IAEA
International Atomic Energy Agency

INDC(NDS)-0584
Distr. RD

INDC International Nuclear Data Committee

EVALUATION OF CROSS-SECTION DATA FROM THRESHOLD TO 40 MeV FOR SOME NEUTRON REACTIONS IMPORTANT FOR FUSION DOSIMETRY APPLICATIONS

Part 2
Evaluation of the excitation functions for the
^{59}Co(n,3n)^{57}Co, ^{89}Y(n,2n)^{88}Y, ^{93}Nb(n,2n)^{92m}Nb, ^{169}Tm(n,2n)^{168}Tm and ^{209}Bi(n,3n)^{207}Bi reactions

K.I. Zolotarev

Institute of Physics and Power Engineering,
Obninsk, Russia

Final Report on Research Contract No. 14745

Obninsk, Russia
November 2010

Selected INDC documents may be downloaded in electronic form from
http://www-nds.iaea.org/reports-new/indc-reports/
or sent as an e-mail attachment.
Requests for hardcopy or e-mail transmittal should be directed to services@iaeand.iaea.org
or to:
Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
A-1400 Vienna
Austria

Produced by the IAEA in Austria
November 2010

INDC(NDS)-0584
Distr. RD

EVALUATION OF CROSS-SECTION DATA FROM THRESHOLD TO 40 MeV FOR SOME NEUTRON REACTIONS IMPORTANT FOR FUSION DOSIMETRY APPLICATIONS

Part 2
Evaluation of the excitation functions for the $^{59}Co(n,3n)^{57}Co$, $^{89}Y(n,2n)^{88}Y$, $^{93}Nb(n,2n)^{92m}Nb$, $^{169}Tm(n,2n)^{168}Tm$ and $^{209}Bi(n,3n)^{207}Bi$ reactions

K.I. Zolotarev

Institute of Physics and Power Engineering,
Obninsk, Russia

Final Report on Research Contract No. 14745

Abstract

Evaluations of cross sections and their associated covariance matrices have been carried out for five dosimetry reactions:
- excitation functions were re-evaluated for the $^{89}Y(n,2n)^{88}Y$, $^{93}Nb(n,2n)^{92m}Nb$ and $^{169}Tm(n,2n)^{168}Tm$ reactions over the neutron energy range from threshold up to 40 MeV;
- excitation functions were re-evaluated for the $^{59}Co(n,3n)^{57}Co$ and $^{209}Bi(n,3n)^{207}Bi$ reactions over the neutron energy range from threshold to 85 and 45 MeV, respectively.

Uncertainties in the cross sections for all of those reactions were also derived in the form of relative covariance matrices. Benchmark calculations performed for ^{235}U thermal fission and ^{252}Cf spontaneous fission neutron spectra show that the integral cross sections calculated from the newly evaluated excitation functions exhibit improved agreement with related experimental data when compared with the equivalent data from the IRDF-2002 library.

November 2010

TABLE OF CONTENTS

1. INTRODUCTION

Cross-section data for $^{59}Co(n,3n)^{57}Co$, $^{89}Y(n,2n)^{88}Y$, $^{93}Nb(n,2n)^{92m}Nb$, $^{169}Tm(n,2n)^{168}Tm$ and $^{209}Bi(n,3n)^{207}Bi$ reactions are needed to solve a wide spectrum of scientific and technical tasks. Activation detectors based on these reactions are commonly used in the field of reactor dosimetry. Furthermore, the $^{93}Nb(n,2n)^{92m}Nb$ reaction is often used in experimental nuclear physics as monitor reaction for measurements of unknown cross sections by means of the activation method over the neutron energy range from 13 to 15 MeV. The $^{93}Nb(n,2n)^{92}Nb$ reaction combined with the $^{90}Zr(n,2n)^{89m+g}Zr$ reaction are also used in experimental nuclear physics for the determination of incident neutron energy.

At the IAEA Consultants' Meeting on "Review the Requirements to Improve and Extend the IRDF library (International Reactor Dosimetry File (IRDF-2002))" all the above mentioned reactions were included in the list of "Proposed Extension to IRDF-2002 Database: Fusion Applications (up to 60 MeV)" [1.1]. In the current version of the International Reactor Dosimetry File [1.2], excitation functions for $^{89}Y(n,2n)^{88}Y$, $^{93}Nb(n,2n)^{92m}Nb$ and $^{169}Tm(n,2n)^{168}Tm$ reactions are given from threshold to 20 MeV. Evaluated data for these reactions were taken from the IRDF-90 version 2 library. Cross-section data for the $^{59}Co(n,3n)^{57}Co$ and $^{209}Bi(n,3n)^{207}Bi$ reactions are absent in the IRDF-2002 and JENDL/D-99 files. For these reactions excitation functions are presented in the new library ENDF/B-VII [1.3] and have been evaluated from threshold up to 20 MeV. Uncertainties in cross sections are not given. Cross section data for all analysed reactions are given in the specialized libraries MENDL-2 [1.4] (up to 100 MeV) and TENDL-2009 [1.5] (up to 200 MeV). However, the MENDL-2 and TENDL-2009 libraries were prepared on the basis of pure theoretical model calculations and are not appropriate for reactor and fusion dosimetry applications.

The main aim of this work was the evaluation of the cross-section data and related uncertainty covariance matrixes for $^{59}Co(n,3n)^{57}Co$, $^{89}Y(n,2n)^{88}Y$, $^{93}Nb(n,2n)^{92m}Nb$, $^{169}Tm(n,2n)^{168}Tm$ and $^{209}Bi(n,3n)^{207}Bi$ reactions with extension to higher neutron energies up to 40 – 85 MeV. New evaluations were proposed on the basis of corrected to the new standards experimental data combined with data obtained from consistent theoretical model calculations.

REFERENCES TO SECTION 1

[1.1] GREENWOOD, L.R., NICHOLS, A.L., Summary Report of Consultants' Meeting on "Review the Requirements to Improve and Extend the IRDF library (International Reactor Dosimetry File (IRDF-2002))", Report INDC(NDS)-0507, IAEA, Vienna, Austria, January 2007.

[1.2] BERSILLON, O., GREENWOOD, L.R., GRIFFIN, P.J., MANNHART, W., NOLTHENIUS, H.J., PAVIOTTI-CORCUERA, R., ZOLOTAREV, K.I., ZSOLNAY, E.M., McLAUGHLIN, P.K., TRKOV, A., International Reactor Dosimetry File–2002 (IRDF-2002), Technical Reports Series No. 452, IAEA, Vienna, Austria (2006).

[1.3] CHADWICK, M.B., OBLOZINSKY, P., HERMAN, M., *et al.*, ENDF/V-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology, Nucl. Data Sheets **107** (2006) 2931-3060.

[1.4] SHUBIN, Yu.N., LUNEV, V.P., KONOBEEV, A.Yu., DITYUK, A.I., Cross-Section Data Library MENDL-2 to study activation as transmutation of materials irradiated by nucleons of intermediate energies, Report INDC(CCP)-385, IAEA, Vienna, Austria, May 1995.

[1.5] KONING, A.J., ROCHMAN, D., Talys Evaluated Nuclear Data Library (TENDL-2009), NRG Petten, Netherlands, 2009.

2. METHOD OF EVALUATION OF EXCITATION FUNCTIONS FOR DOSIMETRY REACTIONS

2.1. Sources of information used in the evaluation

Differential and integral experimental data taken mainly from the EXFOR library were used for the ^{59}Co(n,3n)^{57}Co, ^{89}Y(n,2n)^{88}Y, ^{93}Nb(n,2n)^{92m}Nb, ^{169}Tm(n,2n)^{168}Tm and ^{209}Bi(n,3n)^{207}Bi dosimetry reactions:. Where no records were found in EXFOR, data and other relevant information were taken from the original publications.

2.2. Analysis of experimental data

All experimental data were analyzed and, if needed, corrected with respect to the recommended cross-section standards for monitor reactions and recommended decay data. Corrections to the experimental data based on the new standards lead to reductions in the discrepancies, and thus resulted in decreases in the uncertainties of the re-evaluated cross sections. The standards used to correct the microscopic experimental data under investigation are given in Table 2.1.

TABLE 2.1. DATA USED AS STANDARDS TO CORRECT THE MICROSCOPIC EXPERIMENTAL CROSS SECTIONS

Monitor Reaction	Cross section used as standard	Half-life for residual nucleus	Radiation and energy	Emission probability per decay
^{1}H(n,n)^{1}H	Carlson+ [2.1]			
^{6}Li(n,t)^{4}He	Carlson+ [2.1]			
^{19}F(n,2n)^{18}F	IRDF-2002 [2.2]	109.77 (5) m	Gamma 511 keV	1.9346 (8) [2.8]
^{24}Mg(n,p)^{24}Na	Zolotarev [2.3]	14.997 (12) h	Gamma 1368.626 keV	0.999936(15) [2.8]
^{27}Al(n,α)^{24}Na	Zolotarev [2.4]	14.997 (12) h	Gamma 1368.626 keV	0.999936(15) [2.8]
^{27}Al(n,p)^{27}Mg	Zolotarev+ [2.5]	9.458 (12) m	Gamma 843.76 keV Gamma 1014.44 keV	0.718 (4) [2.8] 0.280 (4) [2.8]
^{32}S(n,p)^{32}P	Zolotarev [2.3]	14.263 (3) d	Beta+ 1710.48 keV	1.000 [2.8]
^{56}Fe(n,p)^{56}Mn	IRDF-2002 [2.2]	2.5789 (1) h	Gamma 846.754 keV Gamma 1810.72 keV	0.989 (3) [2.8] 0.272 (8) [2.8]
^{58}Ni(n,p)^{58}Co	IRDF-2002 [2.2]	70.86 (6) d	Gamma 511 keV Gamma 810.759 keV	0.298 (4) [2.8] 0.99450 (10) [2.8]
^{63}Cu(n,2n)^{62}Cu	Zolotarev [2.3]	9.73 (2) m	Beta+ 2925.8 keV Gamma 511 keV Gamma 1173.02 keV	0.9720 (2) [2.8] 1.9486 (5) [2.8] 0.00342 (5) [2.8]
^{65}Cu(n,2n)^{64}Cu	Zolotarev [2.3]	12.700 (2) h	Beta+ 653.1 keV Beta– 578.7 keV Gamma 511 keV Gamma 1345.77 keV	0.1740 (22) [2.7] 0.390 (3) [2.7] 0.348 (4) [2.7] 0.00473 (10) [2.7]
^{93}Nb(n,2n)^{92m}Nb	Zolotarev [*]	10.15 (2) d	Gamma 934.44 keV	0.9907 (4) [2.7]
^{197}Au(n,2n)^{196}Au	Zolotarev [2.3]	6.183 (10) d	Gamma 333.03 keV Gamma 355.73 keV Gamma 426.10 keV	0.229 (6) [2.7] 0.870 (4) [2.7] 0.066 (4) [2.7]
^{235}U(n,f)	Carlson+ [2.1]			
^{238}U(n,2n) ^{238}U	Zolotarev [2.6]	6.75 (1) d	Gamma 208.005 keV	0.212 (3) [2.8]
^{238}U(n,f)	Carlson+ [2.1]			

Beta transition: - $E_{\beta max}$ values are listed.
[*] - Cross-section data were taken from this work.

Recommended cross-section data for the monitor reactions used in measurements of integral cross sections in ^{235}U neutron-induced thermal fission and ^{252}Cf spontaneous fission neutron spectra were taken from Refs. [2.9] and [2.10]. Digital data for ^{235}U thermal fission and ^{252}Cf spontaneous fission neutron spectra were taken from Refs. [2.11] and [2.12], respectively. Information about the isotopic compositions of the elements was taken from Ref. [2.13].

2.3. Theoretical model calculations for the cross sections of dosimetry reactions

Theoretical model calculations provided an additional source of cross-section information for reactions with inadequate experimental data. Hence, theoretical calculations were carried out to determine the excitation functions of the ^{59}Co(n,3n)^{57}Co, ^{89}Y(n,2n)^{88}Y, ^{93}Nb(n,2n)$^{92m+g}$Nb, ^{169}Tm(n,2n)^{168}Tm and ^{209}Bi(n,3n)^{207}Bi reactions above 20 MeV.

The optical-statistical method was used for a theoretical description of the excitation function of the ^{59}Co(n,3n)^{57}Co, ^{89}Y(n,2n)^{88}Y, ^{93}Nb(n,2n)$^{92m+g}$Nb, ^{169}Tm(n,2n)^{168}Tm and ^{209}Bi(n,3n)^{207}Bi reactions, taking into account the contribution of the direct, pre-equilibrium and statistical equilibrium processes in different outgoing channels. These calculations were carried out by means of a modified version of the GNASH code [2.14, 2.15] and EMPIRE-2.19 code [2.16]. A modified version of the GNASH code includes a subroutine for width fluctuation corrections.

Penetrability coefficients for neutrons were calculated on the basis of the generalized optical model, which estimates the cross sections for the direct excitations of collective low-lying levels. The ECIS coupled-channel deformed optical model code was used for these calculations [2.17], and the optical coefficients of the proton- and alpha-particle penetrabilities were determined by means of the SCAT2 code [2.18].

The data on discrete level parameters for ^{89}Y, ^{93}Nb, ^{169}Tm, ^{209}Bi and all residual nuclei were obtained from Ref. [2.7]. Unknown branching ratios were estimated on the basis of statistical calculations of the possible E1, E2 and M1 gamma-ray transitions. Intensities of such transitions were calculated from the radiation strength functions recommended in Ref. [2.19].

Continuum level densities were represented by means of the Gilbert-Cameron model [2.20] based on the Cook parameters [2.21] (mode IBSF = 1 in the GNASH code). Calculations of the gamma-ray transition probabilities in the continuum region of the excited states of all nuclei under consideration were made in terms of the hypothesis of the domination of the giant dipole resonance with the radiative strength function from the Kopecky-Uhl systematics [2.22]. Recommended parameters for the giant dipole resonances were taken from Ref. [2.23].

The modified GNASH code was used to calculate the cross sections of the ^{89}Y(n,2n)^{88}Y, ^{93}Nb(n,2n)$^{92m+g}$Nb, ^{169}Tm(n,2n)^{168}Tm and ^{209}Bi(n,3n)^{207}Bi reactions from 20 to 40-45 MeV. Data for the ^{59}Co(n,3n)^{57}Co reaction were calculated from threshold to 40 MeV by means of the EMPIRE-2.19 code.

2.4. Statistical analyses of cross sections from the database

The method of statistical analysis of the correlated data was used to evaluate the excitation functions of the dosimetry reactions, as described in Refs. [2.24, 2.25]. Statistical analyses of the experimental reaction cross sections were carried out using the non-linear regression model. The following rational function was used as the model function (Pade approximation):

$$f(E) = C + \sum_{i=1}^{l_1} \frac{a_i}{E - r_i} + \sum_{k=1}^{l_2} \frac{\alpha_k (E - \varepsilon_r) + \beta_k}{(E - \varepsilon_k)^2 + \gamma_k^2},$$

where E is the neutron energy, and C, a_i, r_i, α_k, β_k, ε_k and γ_k are the parameters to be determined. The total number of parameters of the Pade approximation is equal to $L = 2l_1 + 4l_2 + 1$.

Parameters of the model function are determined from the minimum of the functional:

$$S(\vec{\beta}) = (\vec{\sigma} - \vec{f})^T (DPD)^{-1} (\vec{\sigma} - \vec{f}),$$

in which the functional to be minimized ($\vec{\beta}$) is the vector of the parameters to be determined; $\vec{\sigma}$ is the vector of cross sections from the database; D is the diagonal matrix of the uncertainty of the cross sections from the database; P is the correlation matrix of the experimental data used to evaluate the excitation function; and the superscript T denotes a transpose.

Technical aspects of the minimization process based on the use of the discrete optimization method and Newton-Gauss algorithm are described in Ref. [2.26]. The algorithm used to minimize $S(\vec{\beta})$ contains two approximations that simplify the calculation scheme appreciably:

1) the cross-section data obtained in different experiments are assumed to be uncorrelated;
2) the average correlation coefficient is used to describe the correlations between cross sections measured in one experiment.

The covariance matrix of the uncertainties of the evaluated parameters $W(\vec{\beta})$ and the uncertainties of the evaluated function at point $\Delta f(E_{i_k}^k, \vec{\beta})$ are determined from the relationships:

$$W(\vec{\beta}) = \tfrac{s}{n-L} (X^T V^{-1} X)^{-1},$$

$$\Delta f(E_{i_k}, \vec{\beta}) = \sum_{m=1}^{L} \sum_{j=1}^{L} X_{i_k m}^k \, X_{i_k j}^k \, W_{mj},$$

where n is the total number of cross-section data used in the analysis of a reaction, and X is the $(n \times L)$ sensitivity matrix of the coefficients of the rational function:

$$X_{i_k m} = \frac{\partial f(E_{i_k}, \vec{\beta})}{\partial \beta_m}.$$

The structure of the uncertainties for all experimental data was analyzed to determine the average correlation coefficients. The average correlation coefficient $\vec{p}^k$ for the k^{th} experiment containing information on the n_k values of the reaction excitation function was determined by means of the formula:

$$\vec{p}^k = \frac{2}{(n_k - 1)n_k} \sum_{i=1}^{n_k - 1} \sum_{j=i+1}^{n_k} \frac{\sum_{m=1}^{l} P_{ij}^m e_i^m e_j^m}{e_i e_j},$$

where $e_i(e_j)$ is the total uncertainty (standard deviation) of the cross section at the i^{th} (j^{th}) point corresponding to a standard deviation of 1σ; e_i^m (e_j^m) is the m^{th} component of the systematic uncertainty of the cross section at the i^{th} (j^{th}) point; P_{ij}^m is the coefficient of the correlation between the mth components of the systematic uncertainties at the ith (jth) points; and l is the number of components of the systematic uncertainty.

This method of statistical analysis of the correlated data was performed by means of the PADE-2 code [2.24].

REFERENCES TO SECTION 2

[2.1] CARLSON, A.D., PRONYAEV, V.G., SMITH, D.L., LARSON, N.M., CHEN ZHENPENG, HALE, G.M., HAMBSCH, F.-J., GAI, E.V., SOO-YOUL OH, BADIKOV, S.A., KAWANO, T., HOFMANN, H.M., VONACH, H., TAGESEN, S., International Evaluation of Neutron Cross Section Standards, Nucl. Data Sheets **110** (2009) 3215-3324.

[2.2] BERSILLON, O., GREENWOOD, L.R., GRIFFIN, P.J., MANNHART, W., NOLTHENIUS, H.J., PAVIOTTI-CORCUERA, R., ZOLOTAREV, K.I., ZSOLNAY, E.M., McLAUGHLIN, P.K., TRKOV, A., International Reactor Dosimetry File 2002 (IRDF-2002), Technical Reports Series No. 452, IAEA, Vienna, Austria (2006).

[2.3] ZOLOTAREV, K.I., Re-evaluation of Microscopic and Integral Cross-Section Data for Important Dosimetry Reactions. Re-evaluation of the excitation functions for the ^{24}Mg(n,p)^{24}Na, ^{32}S9n,p)^{32}P, ^{60}Ni(n,p)$^{60m+g}$Co, ^{63}Cu(n,2n)^{62}Cu, ^{65}Cu(n,2n)^{64}Cu, ^{64}Zn(n,p)^{64}Cu, ^{115}In(n,2n)^{114m}In, ^{127}I(n,2n)^{126}I, ^{197}Au(n,2n)^{196}Au and ^{199}Hg(n,n')^{199m}Hg reactions, Report INDC(NDS)-0526, IAEA, Vienna, Austria, August 2008.

[2.4] ZOLOTAREV, K.I., Evaluation of Cross-Section Data from Threshold to 40-60 MeV for Specific Neutron Reactions Important for Neutron Dosimetry Applications. Part 1. Evaluation of the excitation functions for the ^{27}Al(n,α)^{24}Na, ^{55}Mn(n,2n)^{54}Mn, ^{59}Co(n,p)^{59}Fe, ^{59}Co(n,2n)$^{58m+g}$Co and ^{90}Zr(n,2n)$^{89m+g}$Zr reactions, Report INDC(NDS)-0546, IAEA, Vienna, Austria, April 2009.

