.51 |
| 53 | 1.800E+01 – 1.900E+01 | 2151.27 | 91.21 | 4.24 |
| 54 | 1.900E+01 – 2.000E+01 | 2122.90 | 117.82 | 5.55 |

## 6. Conclusion

New evaluations of cross sections and their uncertainties for dosimetry reactions $^{27}Al(n,p)^{27}Mg$, $^{56}Fe(n,p)^{56}Mn$ and $^{237}Np(n,f)$ have been carried out in the frame work of IAEA Research Contract No. 11372/RB.

Comparison of evaluated and experimental data show that excitation functions for the $^{27}Al(n,p)^{27}Mg$, $^{56}Fe(n,p)^{56}Mn$ and $^{237}Np(n,f)$ reactions from present evaluation in common more better agree with microscopic and integral experimental data than evaluated data from IRDF-90v.2 and JENDL/D-99 libraries. The $^{27}Al(n,p)^{27}Mg$ and $^{56}Fe(n,p)^{56}Mn$ reaction cross sections for neutron energies between 13 – 15 MeV are determined in the new evaluation with accuracy (1.45 – 1.88) % and (1.07 – 1.47) %, respectively. This permit to use the above mentioned cross sections as the reference cross section data in the energy rage 13 – 15 MeV.

Prepared in the ENDF-6 format data files for the $^{27}Al(n,p)^{27}Mg$, $^{56}Fe(n,p)^{56}Mn$ and $^{237}Np(n,f)$ reactions may be consider as candidates to the new International Reactor Dosimetry File: IRDF-2002.

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**References:**

**Section 1**

1. N.P.Kocherov, P.K.McLaughlin The International Reactor Dosimetry File (IRDF-90) Report IAEA-NDS-141 Rev.2, Vienna, October 1993
2. K.Kobayashi Evaluated cross section data for the Np-237(n,f) reaction, MAT-9346, eval. April 1996, JENDL/D-99 Library, 1999
3. Y.Ikeda et al. J. of Nuclear Science and Technology, v.30, pp.870-880, September 1993
4. A.Filatenkov et al. Report, RI-252, St. Petersburg, May 1999
5. J.Csikai et al. Private communication, Debrecen, Hungary, May 1998
6. A.Fesseler Private communication, Geel, Belgium, June 2000
7. A.Fesseler Activation Cross Sections and Isomeric Cross Section Ratios in Neutron Induced Reactions on Cr-, Fe-, and Ni-Isotopes in the Energy Range 9 to 21 MeV. Report Jui-3502, Julich, January 1998
8. W.Mannhart, G.Boerker Progress Report, INDC(Ger)-036/L, p.59, July 1992
9. Bao Zongyu et al. China J. Nucl. Phys., v.15,no.4,p.341, 1993
10. Lu Hanlin et al. Report INDC(CPR)-045, IAEA, Vienna, October 1998
11. P.W.Lisowski et al. Proc. of an International Conference on Nuclear Data for Science and Technology, Mito, Japan, 30 May - 3 June 1988, Saikon Publishing Co., LTD, 1989, p.97.
12. P.W.Lisowski et el. Proc. of Conference: 50 Years with Nuclear Fission, Washington D.C., 25-28 April 1989, NIST, Gaithersburg, MD, 1989, p. 443.
13. A.D.Carlson et al. Proc. of an Int. Conf. on Nuclear Data for Science and Technology, Gatlinburg, Tennessee, USA, May 9-13, 1994, Vol.1, p. 40
14. A.A. Goverdovski et al. Rus. J. Nucl. Phys., 1995, v.58, p.27.

**Section 2**

1. S.F.Mughabghab et al. Neutron Cross Sections, vol.1, part B, New York, Academic Press, 1984

2. S.I.Sukhoruchkin et al. Landolt Bornstein New Series, v.I/16B, ed. H.Schopper, Springer, 1998
3. G.M.Hale, P.G.Young The H(n,n) Cross Section Below 20 MeV. In Nuclear Data Standards for Nuclear Measurements. Report NEANDC-311"U", OECD 1992, pp.10-16
4. G.M.Hale, P.G.Young The $^{6}$Li(n,t)$^{4}$He Cross Section. In Nuclear Data Standards for Nuclear Measurements. Report NEANDC-311"U", OECD 1992, pp.22-26
5. K.I.Zolotarev et al. The Al-27(n,p)Na-24 reaction excitation function in the energy range from threshold to 23 MeV, Obninsk, IPPE, eval. March 2003
6. K.I.Zolotarev The Al-27(n,a)Na-24 reaction excitation function in the energy range from threshold to 20 MeV, Obninsk, IPPE, eval. March 2003
7. H.Kitazawa et al. Evaluated Neutron Data for Si-28, JENDL-3.2 Library, MAT-3141, eval. March 1988.
8. J.Janczyszyn Proc. of an Int. Conference on Nuclear Data for Science and Technology, 6 - 10 September 1982, Antwerp, Holland, D.Reidel Publishing Company, p.869, 1983
9. N.P.Kocherov, P.K.McLaughlin The International Reactor Dosimetry File (IRDF-90) Report IAEA-NDS-141 Rev.2, Vienna, October 1993
10. K.I.Zolotarev The Fe-56(n,p)Mn-56 reaction excitation function in the energy range from threshold to 20 MeV, Obninsk, IPPE, eval. October 2002
11. T.B.Ryves et al. Proc. of a Specialist's Meeting on Neutron Activation Cross Sections for Fission and Fusion Energy Applications, ANL, USA, 13 - 15 September 1989, p.65-68
12. K.I.Zolotarev et al. Proc. of Int. Conf. on Nuclear Data for Science and Technology, May 19-24, 1997, Trieste, Italy, Part II, pp.1258-1261
13. K.I.Zolotarev The In-115(n,n')In-115m reaction excitation function in the energy range from threshold to 20 MeV, Obninsk, IPPE, eval. March 2003
14. M.Sowerby The U235 Fission Cross Section. In Nuclear Data Standards for Nuclear Measurements. Report NEANDC-311"U", OECD 1992, pp.51-58;
    L.W.Weston et al. Evaluated Neutron Data for U-235, ENDF/B-VI Library, MAT-9228, eval. April 1989, rev.5 October 1997
15. Y.Nakajima, Y.Kanda The U238 Fission Cross Section. In Nuclear Data Standards for Nuclear Measurements. Report NEANDC-311"U", OECD 1992, pp.70-74;
    W.Weston et al. Evaluated Neutron Data for U-238, ENDF/B-VI Library, MAT-9237, eval. November 1989, rev.3 February 1997
16. M.Kawai et al. Evaluated Neutron Data for Pu-239, JENDL-3.2 Library, MAT-9437, Rev.2, February 1993.
17. R.B.Firestone Table of Isotopes, Eighth edition, John Wiley & Sons, Inc., New York, 1995
18. O.Bersillon Decay Data and Isotopic Abundances for Dosimetry Application. Proc of the IAEA Technical Meeting on the IRDF-2002 file, IAEA, Vienna, 2003 (to be published)
19. V.P.Yarina, N.B.Galiev Atomnaya Energiya, Vol.52, No.2, p.136, 1982 [in Russian]
20. A.V.Ignatyuk et al. Landolt Bornstein New Series, v.I/16A, Part 1, ed. H.Schopper, Springer, 1998
21. E.L.Trykov, G.Ya.Tertychnyi Private communication, IPPE, Obninsk, May 1999
22. P.G.Young, E.D.Arthur A Preequilibrium Statistical Nuclear Model Code for Calculation of Cross Section and Emission Spectra. Report LA-6947, Los Alamos, 1977
23. J.Raynal Report IAEA SMR-9/8, 1972
24. O.Bersillon, SCAT2-A Spherical Optical Model Code, Prog. Rep. CEA-N-2037, p.111, 1978