[2.5] ZOLOTAREV, K.I., PASHCHENKO, A.B., CSIKAI, J., Re-evaluation of ^{27}Al(n,p)^{27}Mg Reaction Cross Sections for Use as a Standard in Dosimetry and Activation Measurements, Acta Universitas Debreceniensis De Ludovico Kossuth Nominatae, Series Phisica et Chimica, Vol. XXXVIII-XXXIX (2005) 381-404.

[2.6] ZOLOTAREV, K.I., Evaluation of ^{238}U(n,2n)^{237}U Reaction Cross Sections from threshold to 20 MeV (16129-13), IPPE, Obninsk, May 2009.

[2.7] FIRESTONE, R.B., SHIRLEY, V.S., BAGLIN, C.M., FRANK CHU, S.Y., ZIPKIN, J.,Table of Isotopes, Eighth Edition, CD-ROM Version 1.0, March 1996, John Wiley & Sons, 1996.

[2.8] Decay Radiation Data Base, version 12/11/2009, www.nndc.bnl.gov/ nudat2/index dec.jcp.

[2.9] MANNHART, W., Status of the Evaluation of the Neutron Spectrum of ^{235}U + n_{th}, in: Summary Report of the IAEA Consultants' Meeting on International Neutron Cross Section Standards: Measurements and Evaluation Techniques, Report INDC(NDS)-0540, IAEA, Vienna, Austria, November 2008, p 29: presentations.

[2.10] MANNHART, W., Status of the Evaluation of the Neutron Spectrum of ^{252}Cf(sf), in: Summary Report of the IAEA Consultants' Meeting on International Neutron Cross Section Standards: Measurements and Evaluation Techniques, Report INDC(NDS)-0540, IAEA, Vienna, Austria, November 2008, p 29: presentations.

[2.11] WESTON, L.W., YOUNG, P.G., POENITZ, W.P., LUBITZ, C.R., Evaluated Neutron Data File for Uranium-235, ENDF/B-VI Library, MAT = 9228, MF = 5, MT = 18, April 1989.

[2.12] MANNHART, W., Status of the Cf-252 Fission-neutron Spectrum Evaluation with Regard to Recent Experiments, in: Proc. Consultants' Meeting on Physics of Neutron Emission in Fission, Report INDC(NDS)-220, IAEA, Vienna, Austria, 1989, pp. 305-336.

[2.13] ROSMAN, K.J.R., TAYLOR, P.D.P, Isotopic Compositions of the Elements 1997, International Union of Pure and Applied Chemistry, 1997.

[2.14] TRYKOV, E.L., TERTYCHNYI, G.Ya., private communication, IPPE, Obninsk, May 1999.

[2.15] YOUNG, P.G., ARTHUR, E.D., GNASH: A Pre-equilibrium Statistical Nuclear Model Code for Calculation of Cross Sections and Emission Spectra, Technical Report LA-6947, Los Alamos Scientific Laboratory, USA, 1977.

[2.16] HERMAN, M., CAPOTE, R., CARLSON B.P., OBLOŽINSKÝ, P., SIN, M., TRKOV, A., WIENKE, H., ZERKIN, V., EMPIRE: Nuclear Reaction Model Code System for Data Evaluation, Nucl. Data Sheets **108** (2007) 2655-2715.

[2.17] RAYNAL, J., Optical Model and Coupled-Channels Calculations in Nuclear Physics, IAEA SMR-9/8, IAEA, Vienna, Austria, 1972.

[2.18] BERSILLON, O., SCAT2-A Spherical Optical Model Code, Report CEA-N-2037 (1978) 111.

[2.19] Handbook for Calculations of Nuclear Reaction Data - Reference Input Parameter Library, IAEA-TECDOC-1034, IAEA, Vienna, Austria, August 1998.

[2.20] GILBERT, A., CAMERON, A.G.W., A Composite Nuclear-Level Density Formula with Shell Corrections, Can. J. Phys. **43** (1965) 1446-1496.

[2.21] COOK, J., FERGUSON, H., MUSGROVE, A.R. de L., Nuclear Level Densities in Intermediate and Heavy Nuclei, Aust. J. Phys. **20** (1967) 477-487.

[2.22] UHL, M., KOPECKY, J., Gamma-ray Strength Function Models and their Parameterization, in: Summary Report of the First Research Coordination Meeting on Development of Reference Input Parameter Library for Nuclear Model Calculations of Nuclear Data, Obložinský, P. (Ed.), Report INDC(NDS)-335, IAEA, Vienna, Austria, May 1995, pp. 157-166.

[2.23] DIETRICH, S.S., BERMAN, B.L., Atlas of Photoneutron Cross Sections Obtained with Monoenergetic Photons, At. Data Nucl. Data Tables **38** (1988) 199-338.

[2.24] BADIKOV, S.A., VINOGRADOV, V.N., GAY, E.V., RABOTNOV, N.S., FEI-1686, Obninsk, 1985 (in Russian).

[2.25] BADIKOV, S.A., RABOTNOV, N.S., ZOLOTAREV, K.I., Evaluation of neutron dosimetry reactions cross sections and covariance analysis with rational functions, in: Proc. NEANSC Specialists' Meeting on Evaluation and Processing of Covariance Data, 7-9 September 1992, Oak Ridge, USA, OECD, Paris, 1993, pp. 105-118.

[2.26] VINOGRADOV, V.N., GAY, E.V., RABOTNOV, N.S., Analytical Approximation of the Data in Nuclear and Neutron Physics, Energoatomizdat, Moscow, 1987 (in Russian).

3. EVALUATION OF THE EXCITATION FUNCTION OF THE ^{59}Co(n,3n)^{57}Co REACTION

The isotopic abundance of ^{59}Co in natural cobalt is 100 atom percent, and the ^{57}Co obtained via the (n,3n) reaction undergoes 100% ε capture decay with a half-life of (271.74 ± 0.06) days. The 122.06-keV gamma radiation (I_γ = 0.8560 ± 0.0017) and 136.47-keV gamma radiation (I_γ = 0.1068±0.0008) are normally used to determine the ^{59}Co(n,3n)^{57}Co reaction rate. Recommended decay data for the half-life and gamma ray emission probabilities per decay of ^{57}Co were taken from Ref. [2.8] of Section 2.

Experimental information about the ^{59}Co(n,3n)^{57}Co reaction excitation function is still very poor. Microscopic cross sections for the ^{59}Co(n,3n)^{57}Co reaction are given only in three works [3.1-3.3]. Experimental data of Uno [3.2] obtained in measurements with ^{7}Li(p,n)^{7}Be neutron source were renormalized to a factor Fc = 1.07378, which was determined from analysis of ^{59}Co(n,2n)^{58}Co data. Corrections to the experimental data of Veeser [3.1] and Eun Joo Kim *et al.* [3.3] were not applied.

The database used to evaluate the ^{59}Co(n,3n)^{57}Co reaction cross section from threshold to 85 MeV was assembled from microscopic experimental data [3.1-3.3] and data from theoretical modeling calculation carried out by means of EMPIRE-2.19 code.

Uncertainties in the evaluated excitation function for the ^{59}Co(n,3n)^{57}Co reaction are given in the form of a relative covariance matrix for 39-neutron energy groups (LB = 5). Covariance matrix uncertainties were calculated simultaneously with the recommended cross-section data by means of the PADE-2 code.

Six-digit eigenvalues for the relative covariance matrix in File-33 are as follows:

8.33452E-06	8.58035E-06	9.03318E-06	9.59768E-06
1.04456E-05	1.14678E-05	1.25643E-05	1.41888E-05
1.59404E-05	1.76322E-05	2.01039E-05	2.31221E-05
2.72359E-05	3.26333E-05	4.29541E-05	5.07083E-05
6.20570E-05	7.99376E-05	9.68474E-05	1.08456E-04
1.31791E-04	1.60861E-04	1.93303E-04	2.25159E-04
2.43294E-04	2.75947E-04	3.19283E-04	3.67215E-04
4.19165E-04	4.75056E-04	5.34932E-04	5.98807E-04
6.66521E-04	7.14806E-04	3.72924E-03	1.99128E-02
2.88573E-02	1.09197E-01	1.94886E-01	

All of these eigenvalues are positive.

Evaluated group cross sections and their uncertainties for the excitation function of the ^{59}Co(n,3n)^{57}Co reaction are listed in Table 3.1. Group boundaries are the same as in File-33.

One can see from Table 3.1 that the smallest uncertainties in the evaluated cross sections of 4.73% to 4.99% are found in the neutron energy range from 28 to 35 MeV. For remaining energy intervals uncertainties are between 5 and 10 %. A significant uncertainty of 40.33% in the interval 19.353 – 20.000 MeV arises from the large uncertainties in the experimental data near threshold.

TABLE 3.1. EVALUATED CROSS SECTIONS AND THEIR UNCERTAINTIES FOR THE ^{59}Co(n,3n)^{57}Co REACTION IN THE ENERGY RANGE FROM THRESHOLD TO 85 MeV.

Neutron energy (MeV) from – to	**Cross-Section (mb)**	**Uncer-tainty (%)**	**Neutron energy (MeV) from – to**	**Cross-section (mb)**	**Uncer-tainty (%)**
19.353 – 20.000	2.677	40.33	39.000 – 40.000	208.461	5.57
20.000 – 21.000	15.067	9.91	40.000 – 42.500	183.554	5.80
21.000 – 22.000	34.502	8.38	42.500 – 45.000	154.639	6.12
22.000 – 23.000	59.168	7.85	45.000 – 47.500	132.392	6.40
23.000 – 24.000	89.776	7.35	47.500 – 50.000	115.071	6.64
24.000 – 25.000	126.553	6.80	50.000 – 52.500	101.370	6.78
25.000 – 26.000	168.682	6.20	52.500 – 55.000	90.334	6.94
26.000 – 27.000	213.851	5.61	55.000 – 57.500	81.308	7.07
27.000 – 28.000	258.094	5.13	57.500 – 60.000	73.818	7.19
28.000 – 29.000	296.472	4.84	60.000 – 62.500	67.519	7.28
29.000 – 30.000	324.565	4.73	62.500 – 65.000	62.161	7.37
30.000 – 31.000	339.887	4.74	65.000 – 67.500	57.554	7.44
31.000 – 32.000	342.706	4.79	67.500 – 70.000	53.557	7.50
32.000 – 33.000	335.328	4.85	70.000 – 72.500	50.059	7.56
33.000 – 34.000	320.932	4.91	72.500 – 75.000	46.974	7.61
34.000 – 35.000	302.532	4.99	75.000 – 77.500	44.237	7.66
35.000 – 36.000	282.463	5.07	77.500 – 80.000	41.791	7.70
36.000 – 37.000	262.298	5.18	80.000 – 82.500	39.595	7.73
37.000 – 38.000	242.968	5.30	82.500 – 85.000	37.613	7.77
38.000 – 39.000	224.958	5.44			

The evaluated excitation function for the ^{59}Co(n,3n)^{57}Co reaction in the neutron energy range from threshold to 85 MeV is shown in Fig. 3.1 in comparison with the equivalent data from TENDL-2009, MENDL-2 and experimental data. The current evaluation agrees well with experimental data in the whole energy range from threshold to 85 MeV. In comparison with other evaluations and experimental data, the MENDL-2 library gives systematically overestimated cross-section values in the energy range from threshold to 60 MeV. Results of the EMPIRE-2.19 calculation also agree well with experimental data.

Unfortunately integral experimental data of Qaim *et al.* [3.4] obtained for the neutron spectrum from D(Be,n) reaction can't be used for testing evaluated ^{59}Co(n,3n)^{57}Co reaction excitation functions. Neutron spectrum formed in 1 cm thick Be target by bombarding of 30 MeV deuterons was determined in Ref. [3.4] between 2 – 30 MeV in three wide energy groups only. The neutron spectrum must be measured for benchmark calculations in narrow energy intervals with uncertainties not higher than 5 - 10 %.

Average cross sections for ^{235}U thermal fission neutron spectrum calculated from three different excitation functions are compared in Table 3.2. The 90%-response energy range of the ^{59}Co(n,3n)^{57}Co reaction indicates that the excitation function can seldom be tested using experimental data measured in the ^{235}U thermal fission neutron spectrum. Calculation of the averaged cross sections over ^{252}Cf spontaneous fission neutron spectrum was not carried out, because this reference spectrum is evaluated only up to 20 MeV.

TABLE 3.2. CALCULATED INTEGRAL CROSS SECTIONS FOR THE $^{59}Co(n,3n)^{57}Co$ REACTION IN ^{235}U THERMAL FISSION NEUTRON SPECTRUM.

Library	Calculated integral cross section, mb	90%-Response range, MeV
Present evaluation	1.6828E-05	20.0 – 26.0
MENDL-2	3.0162E-05	20.1 – 26.1
TENDL-2009	2.0032E-05	20.4 – 26.0

The D(Be,n) reaction is one of the best benchmark neutron fields for testing of neutron induced reactions with a high threshold. Precise measurements of the integral cross section of the $^{59}Co(n,3n)^{57}Co$ reaction in a well determined neutron spectra from the D(Be,n) reaction are required for a final testing of the evaluated excitation function. Measurements of the integral cross section of the $^{59}Co(n,3n)^{57}Co$ reaction for the ^{235}U thermal fission neutron spectrum will also be useful for testing the evaluated excitation function.

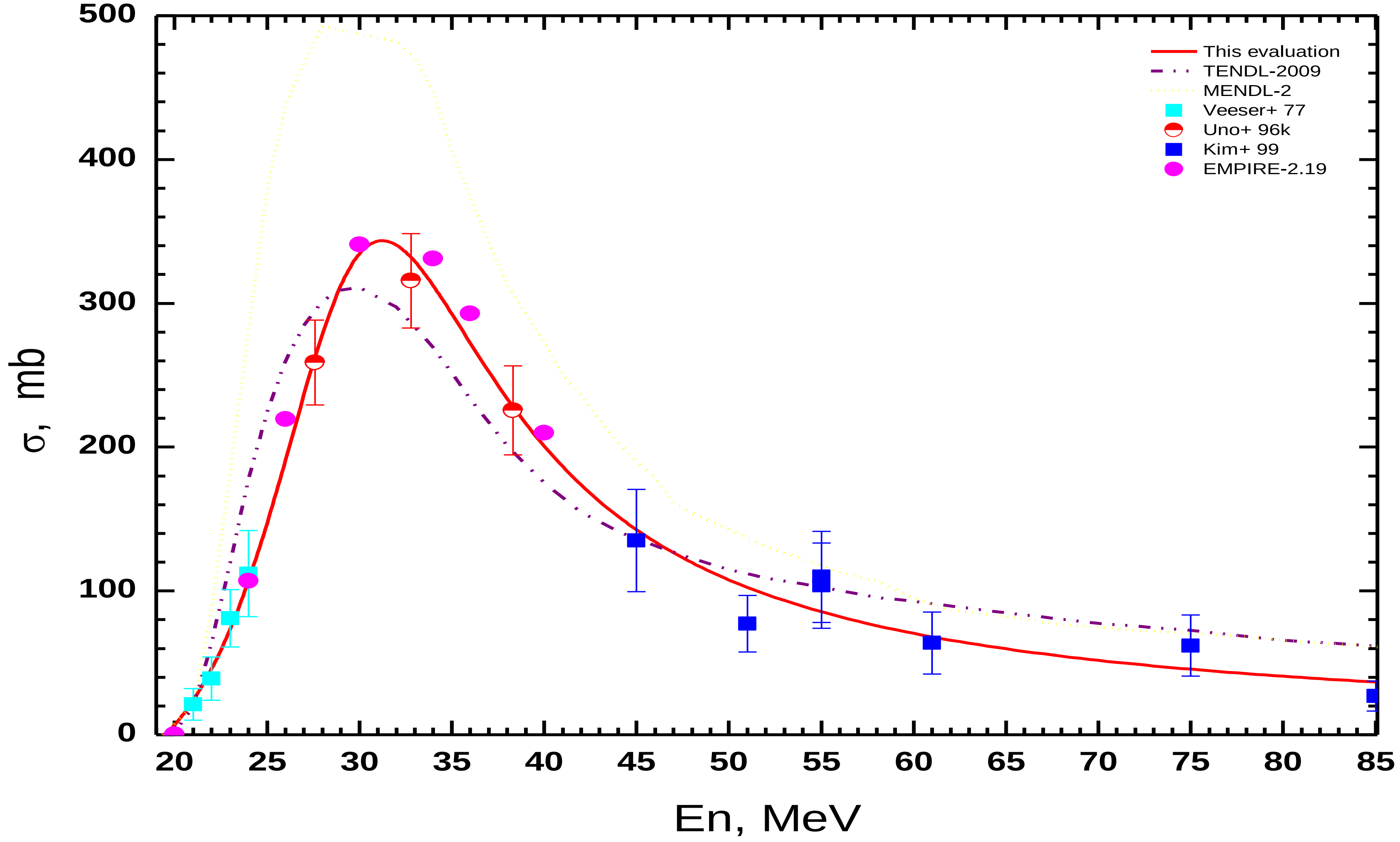

FIG. 3.1. Evaluated excitation function of the $^{59}Co(n3n)^{57}Co$ reaction in the energy range from threshold to 85 MeV in comparison with TENDL-2009, MENDL-2, EMPIRE-2.19 and experimental data

REFERENCES TO SECTION 3

[3.1] VEESER, L.R., ARTHUR, E.D., YOUNG, P.G., Cross Sections for (n,2n) and (n,3n) Reactions Above 14 MeV., Phys. Rev. C **16** (1977) 1792-1802.

[3.2] UNO, Y., UWAMINO, Y., SOEWARSONO, T.S., KONDO, Y., NAKAMURA, T., Measurement of Neutron Activation Cross Sections of ^{12}C, ^{30}Si, ^{47}Ti, ^{52}Cr, ^{59}Co and ^{58}Ni Between 15 and 40 MeV., Nucl. Sci. Eng. **122** (1996) 247-257.

[3.3] EUN JOO KIM, NAKAMURA, T., UWAMINO, Y., NAKANISHI, N., IMAMURA, M., NAKAO, N., SHIBATA, S., TANAKA, S., Measurements of Activation Cross Sections on Spallation Reactions for ^{59}Co and Nat-Cu at Incident Neutron Energies of 40 to 120 MeV., Nucl. Sci. Technology **36** (1999) 29.

[3.4] QAIM, S.M., KHATUN, S., WOELFLE, R., Integral Cross Section Measurements on (n,x) reactions induced by 30 MeV D(Be) break-up Neutrons on FRT Wall and Structural Materials., Proc. Symp. on Neutron Cross Sections from 10-50 MeV, Brookhaven National Laboratory, Upton, N.Y., 12-14 May 1980, Report BNL-NCS-51245, July 1980, Vol. 1-2.

4. EVALUATION OF THE EXCITATION FUNCTION OF THE ^{89}Y(n,2n)^{88}Y REACTION

The isotopic abundance of ^{89}Y in natural yttrium is 100 atom percent. The ^{88}Y obtained via the (n,2n) reaction undergoes 100% ε decay with a half-life of (106.626 ± 0.021) days. The 898.042-keV gamma radiation (I_γ = 0.937 ± 0.003) and 1836.063-keV gamma radiation (I_γ = 0.992 ± 0.003) are normally used to determine the ^{89}Y(n,2n)^{88}Y reaction rate. Recommended decay data for the half-life and gamma ray emission probability per decay of ^{88}Y were taken from Ref. [2.8] of Section 2.

Microscopic experimental data were analyzed during the preparation of the input database assembled in order to evaluate the cross sections and uncertainties for the ^{89}Y(n,2n)^{88}Y reaction [4.1-4.38]. Various experimental data of Refs. [4.1], [4.3-4.12], [4.14], [4.16-4.19], [4.21-4.27], [4.29-4.31], [4.33], [4.35], [4.37] and [4.38] were corrected on the basis of the newly recommended cross-section data for the relevant monitor reactions and the recommended decay data (see Table 2.1).