**Section 3**

1. S.G.Forbes Phys. Rev., v.88, p.1309, December 1952
2. R.L.Henkel EXFOR 11524.002, 1954

3. O.M.Hudson jr, I.L.Morgan Bull. Am. Phys. Soc., v.4, p.97 (G2), March 1959
4. M.J.Depraz et al. Journal de Physique-Colloque, v.21, p.377, May 1960
5. G.S.Mani et.al. Nucl. Phys., v.19, n.5, p.535, November 1960
6. H.Pollehn, H.Neuert Zeitschrift fuer Naturforschung, Sect. A, v.16, p.227, 1961
7. S.K.Mukherjee et al. Proc. of the Physical Society, v.77, p.508, February 1961
8. F.Gabbard, B.D.Kern Phys. Rev., v.128, p.1276, 1962
9. J.Csikai et al. Atomki Koezlemenyek v.4, p.137, June 1962 ;
   J.Csikai et al. Nucl. Phys., v.46, p.141, July 1963
10. C.G.Bonazzola et al. Nucl. Phys., v.51, p.337, February 1964
11. J.E.Strain, W.J.Ross Report ORNL-3672, January 1965
12. R.Bass et al. Progress Report EANDC(E)-66, p.64, Feb. 1966
13. G.Calvi et al. EXFOR 20924.003, February 1966 ;
    G.Calvi et al. Nucl. Phys., v.39, p.621, December 1962
14. J.A.Grundl Nucl. Sci. Eng., v.30, p.39, October 1967
15. J.M.Ferguson, J.C.Albergotti Nucl. Phys., Sec.A, v.98, p.65, May 1967
16. N.Ranakumar et al. Nucl. Phys., v.A122, p.679, 1968
17. P.Cuzzocrea et al. Nuovo Cimento B, v.54, p.53, March 1968
18. P.N.Tiwari, E.Kondaiah Phys. Rev., v.167, p.1091, March 1968
19. P.Rama Prasad et al. Nucl. Phys., v.A138, p.85, November 1969
20. L.Husain et al. Phys. Rev. C, v.1, p.1233, April 1970
21. W.Schantl Abstract communicated by Nuclear Data Section, IAEA, Vienna, 1970
22. G.N.Salaita Nucl. Phys., v.A170, p.193, July 1971
23. R.Mogharrab, H.Neuert Atomkernenergie, v.19, p.107, 1972
24. Ju.A.Nemilov, Ju.N.Trofimov Report "Yadernye Konstanty", v.9, p.53, 1972
25. J.Dresler, J.Araminowicz, U.Gaguska Progress Report INR-1464, p.12, May 1973
26. J.C.Robertson, B.Audric, P.Kolkowski Journal Nuclear Energy, v.27, p.531, August 1973
27. D.L.Smith, J.W.Meadows Nucl. Sci. Eng., v.58, p.314, 1975
28. A.Mostafa Nuclear Science and Applications, Ser. B: Phys. sciences, v.9, p.10, October 1976
29. R.A.Sigg Dissertation Abstracts, v.B37, p.2237, November 1976
30. C.E.Ai et al. Nucl. Science Jour., v.14, no.4, p.1, December 1977
31. P.Andersson et al. Report LUNF-D6-3021, November 1978
32. A.M.Ghose Report IAEA/TA-1390, October 1978
33. N.Lakshmana et al. Pramana, v.11, no.5, p.595, November 1978
34. T.B.Ryves et.al. J. of Physics, pt.G, v.4, no.11, p.1783, 1978
35. V.I.Melent'jev, V.V.Ovechkin Atomnaya Energiya, v.44, no.2, p.271, Feb. 1978
36. P.N.Ngoc et al. Proc. of the 2-nd Int. Symposium on Neutron-induced Reactions, Smolenice,CSSR, 25-29 June 1979, v.6,p.415
37. P.Welch et al. Bull. Amer. Phys. Soc., v.26, p.708, May 1981
38. R.C.Harper, W.L.Alford Jour. of Physics, Part G, v.8, p.153, January 1982
39. S.M.Qaim Nucl. Phys. A, v.382, p.255, July 1982
40. A.Chiadli et al. Proc. of an International Conference on Nuclear Data for Science and Technology, 6 - 10 September 1982, Antwerp, Holland, D.Reidel Publishing Company, p.404, 1983
41. J.Janczyszyn Proc. of an Int. Conference on Nuclear Data for Science and Technology, 6-10 September 1982, Antwerp, Holland, D.Reidel Publishing Company, p.869, 1983
42. H.A.Husain, S.E.Hunt International J. of Applied Radiation and Isotopes, v.34, no.4, p.731, 1983
43. V.T.Shchebolev et al. Atomnaya Energiya (Sov.), v.54, no.6, p.417, June 1983