Specific adjustments were also applied to some of the experimental data as outlined below. Cross sections measured by Wagner *et al.* [4.20], Huang Jianzhou *et al.* [4.21], Konno *et al.* [4.22], Filatenkov and Chuvaev [4.25] were used as reference data in the energy range 13.5 - 15.0 MeV for correction of experimental data from Refs. [4.1], [4.13] and [4.24]. After corrections to the new standards experimental data of Prestwood and Bayhurst [4.1] and data of Klopries *et al.* [4.24] obtained in measurements with T(d,n)^{4}He source were renormalized to factors of Fc = 5.64801 and Fc = 1.08071, respectively. Original experimental data of Bormann *et al.* [4.13] were renormalized to a factor of Fc = 1.09615. The incident neutron energy used by Klopries *et al.* [4.24] obtained in measurements with D(d,n)^{3}He source were corrected. The reason for revision of neutron energies was the fact that neutron energy at first point is lying below the threshold of the ^{89}Y(n,2n)^{88}Y reaction, which is equal to 11.6041 MeV. Neutron energies of 11.38, 11.86, 12.31 and 13.28 MeV as reported by Klopies *et al.* [4.24] were shifted by + 0.23 MeV at first two points and by – 0.20 MeV at the last point. The neutron energy in the third point has not been corrected. Cross sections measured by Abboud *et al.* for incident neutron energies 14.61, 15.71 – 17.58 MeV [4.7] were renormalized to a preliminary evaluated value of (968.5 ± 14.53) mb at 14.61 MeV.

The ^{89}Y(n,2n)^{88}Y cross sections are not directly measured [4.28]. They were obtained by summing up partial ^{89}Y(n,2n) cross sections measured by Garrett *et al.* in a wide energy range 11.9 – 19.3 MeV.

The database used to evaluate the excitation of the ^{89}Y(n,2n)^{88}Y reaction was assembled from microscopic experimental data [4.1-4.30] and data from theoretical modeling calculations (above 20 MeV). Cross sections that had been determined in Refs. [4.31-4.38] were rejected due to their significant overestimation or underestimation of the ^{89}Y(n,2n)^{88}Y reaction excitation function. Furthermore, all the rejected experimental data except measurements by Tewes *et al.* [4.32] and Molla *et al.* [4.38] had only been measured at one energy point from 14 to 15 MeV.

Evaluation of the excitation function of the ^{89}Y(n,2n)^{88}Y reaction from threshold to 40 MeV was carried out by means of the generalized least-squares method within the PADE-2 code. Uncertainties in the evaluated excitation function for the ^{89}Y(n,2n)^{88}Y reaction are given in the form of a relative covariance matrix for 42-neutron energy groups (LB = 5). Covariance matrix uncertainties were calculated simultaneously with the recommended cross-section data by means of the PADE-2 code.

Six-digit eigenvalues for the relative covariance matrix in File-33 are as follows:

```
8.06094E-06    8.09518E-06    8.24661E-06    8.24661E-06
8.35531E-06    8.49547E-06    8.70638E-06    9.04991E-06
9.54483E-06    1.01444E-05    1.13129E-05    1.25114E-05
1.32643E-05    1.43223E-05    1.60064E-05    1.86551E-05
2.20343E-05    3.19852E-05    4.84211E-05    6.82562E-05
8.93968E-05    1.17234E-04    1.31898E-04    1.51179E-04
1.54185E-04    1.93535E-04    2.34841E-04    2.76250E-04
3.16877E-04    3.56383E-04    3.89006E-04    4.01050E-04
5.05488E-04    6.90848E-04    8.95586E-04    1.36883E-03
1.57985E-03    4.34718E-03    6.11763E-03    1.18122E-02
2.55468E-02    7.84234E-02
```

All of these eigenvalues are positive.

Evaluated group cross sections and their uncertainties for the excitation function of the ^{89}Y(n,2n)^{88}Y reaction are listed in Table 4.1. Group boundaries are the same as in File-33.

TABLE 4.1. EVALUATED CROSS SECTIONS AND THEIR UNCERTAINTIES FOR THE ^{89}Y(n,2n)^{88}Y REACTION IN THE NEUTRON ENERGY RANGE FROM THRESHOLD TO 40 MeV

Neutron energy (MeV) from – to	**Cross section (mb)**	**Uncer-tainty (%)**	**Neutron energy (MeV) from – to**	**Cross section (mb)**	**Uncer-tainty (%)**
11.604 – 11.900	31.358	15.60	20.000 – 20.500	1267.500	1.89
11.900 – 12.200	106.860	7.16	20.500 – 21.000	1266.250	1.90
12.200 – 12.500	202.996	5.40	21.000 – 22.000	1252.520	1.94
12.500 – 13.000	360.406	3.31	22.000 – 23.000	1205.380	2.22
13.000 – 13.500	572.049	2.11	23.000 – 24.000	1116.160	2.97
13.500 – 14.000	754.756	1.18	24.000 – 25.000	989.591	4.14
14.000 – 14.200	857.257	1.14	25.000 – 26.000	844.573	5.25
14.200 – 14.400	906.471	1.05	26.000 – 27.000	703.422	5.82
14.400 – 14.600	950.559	0.99	27.000 – 28.000	581.115	5.85
14.600 – 14.800	990.082	1.02	28.000 – 29.000	482.749	5.71
14.800 – 15.000	1025.440	1.15	29.000 – 30.000	406.865	5.81
15.000 – 15.500	1077.440	1.49	30.000 – 31.000	349.396	6.27
15.500 – 16.000	1135.150	1.92	31.000 – 32.000	306.024	6.92
16.000 – 16.500	1175.730	2.05	32.000 – 33.000	273.105	7.58
16.500 – 17.000	1203.520	1.96	33.000 – 34.000	247.843	8.15
17.000 – 17.500	1222.470	1.84	34.000 – 35.000	228.191	8.60
17.500 – 18.000	1235.800	1.78	35.000 – 36.000	212.669	8.97
18.000 – 18.500	1245.750	1.80	36.000 – 37.000	200.218	9.26
18.500 – 19.000	1253.720	1.85	37.000 – 38.000	190.077	9.51
19.000 – 19.500	1260.260	1.89	38.000 – 39.000	181.693	9.74
19.500 – 20.000	1265.210	1.91	39.000 – 40.000	174.662	9.97

One can see from Table 4.1 that the smallest uncertainties in the evaluated cross sections between 0.99% and 1.18% are observed in the neutron energy range from 13.5 to 15.0 MeV, while these uncertainties are at their highest near the threshold and above 24 MeV.

Figs. 4.1 and 4.3 show the re-evaluated excitation function for the $^{89}Y(n,2n)^{88}Y$ reaction over the neutron energy range from threshold to 40.0 MeV and over the 13 – 15 MeV interval in comparison with IRDF-2002, ENDF/B-VII, TENDL-2009, MENDL-2 and experimental data obtained in the years 1961-1980. Comparison of the evaluated excitation functions with experimental data obtained between 1980-2008 is shown in Figs. 4.2 and 4.4. The evaluated excitation functions and the rejected experimental data are adduced in Fig. 4.5.

The comparison of excitation functions shows that IRDF-2002, ENDF/B-VII, TENDL-2009 and the new evaluation agree well in the energy range from threshold up to 17 - 18 MeV. In this energy range the MENDL-2 evaluation gives systematically lower cross sections, while above 18 MeV systematically higher cross sections than the present evaluation.

Integral experimental data for the $^{89}Y(n,2n)^{88}Y$ reaction are given in Refs. [4.39-4.44]. All experiments were carried out in neutron fields with similar spectra to the ^{235}U thermal fission neutron spectrum. So far, no experiments in the ^{252}Cf spontaneous fission neutron spectrum have been reported.

Neutron spectra measurements show that the standard ^{235}U thermal fission neutron spectrum may be obtained at facilities with a 90%-enriched ^{235}U fission plate converter with incident neutrons from a thermal column. Experimental data obtained from measurements in reactor cores and critical assemblies need to be corrected for differences between the real spectrum and the standard ^{235}U thermal fission neutron spectrum. Determination of this adjustment factor is a significant problem, and represents the major source of uncertainty in the resulting cross section.

All integral experimental data for the $^{89}Y(n,2n)^{88}Y$ reaction were obtained from measurements in reactor cores [4.39-4.42], [4.44] and uranium critical assembly [4.43]. Measured integral cross sections for the ^{235}U thermal fission neutron spectrum extend over a wide range from (0.133 ± 0.010) mb [4.43] to (0.220 ± 0.051) mb [4.39]. Data from Ref. [4.43] were not taken into account in the calculation of the average-weighted cross-section value for the $^{89}Y(n,2n)^{88}Y$ reaction. These data were rejected because of the lack of information about neutron flux determination and decay data used for the ^{88}Y nuclide. Integral cross sections measured by Bojtcov *et al.* [4.44] were determined in two different reactors: RBT-6 $\langle\sigma\rangle_{U-235}$ = (0.1710 ± 0.0172) mb and BOR-60 $\langle\sigma\rangle_{U-235}$ = (0.1570 ± 0.0096) mb.

The average-weighted value obtained from experimental data [4.40-4.44] is equal to $\langle\sigma\rangle_{U-235}$ = (0.1502 ± 0.0050) mb.
Evaluated excitation functions for the $^{89}Y(n,2n)^{88}Y$ reaction were tested against the above mentioned integral experimental data. Calculated averaged cross sections over ^{235}U thermal fission and ^{252}Cf spontaneous fission neutron spectra are compared with the IRDF-2002, ENDF/B-VII, TENDL-2009, MENDL-2 and experimental data in Table 4.2.

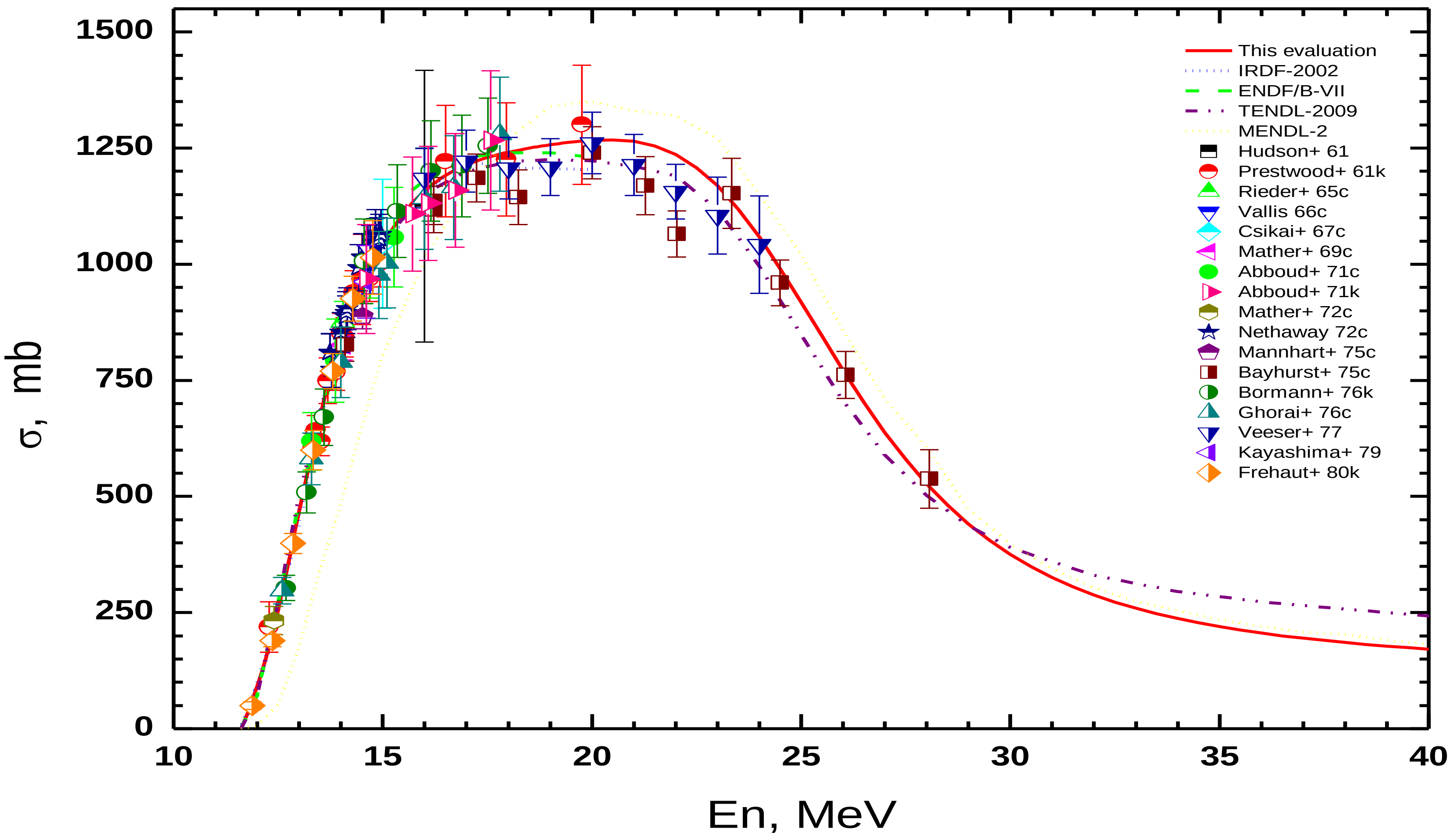

FIG. 4.1. Evaluated excitation function of the ^{89}Y(n,2n)^{88}Y reaction in the energy range from threshold to 40 MeV in comparison with IRDF-2002, ENDF/B-VII, TENDL-2009, MENDL-2 and experimental data (1961-1980)

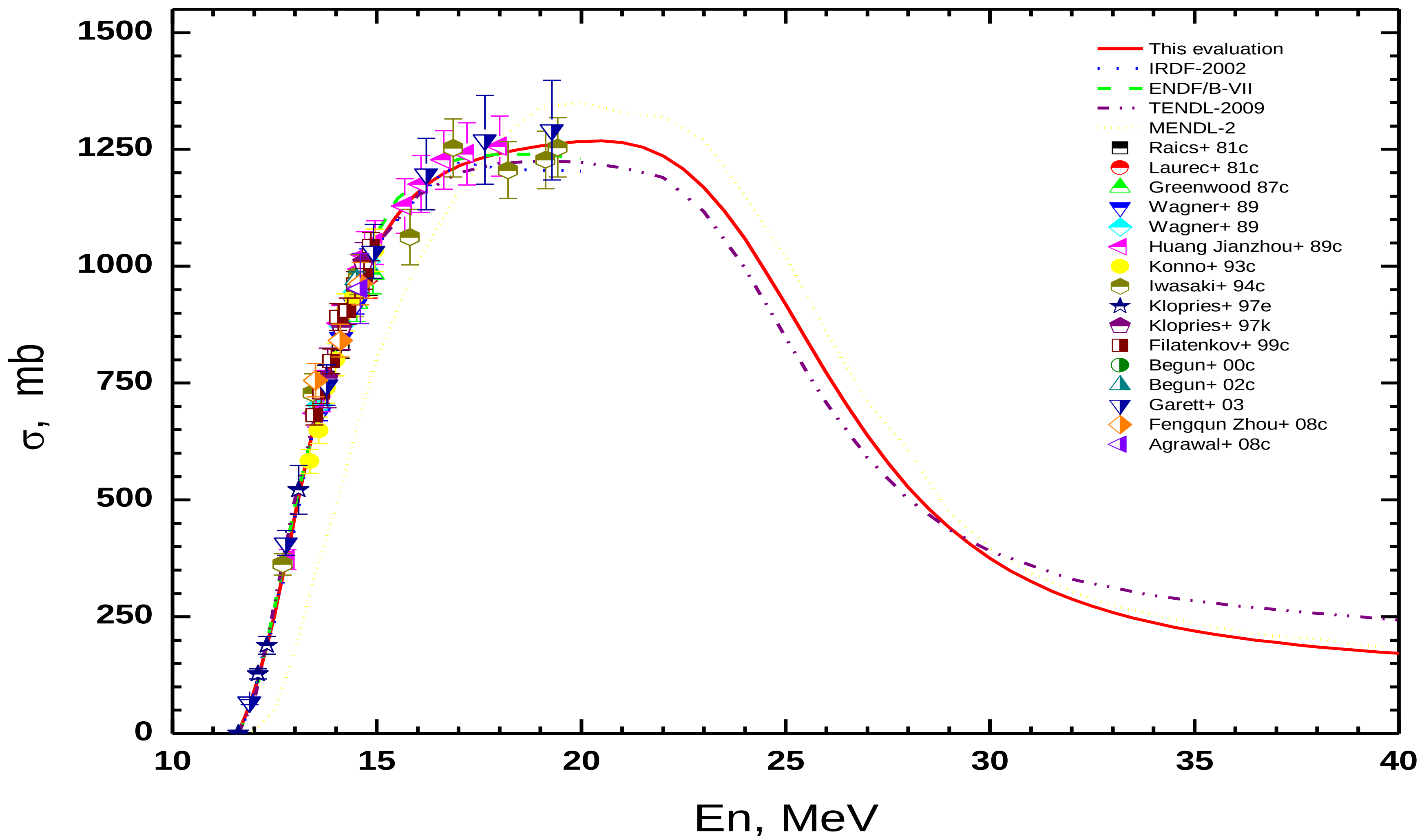

FIG 4.2. Evaluated excitation function of the $^{89}Y(n,2n)^{88}Y$ reaction in the energy range from threshold to 40 MeV in comparison with IRDF-2002, ENDF/B-VII, TENDL-2009, MENDL-2 and experimental data (1981-2008)

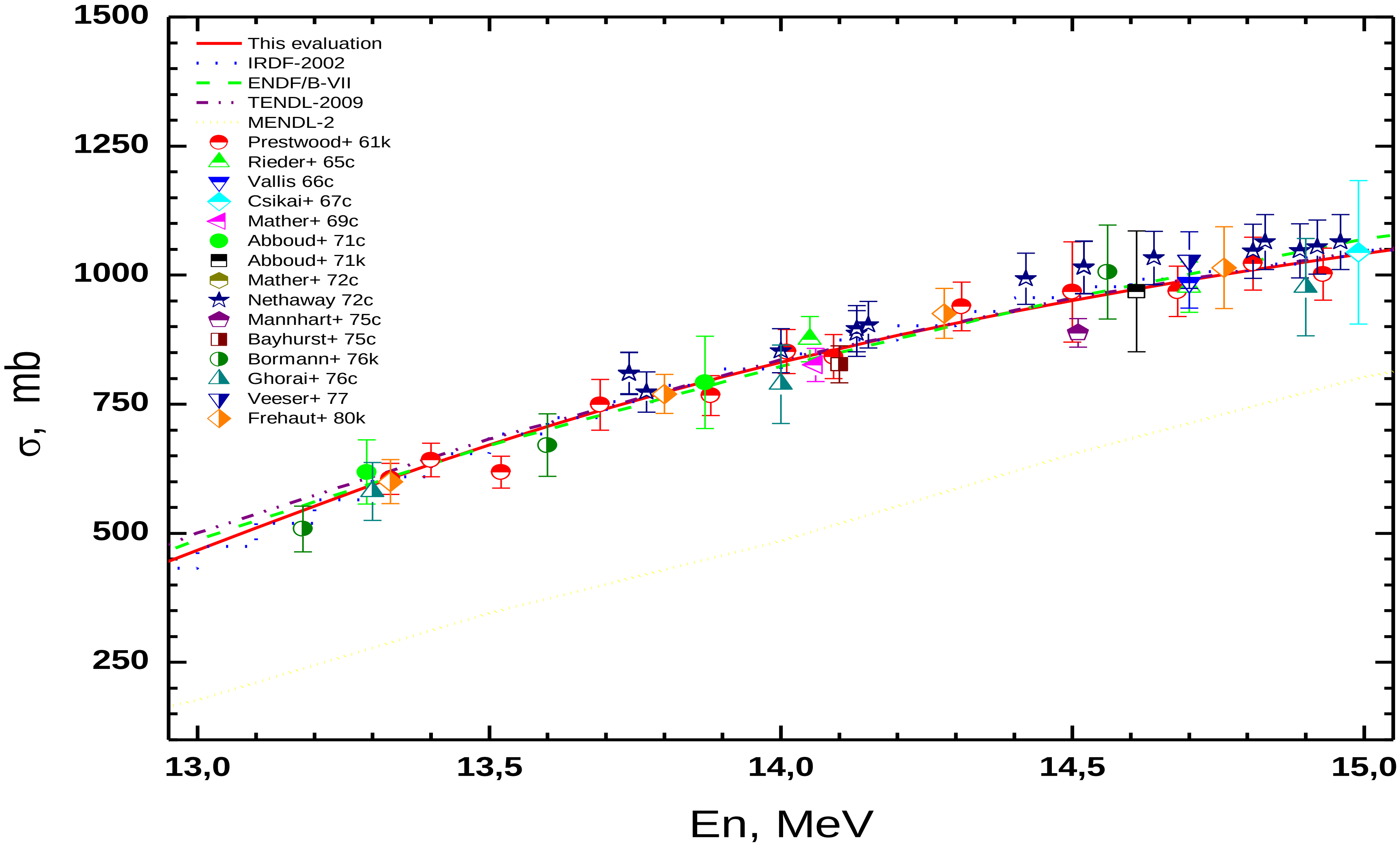

FIG 4.3. Evaluated excitation function of the $^{89}Y(n,2n)^{88}Y$ reaction in the energy range from 13 to 15 MeV in comparison with IRDF-2002, ENDF/B-VII, TENDL-2009, MENDL-2 and experimental data (1961-1980)

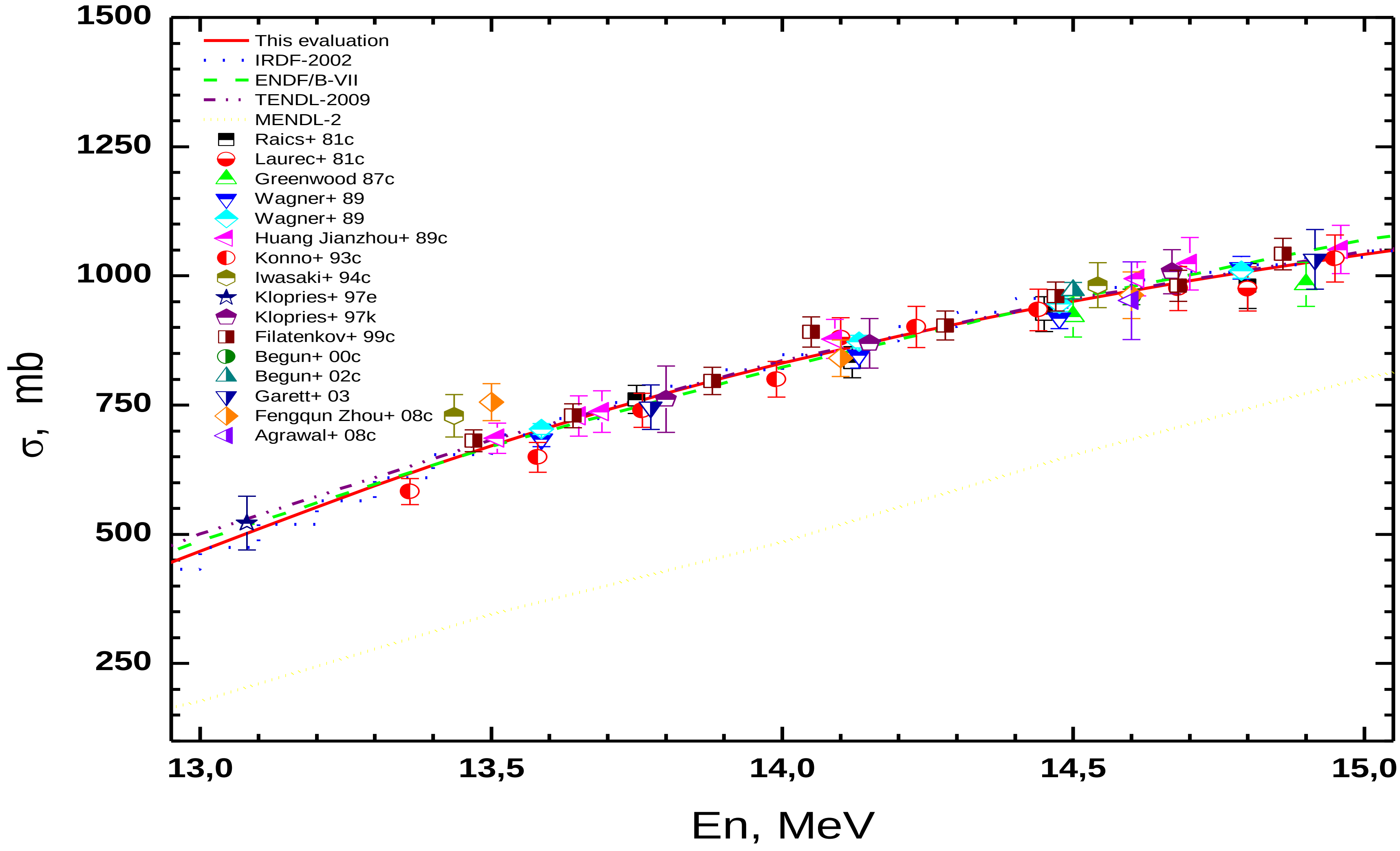

FIG 4.4. Evaluated excitation function of the $^{89}Y(n,2n)^{88}Y$ reaction in the energy range from 13 to 15 MeV in comparison with IRDF-2002, ENDF/B-VII, TENDL-2009, MENDL-2 and experimental data (1981-2008)

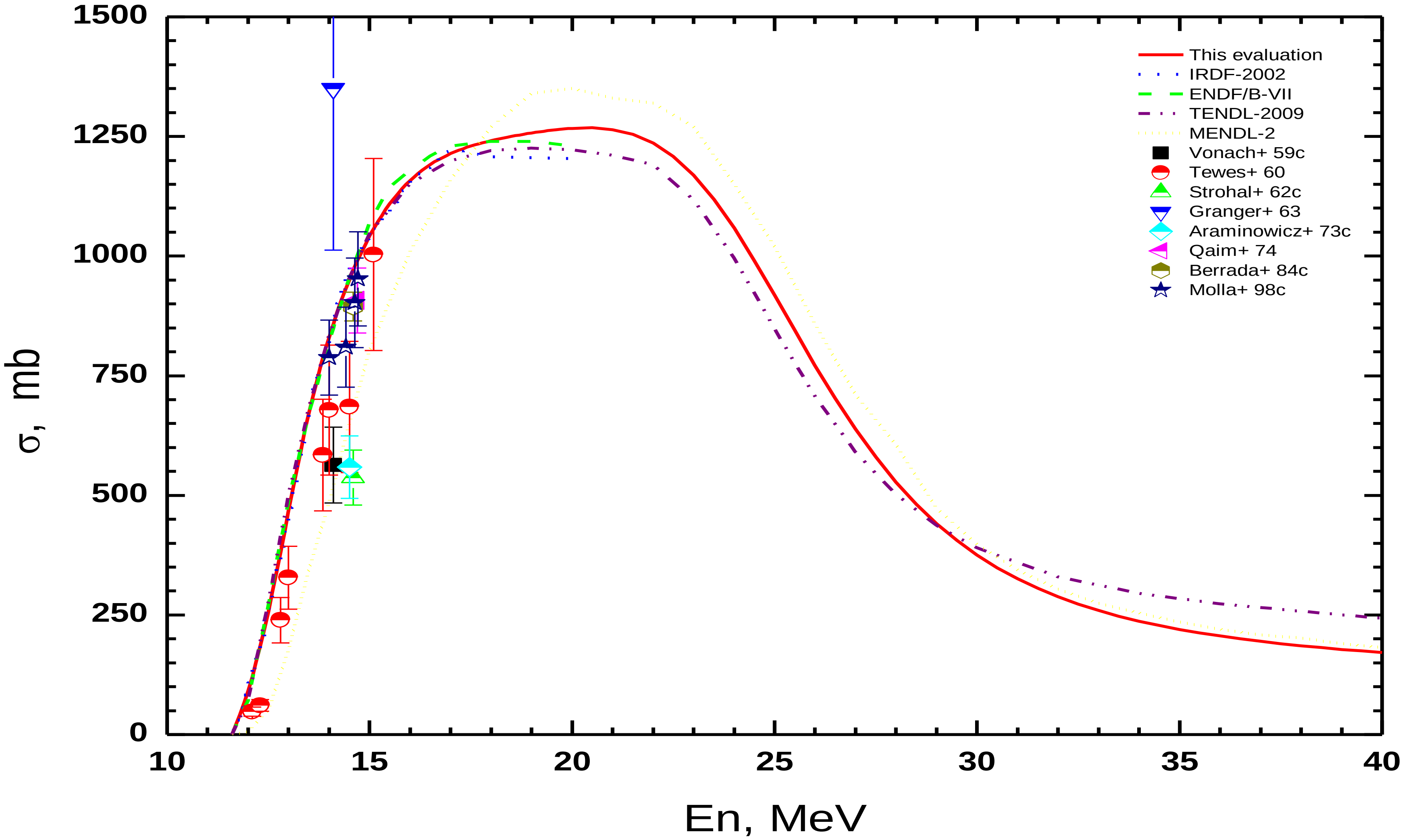

FIG 4.5. Evaluated excitation function of the $^{89}Y(n,2n)^{88}Y$ reaction in the energy range from threshold to 40 MeV in comparison with IRDF-2002, ENDF/B-VII, TENDL-2009, MENDL-2 and rejected experimental data

TABLE 4.2. CALCULATED AND MEASURED AVERAGED CROSS SECTIONS FOR THE $^{89}Y(n,2n)^{88}Y$ REACTION IN ^{235}U THERMAL FISSION AND ^{252}Cf SPONTANEOUS FISSION NEUTRON SPECTRA

Type of neutron field	Averaged cross section, mb		C/E[*]
	Calculated	Measured	
^{235}U thermal fission neutron spectrum	0.14954 [A]	0.1502 ± 0.0050 [**]	0.99561
	0.14844 [B]		0.98828
	0.15040 [C]		1.00133
	0.15169 [D]		1.00992
	0.08090 [E]		0.53862
^{252}Cf spontaneous fission neutron spectrum	0.34545 [A]		
	0.34418 [B]		
	0.34896 [C]		
	0.34978 [D]		
	0.19867 [E]		

[A] - Present evaluation
[B] - IRDF-2002
[C] - ENDF/B-VII r.0
[D] - TENDL-2009
[E] - MENDL-2
[*] - ratio of calculated to experimental cross sections
[**] - Average-weighted value obtained from the experimental data [4.40 - 4.44]

Data presented in Table 4.2 show that calculated from the re-evaluated $^{89}Y(n,2n)^{88}Y$ reaction excitation function average cross-section value for ^{235}U thermal fission neutron spectrum agree within 0.5% with experimental data. The results of the calculation carried out for the IRDF-2002, ENDF/B-VII and TENDL-2009 libraries alsoagree well with experimental data. In comparison with experimental data, the integral cross-section value calculated from the MENDL-2 evaluation is about 47% lower. The 90%-response range of $^{89}Y(n,2n)^{88}Y$ reaction in the ^{235}U thermal fission neutron spectrum is between 12.1 – 16.90 MeV.

REFERENCES TO SECTION 4

[4.1] PRESTWOOD, R.J., BAYHURST, B.P., (n,2n) Excitation Functions of Several Nuclei from 12.0 to 19.8 MeV, Phys. Rev. **121** (1961) 1438-1441.

[4.2] HUDSON, O.M. Jr., MORGAN, I.L., Activation Analysis of Yttrium and Ytterbium. Bulletin of the American Physical Society **6** (1961) 506 (E9).

[4.3] RIEDER, R., MUENZER, H., (n,2n) Cross Sections for Some Nuclei with N near the Magic Number 50 with 14 MeV Neutrons, in: Progress Report EANDC(OR)-38, April 1965, p.1 (in German).

[4.4] VALLIS, D.G., Cross Sections for (n,2n) Reaction at 14.7 MeV of Some ODD-proton Nuclei, Report AWRE-0-76/66, Atomic Weapons Research Establishment, Aldermaston, UK, December 1966.

[4.5] CSIKAI, J., PETO, G., Influence of Direct Inelastic Scattering on (n,2n) Cross Sections, Acta Phys. Hung. **23** (1967) 87.

[4.6] MATHER, D.S., PAIN, L.F., Measurement of (n,2n) and (n,3n) cross sections at 14 MeV incident energy, Report AWRE-O-47/69, Atomic Weapons Research Establishment, Aldermaston, UK, August 1969.

[4.7] ABBOUD, A., DECOWSKI, P., GROCHULSKI, W., MARCINKOWSKI, A., SIWEK, K., TURKIEWICZ, I., WILHELMI, Z., Cross Sections for the ^{89}Y(n,n')^{89m}Y and ^{89}Y(n,2n)^{88}Y Reactions., Acta Physica Polonica B **2** (1971) 527.

[4.8] MATHER, D.S., BAMPTON, P.F., COLES, R.E., JAMES, G., NIND, P.J., Measurement of (n,2n) cross sections for incident energies between 6 and 14 MeV, Report AWRE-O-72/72, Atomic Weapons Research Establishment, Aldermaston, UK, November 1972.

[4.9] NETHAWAY, D.R., Cross Sections for Several (n,2n) Reactions at 14 MeV, Nucl. Phys. A **190** (1972) 635-644.

[4.10] BAYHURST, B.P., GILMORE, J.S., PRESTWOOD, R.J., WILHELMY, J.B., JARMIE, N., ERKKILA, B.H., HARDEKOPF, R.A., Cross-sections for (n,xn) Reactions Between 7.5 and 28 MeV, Phys. Rev. C **12** (1975) 451-467.

[4.11] MANNHART, W., VONACH, H., Precision measurement of cross sections at 14 MeV neutron energy, Z. Physik A **272** (1975) 279 (in German).

[4.12] GHORAI, S.K., HUDSON, C.H., ALFORD, W.L., The Excitation Function for the^{89}Y(n,2n) Reaction, Nucl. Phys. A **266** (1976) 53.

[4.13] BORMANN, M., FEDDERSEN, H-K., HOLSCHER, H.H., SCOBEL, W., WAGNER, H., (n,2n) Excitation Functions for ^{54}Fe, ^{70}Ge, ^{74}Se, ^{85}Rb, ^{86,88}Sr, ^{89}Y, ^{92}Mo and ^{204}Hg in the Neutron Energy Range 13 – 18 MeV, Z. Physik A **277 (**1976) 203 (in German).

[4.14] VEESER, L.R., ARTHUR, E.D., YOUNG, P.G., Cross Sections for (n,2n) and (n,3n) Reactions above 14 MeV, Phys. Rev. C **16** (1977) 1792-1802.

[4.15] KAYASHIMA, K., NAGAO, A., KUMABE, I., Activation Cross Section on Ti, Mn, Cu, Zn, Sr, Y, Cd, In and Te for 14.6-MeV Neutrons, in: Progress Report NEANDC(J)-61U, September 1979, p. 94.

[4.16] FREHAUT, J., BERTIN, A., BOIS, R., JARY, J., Status of (n,2n) Cross-section Measurements at Bruyéres-le-Châtel, in: Proc. Symp. on Neutron Cross Sections from 10-50 MeV, 12-14 May 1980, Upton, USA, Bhat, M.R. and Pearlstein, S. (Eds), BNL-NCS-51245, Brookhaven National Laboratory, Upton, NY, USA, 1980, pp. 399-411.

[4.17] LAUREC, J, ADAM, A., De Bruyne, T., Measurement of the (n,2n) Reaction Cross Sections of the Nuclei ^{89}Y, ^{93}Nb, ^{103}Rh, ^{107}Ag, ^{169}Tm, ^{175}Lu, and ^{197}Au at 14.1 and 14.8 MeV, Report CEA-R-5109, June 1981 (in French).

[4.18] RAICS, P., PASZTI, F., DAROCZY, S., NAGY, S., Measurement of the Cross Sections for the ^{58}Ni(n,2n), ^{58}Ni(n,p), ^{58}Ni(nd) and ^{89}Y(n,2n) Reactions Around 14 Mev, Atomki Koezlemenyek **23** (1981) 45.

[4.19] GREENWOOD, L.R., Recent Research in Neutron Dosimetry and Damage Analysis for Materials Irradiations, ASTM-STP-956 (1987) 743-749.
[4.20] WAGNER, M., WINKLER, G., VONACH, H., BUCZKO, C.M., CSIKAI, J., Measurement of the Cross Sections for the Reactions $^{52}Cr(n,2n)^{51}Cr$, $^{66}Zn(n,2n)^{65}Zn$, $^{89}Y(n,2n)^{88}Y$ and $^{96}Zr(n,2n)^{95}Zr$ from 13.5 to 14.8 MeV, Ann. Nucl. Energy **16** (1989) 623.
[4.21] HUANG JIANZHOU, LU HANLIN, LI JIZHOU, FAN PEIGUO, Measurement of Cross Sections for $^{59}Co(n,\alpha)^{56}Mn$ and $^{59}Co(n,2n)^{58m+g}Co$ Reactions, Chinese J. Nucl. Physics **3** (1981) 59.
[4.22] KONNO, C., IKEDA, Y., OISHI, K., KAWADE, K., YAMAMOTO, H., MAEKAWA, H., Activation Cross Section Measurements at Neutron Energy from 13.3 to 14.9 MeV Using FNS Facility, Report JAERI 1329, October 1993.
[4.23] IWASAKI, S., MATSUYAMA, S., OHKUBO, T., FUKUDA, H., SAKUMA, M, KITAMURA, M., Measurement of activation cross-sections for several elements between 12 and 20 MeV, in: Proc. Int. Conf. Nuclear Data for Science and Technology, 9-13 May 1994, Gatlinburg, USA, Dickens, J.K. (Ed.), Vol. 1, American Nuclear Society, USA, 1994, p. 305.
[4.24] KLOPRIES, R.M., DOCZI, R., SUDAR, S., CSIKAI, J., QAIM, S.M., Excitation Functions of Some Neutron Threshold Reactions on ^{89}Y in the Energy range of 7.8 to 14.7 MeV, Radiochimica Acta **76** (1997) 3.
[4.25] FILATENKOV, A.A., CHUVAEV, S.V., Systematic Activation Cross Sections Measurement at Neutron Energies around 14 MeV, Preprint RI-252, M, Atominform, 1999.
[4.26] BEGUN, S.V., KADENKO, I.M., MAIDANYUK, V.K., NEPLYUEV, V.M., PRIMENKO, G.I., TARAKANOV, V.K., The Cross Sections of (n,x) Nuclear Reactions on Y, La and Ta at the Energy of Neutrons 14.6 MeV, J. Izv. Rossiiskoi Akademii Nauk, Ser. Fiz. **64** (2000) 1017 (in Russian).
[4.27] BEGUN, S.V., KADENKO, I.M., MAIDANYUK, V.K., NEPLYUEV, V.M., PRIMENKO, G.I., TARAKANOV, V.K., Determination of the Cross Sections of (n,x) Nuclear Reactions on Y, La, Ta, Pb and Bi at the Energy of Neutrons about 14 MeV, J. Nucl. Sci. Technol. **2** (2002) 425.
[4.28] GARRETT, P.E., ORMAND, W.E., YOUNES, W., BECKER, J.A., BERNSTEIN, L.A., NELSON, R.O., DEVLIN, M., FOTIADES, N., Cross Sections for n + ^{89}Y for E_n < 20 MeV, Report UCRL-ID-153190, Lawrence Livermore National Laboratory, 2003.
[4.29] FENGQUN ZHOU, HONGWEL ZHANG, HONGCHUN HUANG, KUOHU LI, YANLING YI, FEI TUO, XIANGZHONG KONG, Cross-Section Measurements for (n,2n) and (n,α) Reactions on Yttrium at Neutron Energies from 13.5 to 14.6 MeV, J. Appl. Radiat. Isotopes **66** (2008) 1898.
[4.30] AGRAWAL, H.M., PANDEY KALIASH, SURENDRA BABU, K., KUMAR ASHOK, PEPELNIK, R., Neutron Activation Cross-Sections at (14.6±0.3) MeV, Ann Nucl. Energy **35** (2008) 1713.
[4.31] VONACH, H., MUENZER, H., (n,2n) Cross-Sections Measurements on ^{86}Sr, ^{89}Y, ^{93}Nb and ^{133}Cs for 14.1 MeV Neutrons., Oesterr. Akad. Wiss., Math. und Naturw. Anzeiger **96** (1959) 120 (in German).
[4.32] TEWES, H.A, CARETTO, A.A., MILLER, A.E., NETHAWAY, D.R., Excitation Functions of Neutron-induced Reactions., Proc. Nuclear and Radiation Chemical Symposium, 6 September 1960, Chalk River, Ontario, Canada, UCRL-6028-T, University of California Research Laboratory, Livermore, USA, 1960.
[4.33] STROHAL, F., CINDRO, N., EMAN, B, Reaction mechanism and shell effects from the interaction of 14.6 MeV neutrons with nuclei, Nucl. Phys. **30** (1962) 49.