44. D.A.Bradley et al. Proc. of an International Symposium on Fast Neutrons in Science and Technology, Chiang Mai, 4-8 February 1985, p.19
45. W.Enz et al. Annalen der Physik, v.42, no.3, p.283, 1985
46. I.Garlea et al. Rev. Roum. Phys., v.30, no.8, p.673, 1985
47. J.Csikai, T.Chimoye et al. Zeitschrift fuer Physik, Sec.A, v.325, p.69, September 1986
48. J.W.Meadows et al. Ann. Nucl. Energ., v.14, p.489, September 1987
49. Y.Ikeda, C.Konno, K.Oishi et al. Report JAERI-1312, March 1988
50. K.Kudo et.al. Proc. of an International Conference on Nuclear Data for Science and Technology, Mito, Japan, 30 May - 3 June 1988, Saikon Publishing Co., LTD, 1989, pp.1021-1024
51. I.Kimura, K.Kobayashi Nucl. Sci. Eng., v.106, p.332, 1990 ;
K.Kobayashi, I.Kimura Proc. of an International Conference on Nuclear Data for Science and Technology, 30 May - 3 June 1988, Mito, Japan, Saikon Publishing Co., LTD, pp.261-265, 1989 ;
K.Kobayashi, I.Kimura Progress Report NEANDC(J)-116, September 1985
52. A.Ercan et al. Proc. of an International Conference on Nuclear Data for Science and Technology, 13-17 May 1991, Julich, FRG, Springer-Verlag, 1992
53. Y.Ikeda et al. J. of Nuclear Science and Technology, v.30, pp.870-880, September 1993
54. Zhou Hongyu et al. Proc. of an International Conference on Nuclear Data for Science and Technology, Gatlinburg, Tennessee, USA, May 9-13, 1994, Vol.1, pp. 166-169
55. J.Csikai et al. Private communication, Debrecen, April 1998
56. A.A.Filatenkov et al. Report RI-252, St.Petersburg, May 1999;
A.A.Filatenkov et al. VANT, Ser.:Yadernye Konstanty, v.2, p.8, Moscow, 1996
57. A.Fessler, A.J.M.Plompen et al. Nucl. Sci. Eng., v.134, no.2, pp.171-200, February 2000
58. T.Shimizu, S.Furuichi, H.Sakane, M.Shibata, K.Kawade Proc. of The 2000 Symposium on Nuclear Data, November 16-17, 2000 JAERI, Tokai, Japan, pp.194-199
59. E.B.Paul, R.L.Clarke Canadian Journal of Physics, v.31, p.267, 1953
60. S.Yasumi Journal of the Physical Society of Japan, v.12, p.443, May 1957
61. G.Brown et al. Philosophical Magazine, v.2, p.785, 1957
62. A.Poularikas, R.W.Fink Phys. Rev., v.115, p.989, 1959
63. C.S.Khurana, H.S.Hans Proc. of 4th Nuclear Physics and Solid Stata Physics Symposium, 24-26 February 1960, Waltair, India, p.297
64. R.S.Storey, W.Jack, A.Ward Proc. Phys. Soc., v.75, p.526, 1960
65. M.Sakisaka et al. Journal of the Physical Society of Japan, v.16, p.1869, October 1961
66. J.Kantele, D.G.Gardner Nucl. Phys, v.35, p.353, 1962
67. W.Langmann EXFOR 20903.003, September 1962
68. F.L.Hassler, R.A.Peck jr Phys. Rev., v.125, p.1011, 1962
69. B.Mitra, A.M.Ghose Nucl. Phys., v.83, p.157, July 1966
70. R.Prasad, D.C.Sarkar Nuovo Cimento, v.A3, no.3, p.467, 1971
71. J.C.Robertson, K.J.Zieba Annals of Nucl. Energy, v.26, no.1, p.1, 1972
72. R.A.Jarjis Jounal of Physics, pt.G, v.4, n.3, p.445, 1978
73. J.Csikai Proc. of an International Conference on Nuclear Data for Science and Technology, 6 - 10 September 1982, Antwerp, Holland, D.Reidel Publishing Company, p.414, 1983
74. Tahir Indian Journal of Pure and Applied Physics, v.23, p.439, September 1985
75. J.P.Gupta et.al. Indian J. Pramana, v.24, p.637, 1985
76. L.I.Klochkova et al. Voprosy Atomnoy Nauki i Tekhniki, Serija: Jadernye Konstanty, v.1, p.27, 1992 ;
L.I.Klochkova et al. Proc. of the 1-st International Conference on Neutron Phys., Kiev, USSR, 14 - 18 September 1987, v.3, p.315, Moscow 1988

77. R.B.Firestone Table of Isotopes, Eighth edition, Vol. 1, John Wiley & Sons, Inc., New York, 1995
78. K.I.Zolotarev, P.K.Zolotarev The In-115(n,n')In-115m reaction excitation function in the energy range from threshold to 20 MeV, Obninsk, IPPE, eval. March 2003
79. S.A.Badikov et al. Preprint FEI-1686, Obninsk, 1985
80. S.Badikov, N.Rabotnov, K.Zolotarev Proc. of NEANSC Speciali-st's Meeting on Evaluation and Processing of Covariance Data, Oak Ridge, USA, 7-9 September 1992, OECD, Paris, 1993, p.105
81. O.Horibe et al. Proc. of Conference: 50 Years with Nuclear Fission, Washington D.C., 25-28 April 1989, v.2, p.923
82. W.Mannhart Progress Report INDC(Ger)-045, pp.40-43, June 1999
83. W.Mannhart Validation of Differential Cross Sections with Integral Data , Report INDC(NDS)-435, pp.59-64, IAEA, Vienna, September 2002
84. L.W.Weston et al. Evaluated Neutron Data for Uranium-235, ENDF/B-VI Library, MAT=9228, MF=5, MT=18, eval. April 1989
85. W.Mannhart IAEA-TECDOC-410, p.158, IAEA, Vienna, 1987
86. K.J.R.Rosman, P.D.P.Taylor Isotopic Compositions of the Elements 1997
87. H.Vonach The $^{27}Al(n,\alpha)^{24}Na$ Cross Section. In Nuclear Data Standards for Nuclear Measurements. Report NEANDC-311"U", OECD 1992, pp.75-77