[4.34] GRANGER, B., LONGUEVE, M., Measurements of (n,2n) cross sections at 14.1 MeV for Co-59, As-75, Y-89 and Mn-55, in: European American Nuclear Data Committee Report EANDC(E)-49L, October 1963, p. 83, (in French).

[4.35] ARAMINOWICZ, J., DRESLER, J., Investigation of the (n,2n) Reaction at 14.6 MeV for 42 Nuclides, in: Progress Report INR-1464, Marcinkowski, A. (Ed.), Warsaw, Poland, May 1973, pp. 14-18.

[4.36] QAIM, S.M., STOECKLIN, G., Measurement and Systematics of Cross Sections for Common and Low Yield 14 MeV Neutron Induced Nuclear Reactions on Structural Fr-material and Transmuted Species, in: Proc. 8th Symp. On Fusion Technology, Noordwijkerhout, 17-21 June 1974, Report EUR-5182E, September 1974, p. 939.

[4.37] BERRADA, M., Measurement and Analysis of 14 MeV Neutron Nuclear Reaction Cross-Sections by X and Gamma Spectroscopy, Progress Report on Research Contract-3311.R1/RB, IAEA NDS, Vienna, April 1984.

[4.38] MOLLA, N.I., BASUNIA, S., MIAH, R.U., HOSSAIN, S.M., RAHMAN, M., SPELLERBERG, S., QAIM, S.M., Radiochemical Study of the $^{45}Sc(n,p)^{45}Ac$ and $^{89}Y(n,p)^{89}Sr$ Reactions in the Neutron Energy Range of 13.9 to 14.7 MeV, Radiochimica Acta **80 (**1998) 189.

[4.39] BRAUN, H., NAGY, L., Fission spectrum average cross sections for the (n,p)-, (n,α)- and (n,2n)-reactions of C0-59, Ni-58, Fe-54 and Y-89, Radiochimica Acta **10 (**1968) 15 (in German).

[4.40] RAU, G., Averaged Cross Section of the Reaction Y-89(n,2n)Y-88, in: Progress Report EANDC(E)-89, February 1968, p. 41.

[4.41] STEINNES, E., Cross-Sections of Some (n,2n) Reactions Induced by Reactor Fast Neutrons, Radiochimica Acta **13** (1970) 169.

[4.42] QAIM, S.M., WOELFLE, R., STOECKLIN, G., Activation Cross Sections of Fast Neutron Induced Nuclear Reactions. Precision Measurements and Systematics, in: Proc. Conf. on Chemical Nucl. Data, Measurements and Application, University of Kent, Canterbury, 20-22 September 1971, p. 121.

[4.43] BRODSKAJA, A.K., IVANOVA, N.I., NASYROV, F.K., Cross Sections of (n,α), (n,p), (n,2n), (n,n') Reactions Averaged in Fission Neutron Spectrum for Some Elements, Voprocy Atomnoj Nauki i Techniki, Ser.: Yadernye Konstanty **4** (1976) 4-5 (in Russian).

[4.44] BOJTCOV A.A., GRIGOR'EV E.I., TROSHIN V.S., YARYNA V.P., Measurements and Evaluations of the Averaged Cross-Section for $^{89}Y(n,2n)^{88}Y$ Reaction for the Fission ^{235}U Neutrons, Voprocy Atomnoj Nauki i Techniki, Ser.: Yadernye Konstanty, **1** (1992) 55-56 (in Russian).

5. EVALUATION OF THE EXCITATION FUNCTION OF THE ^{93}Nb(n,2n)^{92m}Nb REACTION

The isotopic abundance of ^{93}Nb in natural niobium is 100 atom percent. The 135.5-keV ($J_{\pi} = 2^{+}$) metastable level of ^{92}Nb excited in the (n,2n) reaction undergoes 100% decay via ε capture and β^{+} decay with a half-life of (10.15 ± 0.02) days. The ε capture and β^{+} transition are accompanied by emission of X-ray and gamma-ray radiation. The most intense line in the gamma-ray spectrum is the 934.44-keV line ($I_{\gamma} = 0.9907 \pm 0.0004$). Recommended decay data for the half-life and gamma ray emission probability per decay of ^{92m}Nb were taken from Ref. [2.7] of Section 2.

Microscopic experimental data were analyzed during the preparation of the input database assembled in order to evaluate the cross sections and uncertainties for the ^{93}Nb(n,2n)^{92m}Nb reaction [5.1-5.50]. During this procedure, various experimental data from Refs. [5.1], [5.3-5.12], [5.14-5.18], [5.20], [5.22-5.25], [5.27-5.28], [5.30-5.35], [5.42-5.44], [5.46], [5.48], [5.50] were corrected on the basis of the newly recommended cross-section data for the relevant monitor reactions and the recommended decay data (see Table 2.1).

Other adjustments were also applied to some of the experimental data of Refs. [5.3], [5.9], [5.28], [5.29] and [5.32].

The results of absolute measurement of Ikeda *et al.* in the neutron energy range 13.33 – 14.91 MeV [5.37] were used as reference data for correction of experimental data from Refs. [5.3], [5.9], [5.28] and [5.32]. After corrections to the new standards, relative experimental data of Prestwood and Bayhurst [5.3] were renormalized to a factor of Fc = 26.23228. Cross sections measured by Paulsen and Widera [5.9] in the energy range 12.63 – 14.71 MeV and by Woelfle *et al.* [5.28] in the energy range 12.55 – 14.41 MeV were multiplied by factors Fc = 1.08953, and Fc = 0.949967, respectively. The experimental data of Santry and Werner [5.32] obtained in measurements with D(d,n)^{3}He neutron source after corrections to the new standards were renormalized to a factor of Fc = 1.05106. Cross sections obtained by these authors in measurements with T(d,n)^{4}He neutron source were corrected to a factor of Fc = 1.02732. Correction factors were determined from the ratio of cross-section integral of Ikeda *et al.* [5.37] to the adequate integrals for the above mentioned experimental data.

Corrected to the new standards, data of Paulsen and Widera [5.9] in the energy range 15.09 – 19.59 MeV were multiplied by a factor of Fc = 1.11837, which was determined from two ratio values:

1. ratio of cross-section integrals of Woelfle *et al.* [5.28] and Paulsen and Widera [5.9] in the energy range 16.25 – 19.58 MeV, R = 1.126807, and
2. ratio of cross-section integrals of Fessler *et al.* [5.40] and Paulsen and Widera [5.9] in the energy range 16.25 – 19.58 MeV, R = 1.109934.

Cross sections obtained by Zhao Wenrong *et al.* [5.29] in the energy range 15.69 – 18.24 MeV using the T(d,n)^{4}He neutron source at Van de Graaff accelerator were renormalized by a factor of Fc = 1.05114, which was determined from two ratio values:

1. ratio of cross-section integrals of Woelfle *et al.* [5.28] and Zhao Wenrong *et al.* [5.29] in the energy range 15.69 – 18.24 MeV, R = 1.05934, and
2. ratio of cross-section integrals of Fessler *et al.* [5.40] and Zhao Wenrong *et al.* [5.29] in the energy range 16.03 – 18.24 MeV, R = 1.04295.

Cross-section data given in Refs. [5.10], [5.14], [5.34] and [5.41] were only used partially in this current evaluation. Experimental data of Bormann *et al.* [5.10] for the incident neutron energies 12.66-, 13.39 MeV and Hudson *et al.* [5.14] for the incident neutron energies 13.30 MeV, 14.10 MeV were rejected due to significant overestimation of the ^{93}Nb(n,2n)^{92m}Nb reaction cross section. Experimental data of Ikeda *et al.* [5.34] were taken only for the incident neutron energy 13.2 MeV. Data for 9.5 MeV, 11.0 MeV, 12.0 MeV points were rejected due to significant underestimation of the ^{93}Nb(n,2n)^{92m}Nb reaction cross section. For the same reason the cross section value measured by Kiraly *et al.* at 11.30 MeV [5.41] was not taken into account.

Cross sections given in Refs. [5.43-5.50] have been rejected completely due to their significant deviation from the main bulk of the experimental data. Within these rejected experimental data, the cross-section values reported in Refs. [5.43-5.47] comprised only one or two energy points from 14 to 15 MeV.

The excitation function for the ^{93}Nb(n,2n)^{92m}Nb reaction in the energy range from threshold to 40 MeV was evaluated by means of statistical analyses of the experimental cross-section data [5.1-5.42] and data from theoretical model calculation, which were the main source of information above 20 MeV. Uncertainties in the evaluated excitation function for the ^{93}Nb(n,2n)^{92m}Nb reaction are given in the form of a relative covariance matrix for 49-neutron energy groups (LB = 5). Covariance matrix uncertainties were calculated simultaneously with the recommended cross-section data by means of the PADE-2 code.

Six-digit eigenvalues for the relative covariance matrix in File-33 are as follows:

```
6.12692E-07    6.13349E-07        6.14499E-07        6.16143E-07
6.18265E-07    6.22090E-07        6.26885E-07        6.34111E-07
6.42259E-07    6.52893E-07        6.66366E-07        6.85897E-07
7.07349E-07    7.37742E-07        7.89672E-07        8.47100E-07
9.21725E-07    1.06640E-06        1.23801E-06        1.64082E-06
2.45919E-06    3.39790E-06        6.11854E-06        9.88467E-06
1.25971E-05    1.56256E-05        2.03796E-05        2.52801E-05
3.00823E-05    3.47700E-05        3.93794E-05        4.39588E-05
4.85529E-05    5.32025E-05        5.79424E-05        6.28123E-05
6.78503E-05    7.31571E-05        1.86028E-04        2.46519E-04
2.88252E-04    3.95323E-04        4.11440E-04        7.77483E-04
9.80231E-04    1.03070E-03        2.13425E-03        1.65167E-02
9.65419E-02
```

All of these eigenvalues are positive.

Evaluated group cross sections and their uncertainties for the excitation function of the ^{93}Nb(n,2n)^{92m}Nb reaction are given in Table 5.1. Boundaries for the neutron energy groups are the same as in File-33.

The lowest uncertainties of 0.54% to 0.96% in the evaluated cross sections are observed in the neutron energy range from 12.0 to 17.0 MeV, while the largest uncertainty of 12.86% is found from threshold to 9.25 MeV. Relatively large uncertainty near threshold is caused by discrepancies in the experimental data. Over neutron energies from 9.25 to 12.0 MeV and 17.0 to 21.0 MeV, uncertainties in the cross sections vary between 1.09% and 2.44%, but these values increase from 3.15% to 9.83% in the neutron energy range from 21.0 to 40 MeV due to uncertainty in cross section predictions by theoretical model calculation.

TABLE 5.1. EVALUATED CROSS SECTIONS AND THEIR UNCERTAINTIES FOR THE $^{93}Nb(n,2n)^{92m}Nb$ REACTION IN THE NEUTRON ENERGY RANGE FROM THRESHOLD TO 45 MeV

Neutron energy (MeV) from – to	Cross section (mb)	Uncer-tainty (%)	Neutron energy (MeV) from – to	Cross section (mb)	Uncer-tainty (%)
9.064 – 9.250	2.857	12.86	18.000 – 18.500	405.483	1.21
9.250 – 9.500	16.209	2.44	18.500 – 19.000	386.447	1.20
9.500 – 9.750	54.096	1.75	19.000 – 19.500	363.019	1.20
9.750 – 10.000	102.956	1.50	19.500 – 20.000	335.199	1.38
10.000 – 10.500	171.431	1.33	20.000 – 21.000	288.612	2.05
10.500 – 11.000	250.219	1.28	21.000 – 22.000	227.972	3.15
11.000 – 11.500	315.898	1.24	22.000 – 23.000	175.175	3.88
11.500 – 12.000	368.117	1.09	23.000 – 24.000	136.897	4.27
12.000 – 12.500	406.559	0.91	24.000 – 25.000	111.266	4.60
12.500 – 13.000	432.326	0.77	25.000 – 26.000	94.233	4.98
13.000 – 13.250	444.914	0.68	26.000 – 27.000	82.624	5.42
13.250 – 13.500	450.505	0.63	27.000 – 28.000	74.383	5.88
13.500 – 13.750	455.026	0.59	28.000 – 29.000	68.263	6.35
13.750 – 14.000	458.078	0.56	29.000 – 30.000	63.517	6.80
14.000 – 14.200	459.608	0.55	30.000 – 31.000	59.691	7.22
14.200 – 14.400	460.082	0.54	31.000 – 32.000	56.504	7.62
14.400 – 14.600	460.133	0.55	32.000 – 33.000	53.778	7.98
14.600 – 14.800	460.173	0.56	33.000 – 34.000	51.397	8.32
14.800 – 15.000	460.260	0.59	34.000 – 35.000	49.282	8.63
15.000 – 15.500	459.245	0.64	35.000 – 36.000	47.378	8.91
15.500 – 16.000	455.115	0.74	36.000 – 37.000	45.646	9.17
16.000 – 16.500	448.815	0.84	37.000 – 38.000	44.057	9.41
16.500 – 17.000	441.320	0.96	38.000 – 39.000	42.590	9.63
17.000 – 17.500	432.211	1.07	39.000 – 40.000	41.229	9.83
17.500 – 18.000	421.424	1.16			

Figs. 5.1 and 5.3 show the re-evaluated excitation function for the $^{93}Nb(n,2n)^{92m}Nb$ reaction over the neutron energy range from threshold to 40.0 MeV and over the 13 – 16 MeV interval in comparison with IRDF-2002, JENDL/D-99, IRDF90-V.2 and experimental data obtained in the years 1959-1985. Comparison of the evaluated excitation functions with experimental data obtained from 1986 to 2007 is shown in Figs. 5.2 and 5.4. The evaluated excitation functions and the rejected experimental data are adduced in Fig. 5.5. The $^{93}Nb(n,2n)^{92m}Nb$ reaction excitation function obtained from the GNASH calculation is presented in all Figs. Comparison of excitation functions show that new evaluation and data from dosimetry files IRDF-2002 and IRDF90-V.2 agree well in the energy range from threshold up to 14.7 MeV.

The behaviour of the re-evaluated excitation function above 14.7 MeV is slightly differing from excitation functions given in the IRDF-2002 and IRDF90-V.2 libraries. Above 14.7 MeV the new evaluation gives systematically higher cross section values. The present evaluation agrees better with experimental data and theoretical model calculations than the IRDF-2002 and IRDF90-V.2 evaluations. In the energy range 9.7 – 11.2 MeV the JENDL/D-99 library gives systematically lower cross sections, while between 12 – 14 MeV it gives systematically higher cross sections than the present evaluation and data from dosimetry files IRDF-2002 and IRDF90-V.2. The new evaluation above 21 MeV is based on theoretical model calculation performed by means of GNASH code.

Integral experimental data for the ^{93}Nb(n,2n)^{92m}Nb reaction are given in Refs. [5.51-5.61]. Nine experiments were carried out in neutron fields similar to the ^{235}U thermal fission neutron spectrum [5.51-5.59], while two experiments were performed in a ^{252}Cf spontaneous fission neutron spectrum [5.60-5.61].

Measured integral cross sections for the ^{235}U thermal fission neutron spectrum range from 0.370 to 0.491 mb. The lowest value of (0.370 ± 0.030) mb was obtained by Nasyrov and Sciborskij in measurements at the ^{235}U critical assembly [5.52], and no information about neutron flux determination and decay data is given in this publication. A value of (0.491 ± 0.016) mb was measured in the swimming pool type reactor IEA-R1 by Maidana *et al.* [5.59]. Integral cross sections given in Refs. [5.51], [5.53], [5.57] and [5.58] were measured in the neutron spectra generated in facilities with 90%-enriched ^{235}U fission plate converter. The results of three independent works [5.51], [5.53] and [5.58] agree within their experimental uncertainties. Integral cross section $<\sigma>_{U\text{-}235}$ given for the ^{93}Nb(n,2n)^{92m}Nb reaction in Ref. [5.57] contradicts the earlier result of these authors [5.53]. The average cross section value determined from Refs. [5.51], [5.53] and [5.58] is equal to (0.4348 ± 0.0101) mb. The integral cross section evaluated from experiments performed in the core of reactors is equal to (0.4582 ± 0.0081) mb. The more representative value of $<\sigma>_{U\text{-}235}$ is (0.4348 ± 0.0101) mb, because it was obtained from measurements in facilities with 90%-enriched ^{235}U fission plate converter.

The experimental data obtained in a ^{252}Cf spontaneous fission neutron spectrum by Csikai and Dezsö of (0.7946 ± 0.0378) mb [5.60] and by Shani of (0.7688 ± 0.0980) mb [5.61] differ in the limit of their uncertainties. The average cross section determined from these two works is equal to $<\sigma>_{Cf\text{-}252}$ = (0.7914 ± 0.0353) mb.

Evaluated experimental data for the ^{235}U thermal fission neutron spectrum and ^{252}Cf spontaneous fission neutron spectrum were used in benchmark calculations. The results of tests with the re-evaluated excitation function for the ^{93}Nb(n,2n)^{92m}Nb reaction are given in Table 5.2 compared to IRDF-2002, JENDL/D-99 and IRDF90-v2 data.

TABLE 5.2. CALCULATED AND MEASURED AVERAGED CROSS SECTIONS FOR THE ^{93}Nb(n,2n)^{92m}Nb REACTION IN ^{235}U THERMAL FISSION AND ^{252}Cf SPONTANEOUS FISSION NEUTRON SPECTRA

Type of neutron field	**Averaged cross section, mb**		**C/E[*]**
	Calculated	**Measured**	
^{235}U thermal fission neutron spectrum	0.43469 [A]	0.4348 ± 0.0101 [**]	0.99857
	0.42302 [B]		0.97291
	0.41319 [C]		0.95030
	0.42739 [D]		0.98296
^{252}Cf spontaneous fission neutron spectrum	0.79122 [A]	0.7914 ± 0.0353 [***]	0.99977
	0.77183 [B]		0.97527
	0.75784 [C]		0.95759
	0.77924 [D]		0.98463

[A] - Present evaluation.
[B] - IRDF-2002.

[C] - JENDL/D-99.
[D] - IRDF90-v2.
[*] - ratio of calculated to experimental cross sections
[**] - Average-weighted value obtained from the experimental data [5.51], [5.53], [5.58].
[***] - Average-weighted value obtained from the experimental data [5.60], [5.61].

The obtained C/E values show that the integral cross sections calculated from the re-evaluated excitation function agree best of all with the experimental data for both benchmark spectra. The equivalent data calculated from JENDL/D-99 have the highest discrepancies with integral experimental data. The $<\sigma>_{U-235}$ and $<\sigma>_{Cf-252}$ cross sections calculated from JENDL/D-99 excitation function underestimate experimental data by 4.97% and 4.24%, respectively.

Integral cross sections $<\sigma>_{U-235}$ and $<\sigma>_{Cf-252}$ evaluated by Mannhart for the ^{93}Nb(n,2n)^{92m}Nb reaction are equal, respectively, to (0.4645 ± 0.0117) mb [5.62] and (0.7490 ± 0.0380) mb [5.63]. These values differ from equivalent experimental data evaluated in the present work. The 90%-response ranges for the ^{93}Nb(n,2n)^{92m}Nb excitation function in the ^{235}U thermal fission neutron spectrum and ^{252}Cf spontaneous fission neutron spectrum are 9.7 – 14.3 MeV and 9.8 – 14.8 MeV, respectively. Above mentioned energy intervals are the neutron energies diapason where the ^{93}Nb(n,2n)^{92m}Nb excitation function is tested. The present evaluation of the ^{93}Nb(n,2n)^{92m}Nb reaction excitation function agrees well with new microscopic experimental data of Mannhart and Schmidt obtained in the energy range from 8 to 15 MeV [5.42] and evaluated integral cross sections $<\sigma>_{U-235}$ = (0.4348 ± 0.0101) mb and $<\sigma>_{Cf-252}$ = (0.7914 ± 0.0353) mb. This leads to the conclusion that integral cross sections $<\sigma>_{U-235}$ and $<\sigma>_{Cf-252}$ evaluated by Mannhart for the ^{93}Nb(n,2n)^{92m}Nb reaction are not consistent with available microscopic and integral data.

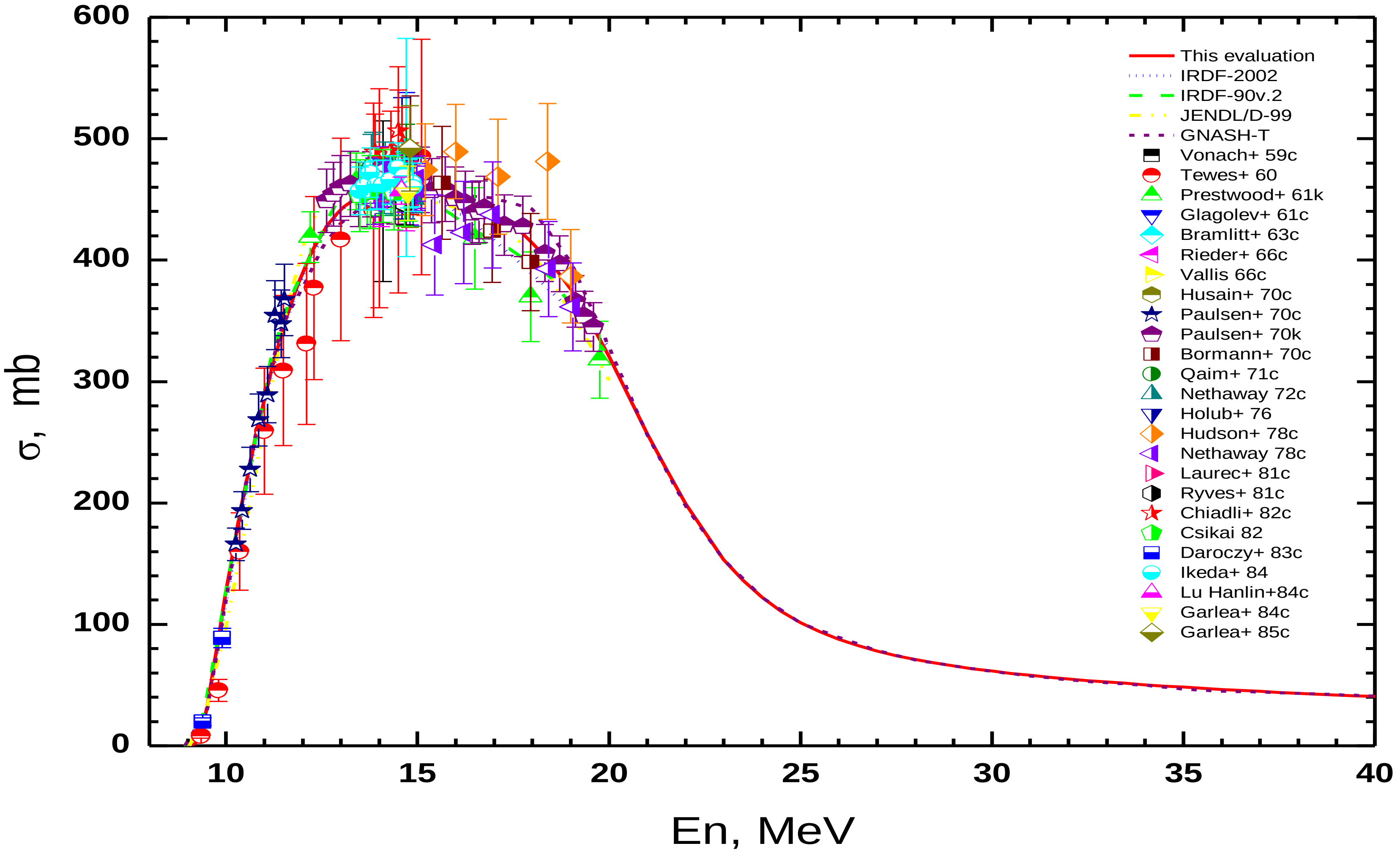

FIG. 5.1. Re-evaluated excitation function of the $^{93}Nb(n,2n)^{92m}Nb$ reaction in the energy range from threshold to 40 MeV in comparison with IRDF-2002, IRDF-90v.2, JENDL/D-99, GNASH and experimental data (1959-1985)

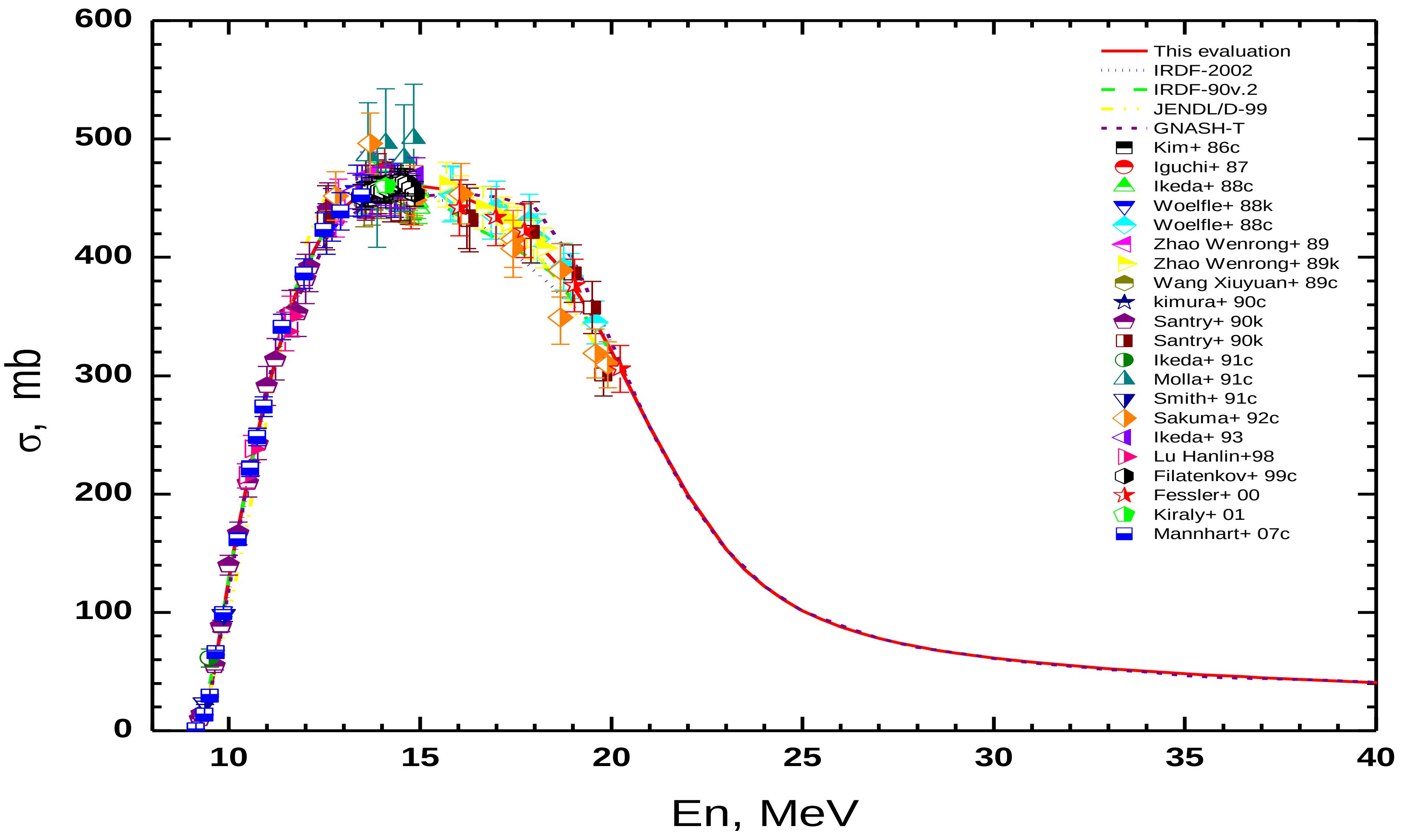

FIG. 5.2. Re-evaluated excitation function of the ^{93}Nb(n,2n)^{92m}Nb reaction in the energy range from threshold to 40 MeV in comparison with IRDF-2002, IRDF-90v.2, JENDL/D-99, GNASH and experimental data (1986-2007)

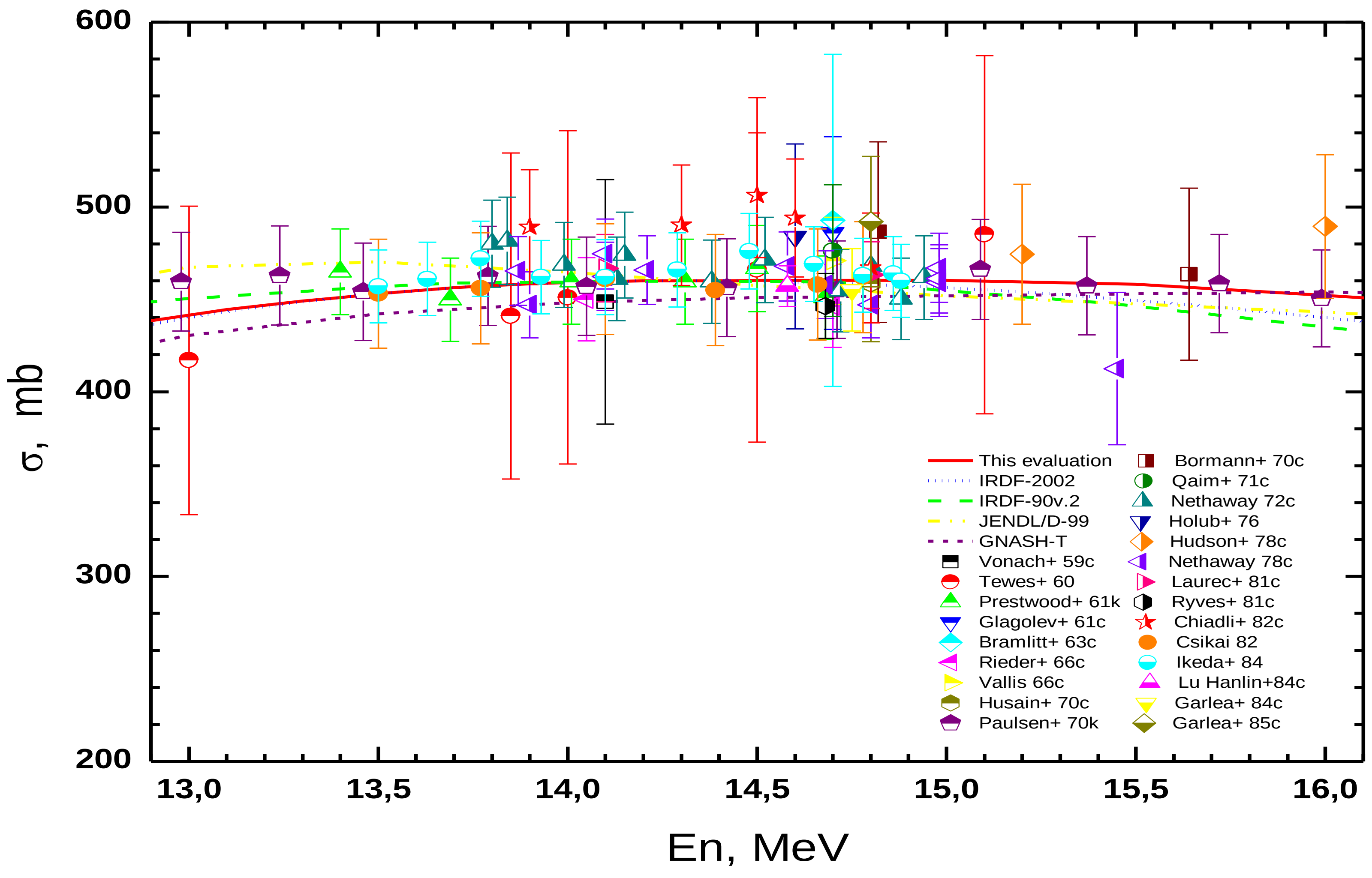

FIG. 5.3. Re-evaluated excitation function of the ^{93}Nb(n,2n)^{92m}Nb reaction in the energy range from 13 to 16 MeV in comparison with IRDF-2002, IRDF-90v.2, JENDL/D-99, GNASH and experimental data (1959-1985)

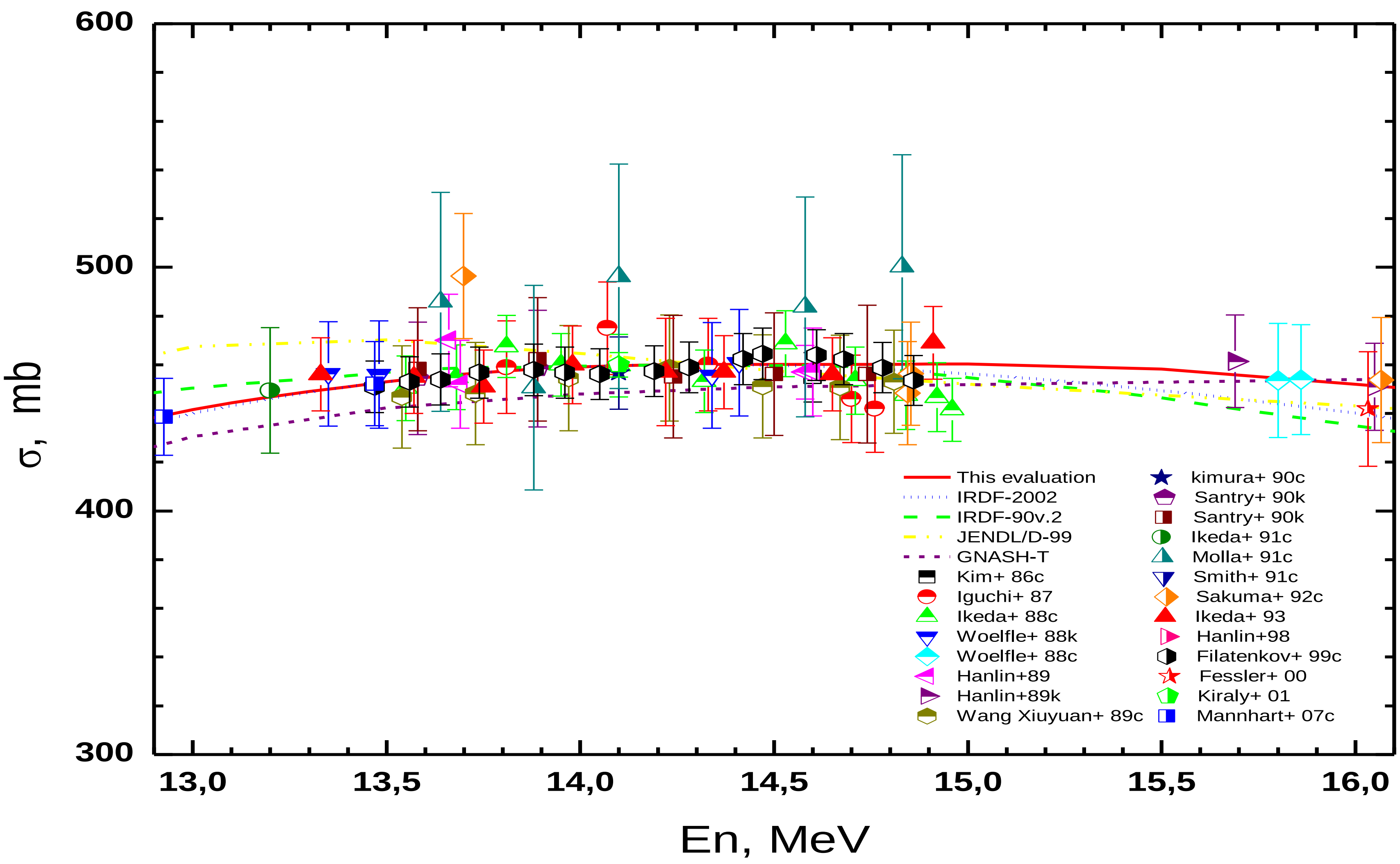

FIG. 5.4. Re-evaluated excitation function of the ^{93}Nb(n,2n)^{92m}Nb reaction in the energy range from 13 to 16 MeV in comparison with IRDF-2002, IRDF-90v.2, JENDL/D-99, GNASH and experimental data (1986-2007)

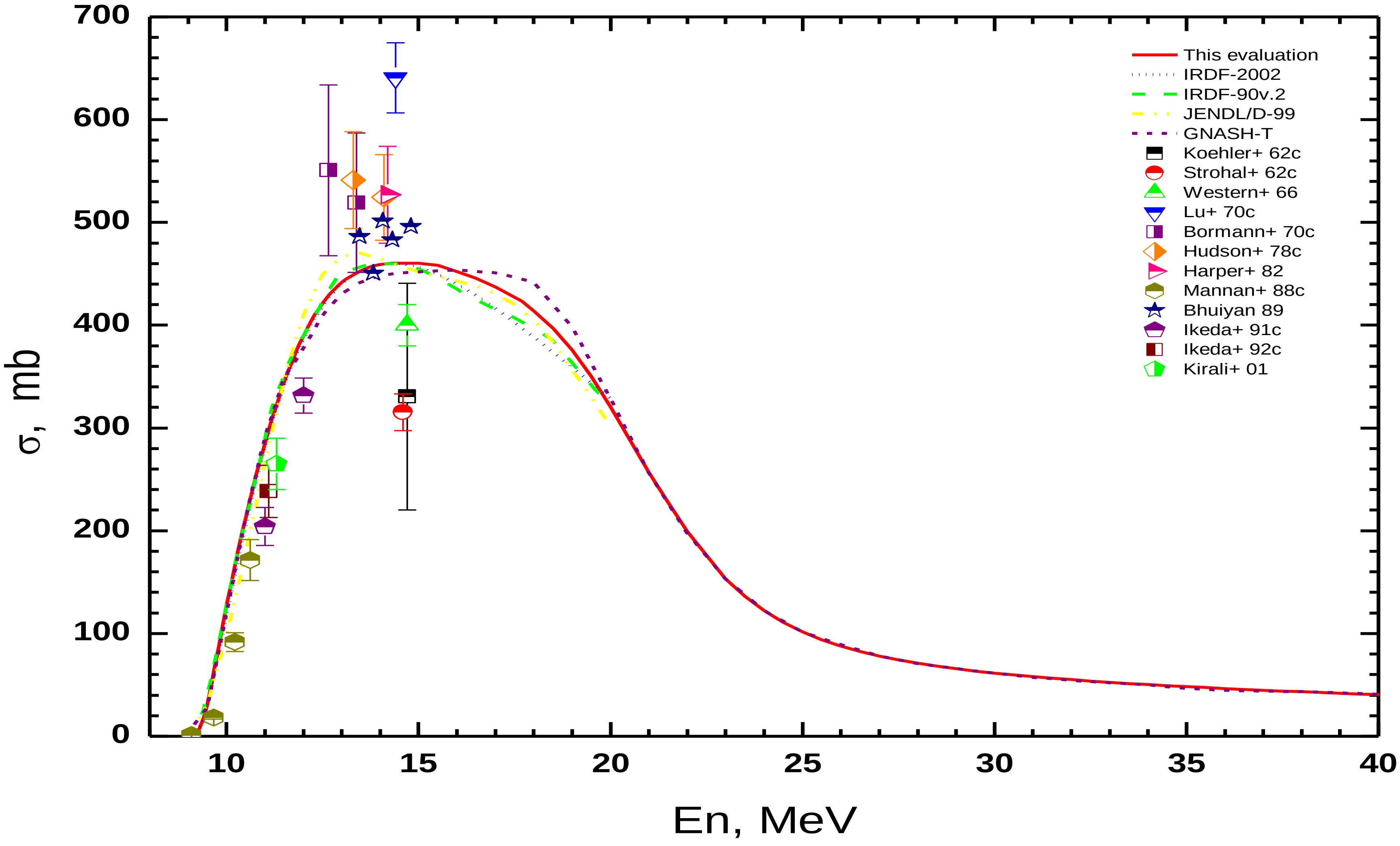

FIG. 5.5. Re-evaluated excitation function of the $^{93}Nb(n,2n)^{92m}Nb$ reaction in the energy range from threshold to 40 MeV in comparison with IRDF-2002, IRDF-90v.2, JENDL/D-99, GNASH and rejected experimental data

REFERENCES TO SECTION 5

[5.1] VONACH, H., MUENZER, H., (n,2n) Cross-Sections Measurements on ^{86}Sr, ^{89}Y, ^{93}Nb and ^{133}Cs for 14.1 MeV Neutrons, Oesterr. Akad. Wiss., Math. and Naturw. Anzeiger **96** (1959) 120 (in German).