**Section 4**

1. G.Brown Philosophical Magazine, v.2, p.785, 1957
2. J.Terrell, D.M.Holm Phys. Rev., v.109, p.2031, 1958
3. H.Pollehn, H.Neuert Zeitschrift f. Naturforschung, sect. A, v.16, p.227, 1961
4. F.Gabbard, B.D.Kern Phys. Rev., v.128, p.1276, 1962
5. W.G.Cross et al. Progress Report EANDC(CAN)-16, p.1, January 1963
6. D.C.Santry, J.P.Batler Can. J. Phys., v.42, p.1030, 1964
7. C.G.Bonazzola et al. Nucl. Phys., v.51, p.337, February 1964
8. M.Bormann et al. Nucl. Phys., v.63, p.438, March 1965
9. H.Liskien, A.Paulsen J. of Nuclear Energy, v.19, p.73, February 1965
10. H.Liskien, A.Paulsen Nukleonik, v.8, p.315, June 1966
11. J.A.Grundl Nucl. Sci. Eng., v.30, p.39, October 1967
12. V.N.Levkovskiy et al. Yadernaja Fizika (Sov.), v.8, no.1, p.7, July 1968
13. H.K.Vonach et al. Proc. of 2nd Conference on Nuclear Cross Sections and Technology, Washington D.C., 4-7 March 1968, v.2, p.885
14. R.C.Barrall et al. Report AFWL-TR-68-134, March 1969
15. N.C.Dyer, J.H.Hamilton Inorg. Nucl. Chem., v.34, p.1119, 1972
16. J.C.Robertson et al. J. of Nuclear Energy, v.27, p.139, March 1973
17. D.L.Smith, J.W.Meadows Nucl. Sci. Eng., v.58, p.314, 1975
18. K.Kudo Nuclear Instruments and Methods, v.141, p.325, March 1977
19. T.B.Ryves et al. J. Metrologia, v.14, n.3, p.127, June 1978
20. Ju.A.Nemilov, Ju.N.Trofimov Progress Report YFI-26, p.25, November 1978
21. P.Raics et al. Proc. of the 5th All Union Conference on Neutron Physics, Kiev, 15-19 September 1980, v.1, p.236
22. K.Kudo Progress Report NEANDC(J)-83/U, p.1, September 1982
23. A.Antov et al. Bulgarian J. of Physics, v.10(6), p.601, 1983
24. K.Kudo The IAEA Advisory Group Meeting on Nuclear Standards Reference Data, Geel, Belgium, 1984
25. B.M.Bahal, R.Pepelnik Report GKSS-84-E-, 1984