[5.2] TEWES, H.A, CARETTO, A.A., MILLER, A.E., NETHAWAY, D.R., Excitation Functions of Neutron-induced Reactions, Proc. Nuclear and Radiation Chemical Symposium, 6 September 1960, Chalk River, Ontario, Canada, UCRL-6028-T, University of California Research Laboratory, Livermore, USA, 1960.

[5.3] PRESTWOOD, R.J., BAYHURST, B.P., (n,2n) Excitation Functions of Several Nuclei from 12.0 to 19.8 MeV, Phys. Rev. **121** (1961) 1438-1441.

[5.4] GLAGOLEV, V.L., YAMPOL'SKIY, P.A., An Investigation of (n,2n) Reactions Leading to Isomer Formation, Zurnal Eksperimental'noi I Teoret. Fiziki (Sov.) **40** (1961) 742 (in Russian).

[5.5] BRAMLITT, E.T., FINK, R.W., Rare Nuclear Reactions Induced by 14.8-MeV Neutrons, Phys. Rev. **131** (1963) 2649.

[5.6] RIEDER, R., MUENZER, H., (n,2n) Cross Sections for Nuclides with neutron numbers near the Magic Number 50 with 14 MeV Neutrons, Acta Phisica Austriaca **23** (1966) 42 (in German).

[5.7] VALLIS, D.G., Cross Sections for (n,2n) Reaction at 14.7 MeV of Some ODD-proton Nuclei, Report AWRE-0-76/66, Atomic Weapons Research Establishment, Aldermaston, UK, December 1966.

[5.8] HUSAIN, L, BARI, A., KURODA, P.K., Neutron Activation Cross Sections at 14.8 MeV for Rubidium, Zirconium and Niobium, Phys. Rev. C **1 (**1970) 1233.

[5.9] PAULSEN, A., WIDERA, R., The (n,2n) Excitation Functions for ^{93}Nb and ^{103}Rh with Special Respect to the Isomeric States in ^{93}Nb and ^{103}Rh, Z. Phys. **238 (**1970) 23 (in German).

[5.10] BORMANN, M., BISSEM, H.H., MAGIERA, E., WARNEMUNDE, R., Total Cross Sections and Isomeric Cross Section Ratios for (n,2n) Reactions in the Energy Region 12 – 18 MeV, Progress Report EANDC(E)-127, March 1970, p.38.

[5.11] QAIM, S.M., WOELFLE, R., STOECKLIN, G., Activation Cross Sections of Fast Neutron Induced Nuclear Reactions. Precision Measurements and Systematics, in: Proc. Conf. on Chemical Nucl. Data, Measurements and Application, University of Kent, Canterbury, 20-22 September 1971, p. 121.

[5.12] NETHAWAY, D.R., Cross Sections for Several (n,2n) Reactions at 14 MeV, Nucl. Phys. A **190** (1972) 635-644.

[5.13] HOLUB, E., CINDRO, N., Study of Some Systematic Trends and Non-Equilibrium Effects in (n,2n) Reactions for Nuclei Far from the Symmetry Line, J. Physics G **2** (1976) 405.

[5.14] HUDSON, C.G., ALFORD, W.L., GHORAI, S.K., Neutron Excitation Functions for ^{45}Sc, ^{93}Nb and ^{58}Ni in the Energy Range 13 – 19 MeV, Ann. Nucl. Energy **5** (1978) 589.

[5.15] NETHAWAY, D.R., The ^{93}Nb(n,2n)^{92m}Nb Cross Section, J. Inorg. Nucl. Chemistry **40** (1978) 1285.

[5.16] LAUREC, J, ADAM, A., De Bruyne, T., Measurement of of the (n,2n) Reaction Cross Sections of the Nuclei ^{89}Y, ^{93}Nb, ^{103}Rh, ^{107}Ag, ^{169}Tm, ^{175}Lu, and ^{197}Au at 14.1 and 14.8 MeV, Report CEA-R-5109, June 1981 (in French).

[5.17] RYVES, T.B., KOLKOWSKI, P., The Nb(n,2n), Nb(n,α) and Nb(n,n') Cross Sections at 14 MeV, J. Physics G **7** (1981) 529.

[5.18] CHIADLI, A., PAIC, G., Cross-Section of (n,2n) Reaction on ^{93}Nb and ^{90}Zr., p. 13 in Progress Report MOH-5, Université Mohammed V de Rabat, 1982 (in French).

[5.19] CSIKAI, J., Study of Excitation Functions Around 14 MeV Neutron Energy, pp. 414-417 in Proc. Int. Conf. Nuclear Data for Science and Technology, 6-10 September 1982, Antwerp, Belgium, Böckhoff, K.H. (Ed.), D. Reidel Publ. Co., Dordrecht, Netherlands, 1983.

[5.20] DAROCZY, S., RAICS, P., PAPP, Z., FUTO, I., CSIKAI, J., KORNILOV, N.V., SALNIKOV, O.A., Cross Sections of the Reactions $^{58}Ni(n,p)^{58}Co$, $^{93}Nb(n,2n)^{92m}Nb$ and $^{197}Au(n,2n)^{196}Au$ at the Energies 8.92, 9.39 and 9.90 MeV, pp. 191-194 in Proc. 6th All Union Conference on Neutron Physics, Kiev, 2-6 October 1983, v. 3, Moscow 1984.

[5.21] IKEDA, Y., MIYADE, H., KAWADE, K., YAMAMOTO, H., Measurement of High Threshold Reaction Cross Sections for 13.5 to 15 Mev, Private communication by Ikeda Y., November 1984, EXFOR 21945002.

[5.22] LU HANLIN, HUANG JIANZHOU, LI JIZHOU, FAN PEIGUO, Measurement of Cross Sections for the (n,2n) Reaction on ^{55}Mn, ^{58}Ni, ^{59}Co, ^{93}Nb, ^{181}Ta and ^{197}Au, Chin. J. of Nucl Phys. **6** (1984) 76.

[5.23] GARLEA, I., MIRON C., DOBREA, D., ROTH, C., MUŞAT, T., ROŞU, H.N., Measuring of the Integral Cross Sections at 14 MeV, for Reactions $^{115}In(n,n')$, $^{197}Au(n,2n)$, $^{93}Nb(n,2n)$, $^{27}Al(n,\alpha)$, $^{56}Fe(n,p)$, $^{239}Pu(n,f)$, $^{238}U(n,f)$, $^{232}Th(n,f)$ and $^{237}Np(n,f)$, Rev. Roum. Phys. **29** (1984) 421.

[5.24] GARLEA, I., MIRON-GARLEA, C., ROSU, H.N., ION, M., RĂDUCU, V., Neutron Cross Sections Measured at 14.8 MeV, p. 126 in Proc. 14th Int. Symp. Interaction of Fast Neutrons with Nuclei, 19-23 November 1984, Gaussig, GDR, Seeliger, D. and Jahn, U. (Eds), ZFK-562, 1985

[5.25] KIM, Y.S., KIM, N.B., CHUNG, K.H., BAK, H.I., Measurements of $^{93}Nb(n,n\alpha)^{89m}Y$, $^{93}Nb(n,\alpha)^{90m}Y$ and $^{93}Nb(n,2n)^{92m}Nb$ Cross Sections for 14 MeV Neutrons, Journal of the Korean Nuclear Society **18** (1986) 92.

[5.26] IGUCHI, T., NAKATA, K, NAKAZAWA, M., Improvement of accuracy of Zr/Nb activation-rate ratio method for D-T neutron source energy determination, J. Nucl. Sci. Technol. **24** (1987) 1076.

[5.27] IKEDA, Y., KONNO, C., OISHI, K., NAKAMURA, T., MIYADE, H., KAWADE, K., YAMAMOTO, H., KATOH, T., Activation Cross-section Measurements for Fusion Reactor Structural Materials at Neutron Energy from 13.3 to 15.0 MeV Using FNS Facility, JAERI-1312, March 1988

[5.28] WOELFLE, R., MANNAN, A., QAIM, C.M., LISKIEN, H., WIDERA, R., Excitation Functions of $^{93}Nb(n,2n)^{92m}Nb$, $^{93}Nb(n,\alpha)^{90m,g}Y$, $^{139}La(n,\alpha)^{136}Cs$ and $^{181}Tl(n,p)^{181}Hf$ Reactions in the Energy Range of 12.5 – 19.6 MeV, Appl. Radiat. Isot. **39** (1988) 407.

[5.29] ZHAO WENRONG, LU HANLIN, YU WEIXIANG, YUAN XIALIN, Compilation of Measurements and Evaluations of Nuclear Activation Cross Sections for Nuclear Data Applications, Report INDC(CPR)-16, IAEA, Vienna, Austria, 1989.

[5.30] WANG XIUYUAN, HAO FANHUA, LI ZHENGTONG, HUANG RUILIANG, Measurement of Activation Cross Section, Private communication by WANG XIUYUAN, June 1989, EXFOR 309305003.

[5.31] KIMURA, I., KOBAYASHI, K., Calibrated Fission and Fusion Fields at the Kyoto University Reactor, Nucl. Sci. Eng. **106** (1990) 332-344.

[5.32] SANTRY, D.C., WERNER, R.D., Cross Sections for the $^{93}Nb(n,2n)^{92m}Nb$ Reaction, Can. J. of Phys. **68** (1990) 582.

[5.33] SMITH, D.L., MEADOWS, J.W., VONACH, H., VAGNER, M., HAIGHT, R.C., MANNHART, W., Comparison of Activation Cross Section Measurements Performed with Different Neutron Source Reactions in the 5 - 13 MeV Range, pp. 281-293 in Proc. Int. Conf. Nuclear Data for Science and Technology, 13-17 May 1991, Jülich, Germany, Qaim, S.M. (Ed.), Springer-Verlag, 1992.

[5.34] IKEDA, Y., KONNO, C., MIZUMOTO, M., HASEGAWA, K., SHIBA, S., YAMANOUCHI, Y., SUGIMOTO, M., Activation cross section measurement at neutron energies of 9.5, 11.0, 12.0 and 13.2 MeV using $^{1}H(^{11}B,n)^{11}C$ neutron source at JAERI, pp. 294-296 in Proc. Int. Conf. Nuclear Data for Science and Technology, 13-17 May 1991, Jülich, Germany, Qaim, S.M. (Ed.), Springer-Verlag, 1992.

[5.35] MOLLA, N.I., MIAH, R.U., RAHMAN, M., AKHTER, A., Excitation Functions of Some (n,p), (n,2n) and (n,α) Reactions on Nickel, Zirconium and Niobium Isotopes in the Energy Range 13.64-14.83 MeV, pp. 355-357 in Proc. Int. Conf. Nuclear Data for Science and Technology, 13-17 May 1991, Jülich, Germany, Qaim, S.M. (Ed.), Springer-Verlag, 1992.

[5.36] SAKUMA, M., IWASAKI, S., SHIMADA, H., ODANO, N., SUDA, K., DUMAIS, J.R., SUGIYAMA, K., Measurement of (n,2n) cross sections for several dosimetry reactions between 12 and 20 MeV, Report JAERI-M- 92-027, 1992.

[5.37] IKEDA, Y., KONNO, C., OYAMA, Y., KOSAKO, K., OISHI, K., MAEKAWA, H., Absolute Measurements of Activation Cross Sections of $^{27}Al(n,p)^{27}Mg$, $^{27}Al(n,\alpha)^{24}Na$, $^{56}Fe(n,p)^{56}Mn$, $^{90}Zr(n,2n)^{89m+g}Zr$ and $^{93}Nb(n,2n)^{92m}Nb$ at Energy Range of 13.3-14.9 MeV, J. Nucl. Sci. Technol. **30** (1993) 870-880.

[5.38] HUANG XIAOLONG, LU HANLIN, ZHAO WENRONG, YU WEIXIANG, HAN XIAOGANG, Neutron Activation Cross-Section Measurements and Evaluations in CIAE, Report INDC(CPR)-045, IAEA, Vienna, Austria, October 1998.

[5.39] FILATENKOV, A.A., CHUVAEV, S.V., Systematic Activation Cross Sections Measurement at Neutron Energies around 14 MeV, Preprint RI-252, Atominform, 1999.

[5.40] FESSLER, A., IKEDA, Y., MEADOWS, J.W., PLOMPEN, A.J.M., SMITH, D.L., Neutron Activation Cross-Section Measurements from 16 to 20 MeV for Isotopes of F, Na, Mg, Al, Si, P, Cl, Ti, V, Mn, Fe, Nb, Sn and Ba, J. Nucl. Sci. Technol. **134** (2000) 171.

[5.41] KIRALY, B., CSIKAI, J., DOCZI, R., Validation of neutron data libraries by differential and integral cross sections, p. 283, Report JAERI-C-2001-006, March 2001.

[5.42] MANNHART, W., SCHMIDT, D., Measurement of Neutron Activation Cross Sections in the Energy Range from 8 to 15 MeV, Report PTB-N-53, Braunschweig, January 2007.

[5.43] KOEHLER, D.R., ALFORD, W.L., Neutron Partial Cross Section Studies, Report NP-11667, 1962

[5.44] STROHAL, F., CINDRO, N., EMAN, B., Reaction mechanism and shell effects from the interaction of 14.6 MeV neutrons with nuclei, Nucl. Phys. **30** (1962) 49.

[5.45] WESTERN, G.T., GIBBONS, F.L., WILLIAMS, J.R., CARTER, H.G., Elastic and Nonelastic Neutron Scattering in Niobium, Vanadium and Carbon, p. 2 in Report AFWL-TR-65-216, Kirtland, June 1966.

[5.46] LU, W.D., RANAKUMAR, N., FINK, R.W., Activation Cross Sections for (n,2n) Reactions at 14.4 MeV in the Region Z = 40-60. Precision Measurements and Systematics, Phys. Rev. C **1** (1970) 350-357.

[5.47] HARPER, R.C., ALFORD, W.L., Experimental and Theoretical Neutron Cross Sections at 14 MeV, J. Phys. G **8** (1982) 153.

[5.48] MANNAN, A., QAIM, S.M., Activation Cross Section and Isomeric Cross-Section Ratio for the$^{93}Nb(n,\alpha)^{90m,g}Y$ Process, Phys. Rev. C **38** (1988) 630.

[5.49] BHUIYAN, S.I., Excitation Functions of $^{90}Zr(n,2n)^{89}Zr$ and $^{93}Nb(n,2n)^{92m}Nb$ Reactions, Private communication by BHUIYAN S., September 1989, EXFOR 30936003.

[5.50] IKEDA, Y., CHIBA, S., FUKAHORI, T., HASEGAWA, K., MIZUMOTO, M., KONNO, C., Neutron Activation Cross Section Measurement at 9.1 and 11.1 MeV Using $^{1}H(^{11}B,n)^{11}C$ Neutron Source at Tandem Facility at JAERI, pp. 24-26 in Progress Report INDC(JPN)-162/U, August 1992.

[5.51] FABRY, A., DEWORM, J.P., Measurements of Mean Fission Spectrum Cross Sections for Threshold Reactions, p. 69 in Progress Report EANDC(E)-57, February 1965.

[5.52] NASYROV, F., SCIBORSKIJ, B.D., Average Cross Sections of (n,2n), (n,p), and (n,α) Reactions for Fission Neutrons, Atomnaya Energiya **25** (1968) 437-439 (in Russian).

[5.53] KIMURA, I., KOBAYASHI, K., SHIBATA, T., Measurement of Average Cross Sections for Some Threshold Reactions for Neutrons with Fission-Type Reactor Spectra, J. Nucl. Sci. Technol. **8** (1971) 59.

[5.54] KOBAYASHI, K., KIMURA, I., NAKAZAWA, M., AKIYAMA, M., Fission Neutron Spectra Averaged Cross-Sections of Some Threshold Reactions Measured with Fast Reactor YAYOI, J. Nucl. Sci. Technol. **13** (1976) 531.

[5.55] GRIGOR'EV, E.I., MELEKHIN, Yu.A., YARYNA, V.P., Integrated Reaction Cross-Sections $^{51}V(n,\alpha)^{48}Sc$, $^{93}Nb(n,2n)^{92m}Nb$, $^{93}Zr(n,2n)^{89}Zr$, Voprocy Atomnoj Nauki i Techniki, Ser.: Yadernye Konstanty **3** (1987) 27 (in Russian).

[5.56] MANNAN, A., QURESHI, I.H., IQBAL, M.Z., WOELFLE, R., QAIM, S.M., Integral Tests of Differential Cross Sections for (n,α) and (n,2n) Reactions on Niobium, Radiochimica Acta **51** (1990) 49.

[5.57] KOBAYASHI, K., KOBAYASHI, T., Measurements of U-235 Fission Spectrum-Averaged Cross Sections for Some Threshold Reactions, p.52 in Progress Report NEANDC(J)-155, August 1990.

[5.58] WILLIAMSON, T.G., LAMAZE, G.P., Measurement of the $^{93}Nb(n,2n)^{92m}Nb$ Cross Section in ^{235}U Fission Spectrum, Proc. of 7th ASTM-EURATOM Symposium on Reactor Dosimetry, Strasbourg, France, 27-31 August 1990, Report 178.

[5.59] MAIDANA, N.L., DIAS, M.S., GERALDO, L.P., Measurements of U-235 Fission Neutron Spectrum Averaged Cross Sections for Threshold Reactions, Radiochimica Acta **64** (1994) 7-9.

[5.60] DEZSÖ, Z., CSIKAI, J., Average Cross Sections for the ^{252}Cf Neutron Spectrum, pp. 32-43 in Proc. 4th All Union Conf. Neutron Physics, Kiev, 18-22 April 1977, Vol. 3, Moscow, 1977.

[5.61] SHANI, G., (n,2n) Cross-Section Measurement of ^{93}Nb, ^{197}Au and ^{238}U with Fission-Neutron Spectrum, Ann. Nucl. Energy **10** (1983) 473.

[5.62] MANNHART, W., Status of the Evaluation of the Neutron Spectrum of $^{235}U + n_{th,}$ Presentations-Web Links, p. 29 in Summary Report of the IAEA Consultants’ Meeting, 13-15 October 2008, Report INDC(NDS)-0540, IAEA, Vienna, Austria, November 2008.

[5.63] MANNHART, W., Status of the Evaluation of the Neutron Spectrum of $^{252}Cf(sf)$, Presentations-Web Links, p. 29 in Summary Report of the IAEA Consultants’ Meeting, 13-15 October 2008, Report INDC(NDS)-0540, IAEA, Vienna, Austria, November 2008.

6. EVALUATION OF THE EXCITATION FUNCTION OF THE ^{169}Tm(n,2n)^{168}Tm REACTION

The isotopic abundance of ^{169}Tm in natural thulium is 100 atom percent. The ^{168}Tm obtained via the (n,2n) reaction undergoes (99.990 ± 0.007)% ε capture decay and (0.010 ± 0.007)% β^- decay with a half-life of (93.1 ± 0.2) days. The ε capture decay is accompanied by the emission of a broad spectrum of gamma rays. The 184.295-keV gamma radiation (I_γ = 0.1745 ± 0.0056), 198.251-keV gamma radiation (I_γ = 0.524 ± 0.016), 447.515-keV gamma radiation (I_γ = 0.2306 ± 0.0071) and 815.989-keV gamma radiation (I_γ = 0.4899 ± 0.0150) are normally used to determine the ^{169}Tm(n,2n)^{168}Tm reaction rate. Recommended decay data for the half-life and gamma-ray emission probabilities per decay of ^{168}Tm were taken from Ref. [2.7] of Section 2.