26. I.Garlea et al. Proc. of the 14-th International Symposium on Nuclear Physics, Gaussig, GDR, 19-23 November 1984, ZFK-562, p.126, July 1985
27. Zhou Muyao et al. China J. Nucl. Phys., v.9, p.34, Feb. 1987
28. Y.Ikeda et al. Report JAERI-1312, March 1988
29. Li Chichou, Lu Hanlin et al. Progress Report INDC(CPR)-16 , IAEA, Vienna, August 1989
30. S.Cabral, G.Boerker, H.Klein, W.Mannhart Nucl. Sci. Eng., v.106, p.308, 1990
31. I.Kimura, K.Kobayashi Nucl. Sci. Eng., v.106, p.332, 1990
32. S.K.Saraf et al. Nucl. Sci. Eng., v.107, p.365, April 1991
33. P.Fuga Nuclear Instruments and Methods, vA309, no.3, p.500, November 1991
34. Y.Ikeda et al. Progress Report INDC(JPN)-162/U, p.24, August 1992
35. W.Mannhart, G.Boerker Progress Report, INDC(Ger)-036/L, p.59, July 1992
36. Bao Zongyu et al. China J. Nucl. Phys., v.15,no.4,p.341, 1993
37. Y.Ikeda et al. J. of Nuclear Science and Technology, v.30, pp.870-880, September 1993
38. Lu Hanlin et al. Report INDC(CPR)-045, IAEA, Vienna, October 1998
39. A.A.Filatenkov et al. Report RI-252, St.Petersburg, May 1999;
A.A.Filatenkov et al. VANT, Ser.:Yadernye Konstanty, v.2, p.8, Moscow, 1996
40. A.Fessler Report JUL-3502, FZ Julich GmbH, Germany, 1998 ;
A.Fessler, A.J.M.Plompen et al. Nucl. Sci. Eng., v.134, no.2, pp.171-200, February 2000
41. S.G.Forbes Phys. Rev., v.88, p.1309, December 1952
42. E.B.Paul, R.L.Clarke Canadian J. Phys., v.31, p.267, 1953
43. G.W.Mc Clure, D.W.Kent J. Franklin Inst., v.260, p.238, 1955
44. D.L.Allan Proc. Physical Society, section A, v.70, p.195, March 1957
45. S.Yasumi J. Phys. Soc. Japan, v.12, p.443, May 1957
46. P.V.March, W.T.Morton Philosophical Magazine, v.3, p.143, 1958
47. B.D.Kern et al. Nucl. Phys., v.10, p.226, May 1959
48. M.J.Depraz et al. Journal Phys. Radium, v.21, p.377, May 1960;
M.J.Depraz et al. Journal de Physique-Colloque, v.21, p.377, May 1960
49. R.S.Storey et al. Proc. Phys. Soc., v.75, p.526, 1960
50. D.M.Chittenden et al. Phys. Rev., v.122, p.860, May 1961
51. M.Bormann et al. Zeitschrift fuer Physik, v.166, p.477, 1962
52. J.E.Strain, W.J.Ross Report ORNL-3672, January 1965
53. J.D.Hemingway et al. Proc. Royal Society, section A, v.292, p.180, May 1966
54. P.Cuzzocrea et al. Nuovo Cimento B, v.54, p.53, March 1968
55. B.Joensson et al. Arkiv fuer Fysik, v.39, p.395, April 1969
56. S.M.Qaim et al. Proc. of Conference on Chemical Nuclear Data, Measurements and Applicat., Univ. of Kent, Canterbury, 20-22 September 1971, p.121
57. J.J.Singh Trans. Amer. Nucl. Soc., v.15, p.147, June 1972
58. R.Spangler et al. Ann. Nucl. Sci., v.22, p.818, November 1975
59. A.B.M.G.Mostafa Nuclear Science and Applications, Series B: Physical sciences, v.9, p.10, October 1976
60. Z.A.Ramendik et al. Atomnaja Energija (Sov.), v.42, no.2, p.136, February 1977
61. S.Sothras Dissertation Abstracts, v.B38, p.280, July 1978
62. D.Sharma et al. Proc. of the 21-st Nuclear Physics and Solid State Physics Symposium, Bombay, India, 28-31 December 1978, v.2, p.349
63. P.N.Ngoc et al. Progress Report INDC(HUN)-20, p.3, March 1983;
P.N.Ngoc et al. Nucleonika (Pol), v.29, p.87, 1984
64. P.N.Ngoc et al. Report INDC(VN)-2, November 1983
65. I.Garlea et al. Rev. Roum. Phys., v.29, p.421, 1984
66. J.P.Gupta et.al. Indian J. Pramana, v.24, p.637, 1985

67. M.Viennot et al. Nucl. Sci. Eng., v.108, p.289, July 1991
68. A.Ercan et al. Proc. of an International Conference on Nuclear Data for Science and Technology, 13-17 May 1991, Julich, FRG, Springer-Verlag, 1992
69. L.I.Klochkova et al. Voprosy Atomnoy Nauki i Tekhniki, Serija: Jadernye Konstanty, v.1, p.27, 1992 ;
L.I.Klochkova et al. Proc. of the 1-st International Conference on Neutron Phys., Kiev, USSR, 14 - 18 September 1987, v.3, p.315, Moscow 1988
70. I.Garlea et al. Rev. Roum. Phys., v.37, no.1, pp.19-25, 1992
71. S.A.Badikov, A.B.Pashchenko Voprosy Atomnoy Nauki i Tekhniki, Ser.: Jadernye Konstanty, 2(53), p.70, 1987
72. Y.Nakajima, Y.Kanda The U238 Fission Cross Section. In Nuclear Data Standards for Nuclear Measurements. Report NEANDC-311"U", OECD, Paris, 1992, pp.70-74;
W.Weston et al. Evaluated Neutron Data for U-238, ENDF/B-VI Library, MAT-9237, eval. November 1989, rev.3 February 1997
73. K.I.Zolotarev The Al-27(n,a)Na-24 reaction excitation function in the energy range from threshold to 20 MeV, Obninsk, IPPE, eval. March 2003
74. S.A.Badikov et al. Preprint FEI-1686, Obninsk, 1985
75. S.Badikov, N.Rabotnov, K.Zolotarev Proc. of NEANSC Speciali-st's Meeting on Evaluation and Processing of Covariance Data, Oak Ridge, USA, 7-9 September 1992, OECD, Paris, 1993, p.105
76. L.W.Weston et al. Evaluated Neutron Data for Uranium-235, ENDF/B-VI Library, MAT-9228, eval. April 1989, rev.5 October 1997
77. W.Mannhart IAEA-TECDOC-410, p.158, IAEA, Vienna, 1987
78. W.Mannhart Proc. 5-th ASTM-EUR. Symp. on Reactor Dosimetry, Geesthacht, FRG, September 24-28, 1984, Vol.2, p.813, 1985
79. O.Horibe et al. Proc. of Conference: 50 Years with Nuclear Fission, Washington D.C., 25-28 April 1989, v.2, p.923
80. W.Mannhart Progress Report INDC(Ger)-045, pp.40-43, June 1999
81. W.Mannhart Handbook on Nuclear Activation Cross Sections, IAEA Tech. Report Ser. No.273, p.413, 1987
82. W.Mannhart Validation of Differential Cross Sections with Integral Data , Report INDC(NDS)-435, pp.59-64, IAEA, Vienna, September 2002
83. K.J.R.Rosman, P.D.P.Taylor Isotopic Compositions of the Elements 1997
84. R.B.Firestone Table of Isotopes, Eighth edition, Vol. 1, John Wiley & Sons, Inc., New York, 1995

**Section 5**

1. E.D.Klema Phys. Rev., v.72, p.88, July 1947
2. R.L.Henkel Report LA-2114, 1957 R.L.Henkel Report LA-2122, June 1957
3. A.N.Protopopov et al. Atomnaja Energija (Sov.),v.4, p.190, 1958
4. H.W.Schmitt, R.B.Murrey Phys. Rev., v.116, p.1575, 1959
5. R.B.Murrey, H.W.Schmitt Phys. Rev., v.115, p.1707, 1959
6. B.M.Gokhberg et al. Doklady Akademii Nauk SSSR, v.128,(6), p.1157, 1959
7. V.M.Pankratov et al. Atomnaja Energija (Sov.),v.9, p.399, 1960
8. V.M.Pankratov Atomnaja Energija (Sov.), v.14, p.177, 1963
9. J.A.Grundl Nucl. Sci. Eng., v.30, p.39, October 1967
10. P.H.White, G.P.Warner J. Nucl. Energy, v.21, p.671, Aug. 1967

11. W.E.Stein, R.K.Smith, H.L.Smith. Proc. of Conf. on Neutron Cross Sections and Technology, Washington, D.C., March 4-7, 1968, NBS Special Publication 299 , p.627 , U.S. National Bureau of Standards, 1968.
12. R.H.Iyer, R.Sampathkumar Proc. of 12th Symp. on Nuclear Phys. and Solid State Phys., Roorkee, India, 28-31 December 1969, v.2, p.289 ;R.H.Iyer, R.Sampathkumar Progress Report BARC/I-79, p.55, 1970
13. W.K.Brown et al. Nucl. Phys., vA156, p.609, November 1970
14. R.J.Jiacoletti, W.K.Brown, H.G.Olson. Nucl. Sci. Eng., v.85, p.271-279, 1983
15. V.M.Kuprijanov et al. Atomnaja Energija (Sov.), v.45, no.6, p.440, December 1978
16. D.J.Grady et al. Proc. of an Int. Conf. on Nuclear Cross Sections for Technology, Knoxville, Tennessee, 22-26 October 1979, p.976, NBS Spec. Publ.594, September 1980
17. R.Arlt et al. Report ZFK-410, p.122,January 1980
18. J.W.Behrens, J.C.Browne, J.C.Malden Nucl. Sci. Eng., v.80, p.393, 1982
19. M.Cance, G.Grenier Proc of an Int. Conference on Nuclear Data for Science and Technology, Antwerp, 6-10 September 1982, Dr. Reidel Publishing Company, 1983, p.51
20. M.Varnagy, S.Juhasz, J.Csikai Nucl. Instr. Meth., v.196, p.465, May 1982
21. J.W.Meadows Nucl. Sci. Eng., v.85, p.271, November 1983
22. I.D.Alkhazov et al. Proc. of the 3-d All-union Conference on the Neutron Radiation Metrology at Reactors and Accelerators, v.2, p.201, Moscow, CNIIATOMINFORM, 1983
23. K.R.Zasadny et al. J. of Trans. Amer. Nucl. Soc., v.47, p.425, November 1984
24. Wu Jingxia et al. Chinese J. of Nuclear Physics, v.6, p.369, November 1984
25. I.Garlea et al. Revue Roumaine de Physique, v.29, p.421, 1984
26. A.A.Goverdovskij et al. Preprint FEI-1552, 1984
27. A.A.Goverdovskij et al. VANT, Serija: Yadernye Konstanty, v.3(57), p.13, September 1984
28. K.Kanda et al. Report JAERI-M-85-035, p.220, 1985.
29. R.Arlt et al. Isotopenpraxis, v.21, p.344, 1985
30. A.A.Goverdovskij et al. Atomnaja Energija (Sov.), v.58, no.2, p.137, February 1985
31. H.Terayama et al. Progress Report NEANDC(J)-122, Sep. 1986
32. I.D.Alkhazov et al. VANT, Serija: Yadernye Konstanty, v.4, p.19, December 1986
33. V.A.Kalinin et al. VANT, Serija: Yadernye Konstanty, v.4, p.3, December 1987
34. P.W.Lisowski et al. Proc. of an Int. Conf. on Nuclear Data for Science and Technology, Mito, Japan, 30 May-3 June 1988, pp. 97-99
35. J.W.Meadows Annals of Nucl. Energy, v.15, p.421, August 1988
36. J.W.Meadows, D.L.Smith, L.P.Geraldo Annals of Nucl. Energy, v.16, p.471, September 1989
37. L.Desdin, S.Szegedi, J.Csikai Acta Physica Hungaria, v.65(2-3), p.271, 1989
38. P.W.Lisowski et al. Proc. of the Conference: Fifty Years with Nuclear Fission, NIST, Gaithersburg, MD, 1989, pp.443-448.
39. K.Merla et al. Proc. of an Int. Conf. on Nuclear Data for Science and Technology, Julich, FRG, 13-17 May 1991. Springer Verlag, Berlin - Heidelberg, 1992, p.510-513
40. A.D.Carlson et al. Proc. of an Int. Conf. on Nuclear Data for Science and Technology, Gatlinburg, Tennessee, USA, May 9-13, 1994, Vol.1, pp. 40-42
41. A.A.Goverdovskiy et al. Jadernaja Fizika (Rus.), v.58, p.27, January 1995
42. V.P.Alfimenkov et al. Jadernaja Fizika (Rus.), v.58, p.799, May 1995
43. V.F.Gerasimov et al. Report JINR-E3-97-213,348, Dubna, May 1997
44. T.Iwasaki et al. J. of Nuclear Science and Technology, v.36, p.127, February 1999
45. J.Kimura J. of Nuclear Science and Technology., v. 30, p.863, 1993.
46. P.Young et al. Evaluated Neutron Data for N-237, ENDF/B-VI Library, MAT-9346, Rev.1, July 1991.

47. P.Young et al. Evaluated Neutron Data for N-237, JENDL-3.2 Library, MAT-9346, Rev.1, July 1991.
48. K.Kobayashi Evaluated cross section data for the Np-237(n,f) reaction, MAT-9346, eval. April 1996, JENDL/D-99 Library, 1999
49. S.F.Mughabghab et al. Neutron Cross Sections, vol.1, part B, New York, Academic Press, 1984
50. L.W.Weston et al. Evaluated Neutron Data for U-235, ENDF/B-VI Library, MAT-9228, eval. April 1989, rev.5 October 1997
51. P.Young et al. Evaluated Neutron Data for Pu-239, ENDF/B-VI Library, MAT-9437, Rev.2, August 1997.
52. M.Kawai et al. Evaluated Neutron Data for Pu-239, JENDL-3.2 Library, MAT-9437, Rev.2, February 1993.
85. S.Badikov, N.Rabotnov, K.Zolotarev Proc. of NEANSC Speciali-st's Meeting on Evaluation and Processing of Covariance Data, Oak Ridge, USA, 7-9 September 1992, OECD, Paris, 1993, p.105
86. S.A.Badikov et al. Preprint FEI-1686, Obninsk, 1985
53. O.Horibe et al. Proc. of Conference: 50 Years with Nuclear Fission, Washington D.C., 25-28 April 1989, v.2, p.923
54. W.Mannhart Progress Report INDC(Ger)-045, pp.40-43, June 1999
55. W.Mannhart Validation of Differential Cross Sections with Integral Data , Report INDC(NDS)-435, pp.59-64, IAEA, Vienna, September 2002
56. W.Mannhart Handbook on Nuclear Activation Cross Sections, IAEA Tech. Report Ser. No.273, p.413, 1987
57. R.A.Anderl et al. Report EGG-PHYS-5608, USDOE, 1981
58. M.Nakazawa et al. Report JAERI-1325, p.56, March 1992
59. O.Bersillon Decay Data and Isotopic Abundances for Dosimetry Application. Proc of the IAEA Tecnical Meeting on the IRDF-2002 file, IAEA, Vienna, 2003 (to be published)

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