Microscopic experimental data were analyzed during the preparation of the input database assembled in order to evaluate the cross sections and uncertainties for the ^{169}Tm(n,2n)^{168}Tm reaction [6.1-6.18]. During this procedure, experimental data given in Refs. [6.2-6.8] and [6.10-6.18] were corrected in terms of the newly recommended cross-section data for the monitor reactions used in the measurements and the recommended decay data (see Table 2.1).

Special correction was applied to the experimental data of Tewes *et al.* [6.1] and Lu Hanlin *et al.* [6.13]. Data of these works were renormalized to Frehaut *et al.* measurements [6.10] in the overlapping energy ranges 9.8 – 13.8 MeV and 12.37 – 13.8 MeV, respectively. Cross sections measured by Tewes *et al.* were multiplied by a factor Fc = 2.06461 . Data from Ref. [6.13] were multiplied by a factor Fc = 1.00652 .

Cross-section data from Refs. [6.17-6.18] have been rejected due to their large deviations from the bulk of experimental data. Values of the excitation function in Refs. [6.17] and [6.18] were determined at 14.7 MeV and 14.8 MeV, respectively.

The excitation function for the ^{169}Tm(n,2n)^{168}Tm reaction in the energy region from threshold to 40 MeV was evaluated by means of statistical analyses of the experimental cross-section data [6.1-6.16] and data from theoretical model calculation carried out by means of GNASH code. Uncertainties in the evaluated excitation function for the ^{169}Tm(n,2n)^{168}Tm reaction are given in the form of a relative covariance matrix for 47-neutron energy groups (LB = 5). Covariance matrix uncertainties were calculated simultaneously with the recommended cross-section data by means of the PADE-2 code.

Six-digit eigenvalues for the relative covariance matrix in File-33 are as follows:

```
1.57657E-05    1.58375E-05    1.59213E-05    1.60186E-05
1.61322E-05    1.62654E-05    1.64900E-05    1.68238E-05
1.72557E-05    1.78860E-05    1.86762E-05    2.01166E-05
2.18605E-05    2.47650E-05    2.81640E-05    3.46838E-05
3.98613E-05    5.12112E-05    6.69115E-05    8.03501E-05
1.11593E-04    1.79908E-04    2.55396E-04    2.93602E-04
3.69888E-04    4.68218E-04    5.71088E-04    6.74878E-04
7.36897E-04    7.92696E-04    9.00694E-04    1.01287E-03
1.12192E-03    1.19057E-03    1.26922E-03    1.38744E-03
1.51388E-03    1.64431E-03    1.77620E-03    1.90190E-03
2.00788E-03    2.12391E-03    2.43571E-03    4.77976E-03
1.51096E-02    6.36854E-02    1.27381E-01
```

All of these eigenvalues are positive.

Evaluated group cross sections and their uncertainties for the ^{169}Tm(n,2n)^{168}Tm reaction are listed in Table 6.1. Group boundaries are the same as in File-33. These data show that the smallest uncertainties in the evaluated cross sections of 1.55% to 2.00% are observed in the neutron energy range from 11.5 to 16.0 MeV. Evaluated cross sections in the energy intervals 9.5-11.5 MeV and 16.0-20.0 MeV may also be qualified as well-determined. A significant uncertainty of 31.31% in the cross sections from threshold to 8.6 MeV arises from the large uncertainties in the experimental data within this region and discrepancies between these experimental data. Experimental cross section data for the neutron energies above 20 MeV are presented only in two works [6.8] and [6.9]. These experimental data have significant uncertainties. Due to the uncertainty in the input parameters, theoretical model calculations do not permit to determine the ^{169}Tm(n,2n)^{168}Tm reaction cross sections for the incident neutron energies 20 - 40 MeV better then 5-10%. So the uncertainty in the evaluated excitation function increased from 3.61% at the interval 20-21 MeV to 9.75% between 39.9-40.0 MeV.

TABLE 6.1. EVALUATED CROSS SECTIONS AND THEIR UNCERTAINTIES FOR THE ^{169}Tm(n,2n)^{168}Tm REACTION IN THE NEUTRON ENERGY RANGE FROM THRESHOLD TO 40 MeV

Neutron energy (MeV) from to	Cross section (mb)	Uncer-tainty (%)	Neutron energy (MeV) from to	Cross section (mb)	Uncer-tainty (%)
8.082 - 8.600	46.977	31.31	18.500 - 19.000	1233.430	2.64
8.600 - 9.000	292.051	5.28	19.000 - 19.500	1076.000	2.55
9.000 - 9.500	661.148	3.57	19.500 - 20.000	940.606	2.79
9.500 - 10.000	1048.580	2.72	20.000 - 21.000	781.967	3.61
10.000 - 10.500	1343.460	2.47	21.000 - 22.000	625.705	4.86
10.500 - 11.000	1548.280	2.35	22.000 - 23.000	518.445	5.78
11.000 - 11.500	1686.850	2.17	23.000 - 24.000	442.802	6.37
11.500 - 12.000	1781.500	2.00	24.000 - 25.000	387.684	6.74
12.000 - 12.500	1848.280	1.89	25.000 - 26.000	346.239	6.99
12.500 - 13.000	1897.670	1.85	26.000 - 27.000	315.915	7.20
13.000 - 13.500	1935.930	1.82	27.000 - 28.000	295.002	7.39
13.500 - 14.000	1965.700	1.75	28.000 - 29.000	278.244	7.59
14.000 - 14.200	1979.520	1.68	29.000 - 30.000	264.182	7.79
14.200 - 14.400	1984.510	1.64	30.000 - 31.000	252.088	8.00
14.400 - 14.600	1987.760	1.60	31.000 - 32.000	241.480	8.20
14.600 - 14.800	1989.150	1.56	32.000 - 33.000	232.030	8.41
14.800 - 15.000	1989.830	1.55	33.000 - 34.000	223.504	8.61
15.000 - 15.500	1989.030	1.59	34.000 - 35.000	215.735	8.82
15.500 - 16.000	1978.880	1.80	35.000 - 36.000	208.598	9.01
16.000 - 16.500	1944.220	2.15	36.000 - 37.000	201.999	9.20
16.500 - 17.000	1868.690	2.54	37.000 - 38.000	195.863	9.39
17.000 - 17.500	1745.780	2.84	38.000 - 39.000	190.134	9.57
17.500 - 18.000	1585.180	2.96	39.000 - 40.000	185.404	9.75
18.000 - 18.500	1407.560	2.85			

Figs. 6.1 and 6.2 show the re-evaluated excitation function for the ^{169}Tm(n,2n)^{168}Tm reaction over the neutron energy range from threshold to 40.0 MeV and over the 12 – 16 MeV interval in comparison with IRDF-2002, TENDL-2009, MENDL-2 and experimental data.

As illustrated in Fig. 6.1 and Fig. 6.2, the IRDF-2002 and data obtained in this work agree reasonable in the whole energy range from threshold to 20 MeV. The TENDL-2009 evaluation overestimated the cross-section values systematically in comparison with the newly re-evaluated data in the energies interval from threshold to 11 MeV and above 21 MeV. The MENDL-2 evaluation significantly underestimated the cross-section values in comparison with all above mentioned evaluations in the energy range from threshold to 12.4 MeV.

Integral experiments for the $^{169}Tm(n,2n)^{168}Tm$ reaction are described in Refs. [6.19-6.21]. Two experiments were carried out in neutron fields with similar spectra to the ^{235}U thermal fission neutron spectrum [6.19-6.20]. Experimental cross section for the ^{252}Cf spontaneous fission neutron spectrum is only presented in Ref. [6.21]. The $^{169}Tm(n,2n)^{168}Tm$ integral cross section for the ^{235}U thermal fission neutron spectrum was obtained from measurements in the core of the ORR reactor [6.19] and uranium critical assembly [6.20]. Original experimental data obtained for ^{235}U thermal fission neutron spectrum and ^{252}Cf spontaneous fission neutron spectrum were corrected with respect to the newly recommended cross sections for the monitor reactions and decay data.

Corrected to the new standards, experimental data from Refs. [6.19-6.20] for ^{235}U thermal fission and Ref. [6.21] for ^{252}Cf spontaneous fission neutron spectra were used in the benchmark calculations. Results of benchmark calculations are presented in Table 6.2.

TABLE 6.2. CALCULATED AND MEASURED INTEGRAL CROSS SECTIONS FOR THE $^{169}Tm(n,2n)^{168}Tm$ REACTION IN ^{235}U THERMAL FISSION AND ^{252}Cf SPONTANEOUS FISSION NEUTRON SPECTRA

Type of neutron field	**Integral cross section, mb**		**C/E [*]**	
	Calculated	**Measured**	**[6.19]**	**[6.20]**
^{235}U thermal fission neutron spectrum	3.7395 [A]	4.867 ± 0.214 [6.19]	0.77126	1.00120
	3.7302 [B]	3.735 ± 0.158 [6.20]	0.76643	0.99871
	4.2360 [C]		0.87035	1.13414
	2.1918 [D]		0.45034	0.58683
^{252}Cf spontaneous fission neutron spectrum	6.2677 [A]	6.384 ± 0.401 [6.21]	0.98178	
	6.2349 [B]		0.97664	
	6.9982 [C]		1.09621	
	3.8983 [D]		0.61064	

[A] - Present evaluation.
[B] - IRDF-2002 (IRDF-90 v2).
[C] - TENDL-2009.
[D] - MENL-2.
[*] - ratio of calculated to experimental cross sections

The C/E values obtained for ^{235}U thermal fission neutron spectrum show that integral experimental data of Lewis [6.19] contradict the microscopic data. Integral cross section measured by Brodskaja *et al.* [6.20] and equivalent values calculated from new evaluations and IRDF-2002 data agree within 0.12-0.13%. The averaged cross section calculated from TENDL-2009 excitation function exceeds experimental data of Brodskaja *et al.* by about 13%. The C/E values show also that the lowest discrepancies between the calculated and experimental data for ^{252}Cf spontaneous fission neutron spectrum are obtained for the newly evaluated and IRDF-2002 data. Discrepancies are equal to 1.82% and 2.34%, respectively. The TENDL-2009 evaluation disagrees with integral experimental data. Averaged cross-sections calculated from the MENDL-2 excitation function are discrepant from the ^{235}U thermal fission and ^{252}Cf spontaneous fission neutron spectra experimental data.

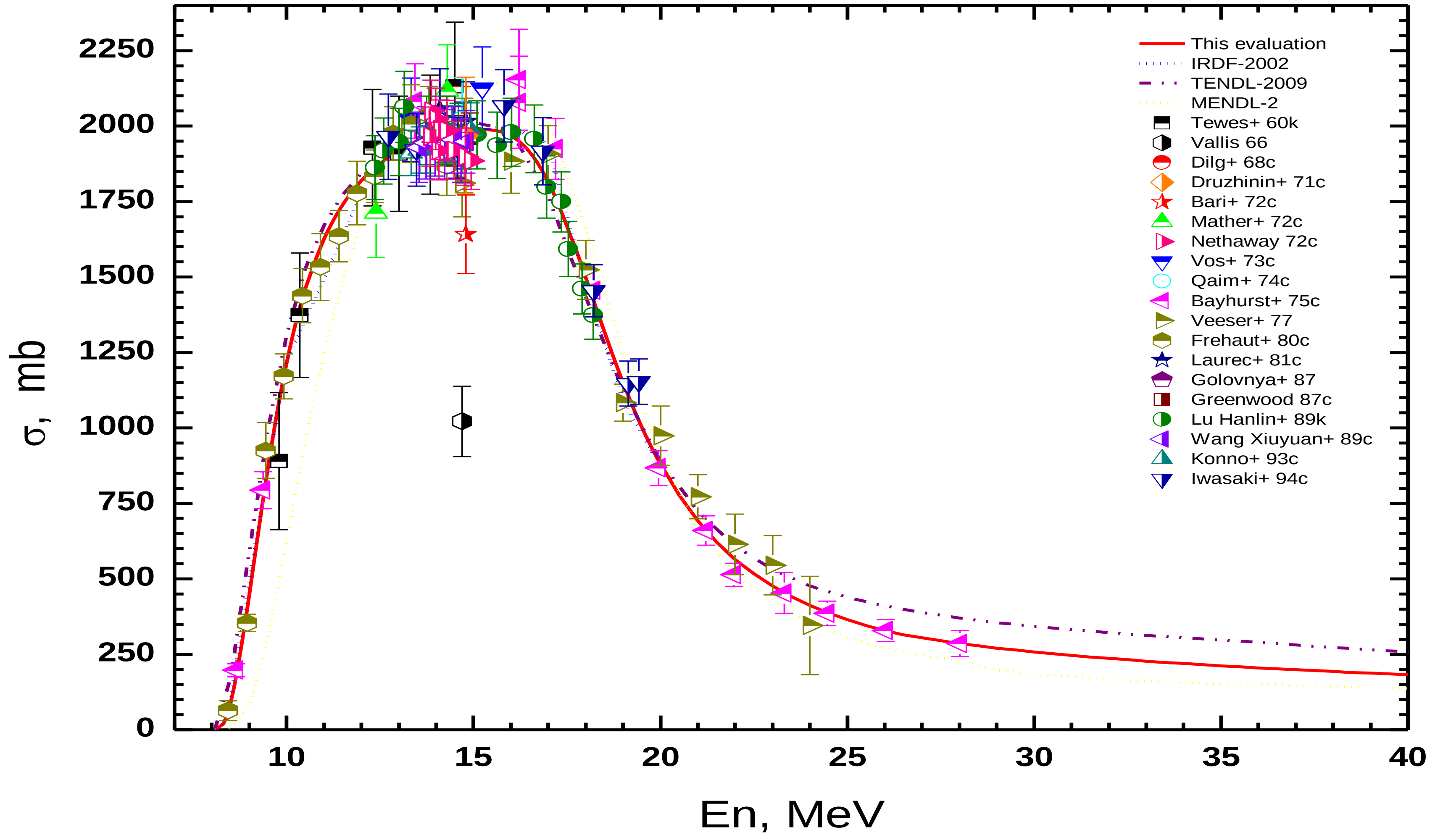

FIG. 6.1. Re-evaluated excitation function of the ^{169}Tm(n,2n)^{168}Tm reaction in the energy range from threshold to 40 MeV in comparison with IRDF-2002, TENDL-2009, MENDL-2 and experimental data

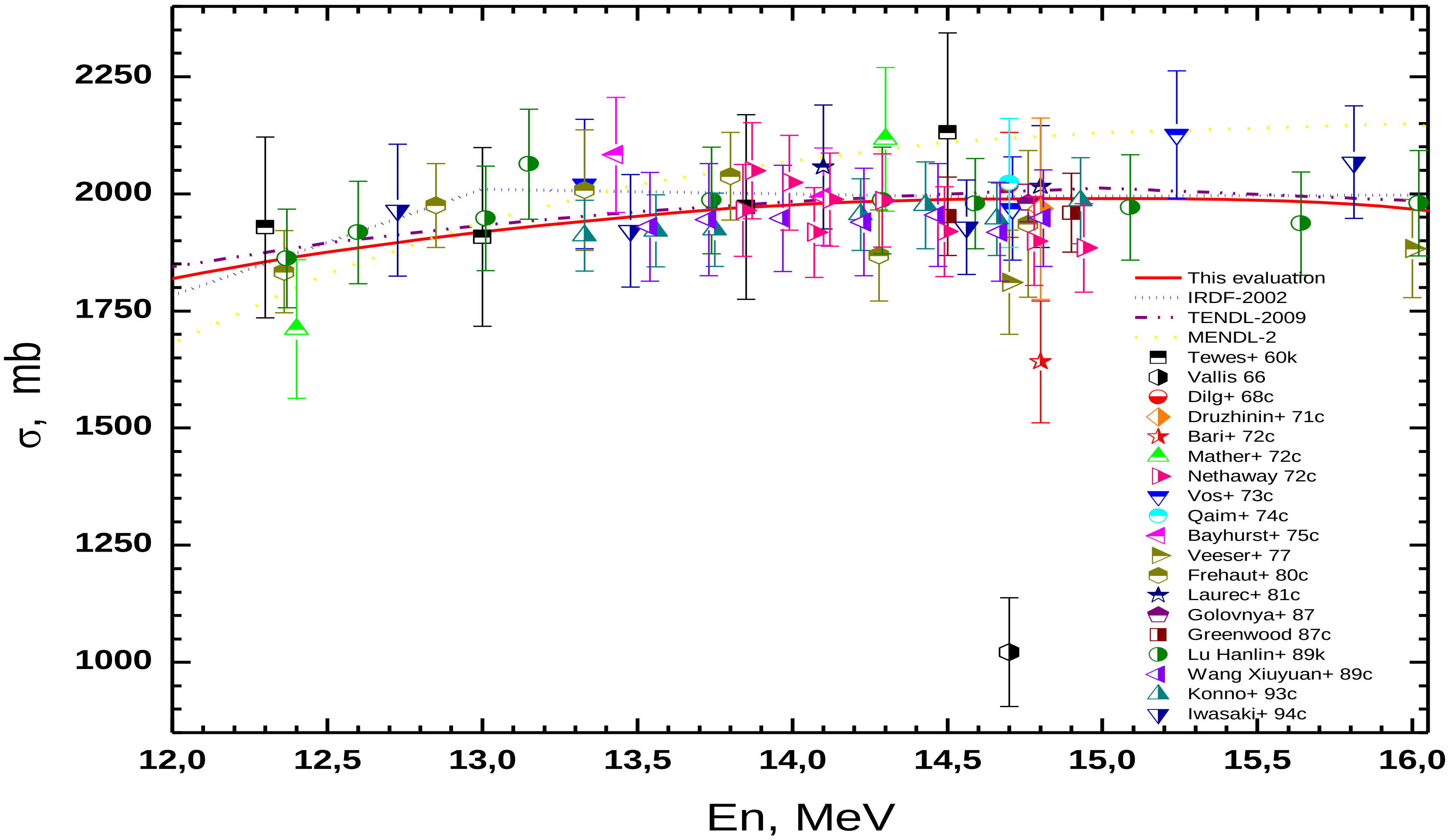

FIG. 6.2. Re-evaluated excitation function of the $^{169}Tm(n,2n)^{168}Tm$ reaction in the energy range from 12 to 16 MeV in comparison with IRDF-2002, TENDL-2009, MENDL-2 and experimental data

REFERENCES TO SECTION 6

[6.1] TEWES, H.A., CARETTO, A.A., MILLER, A.E., NETHAWAY, D.R., Excitation Functions of Neutron-induced Reactions, Proc. Nuclear and Radiation Chemical Symposium, 6 September 1960, Chalk River, Ontario, Canada, UCRL-6028-T, University of California Research Laboratory, Livermore, USA, 1960.

[6.2] DILG, W., VONACH, H., WINKLER, G., HILLE, P., Measurement of (n,2n) Reactions Cross-Sections on Heavy Nuclei., Nucl. Phys. A **118** (1968) 9 (in German).

[6.3] DRUZHININ, A.A., IVANOVA, N.I., LBOV, A.A., Cross-Sections of the (n,2n) Reactions for Isotopes of Thulium, Iridium, Thallium and Lead at the Incident Neutron Energy 14.8 MeV, Yadernaya Fizika (Sov.) **14** (1971) 682 (in Russian).

[6.4] NETHAWAY, D.R., Cross Sections for Several (n,2n) Reactions at 14 MeV, Nucl. Phys. A **190** (1972) 635-644.

[6.5] MATHER, D.S., BAMPTON, P.F., COLES, R.E., JAMES, G., NIND, P.J., Measurement of (n,2n) cross sections for incident energies between 6 and 14 MeV, Report AWRE-O-72/72, Atomic Weapons Research Establishment, Aldermaston, UK, November 1972.

[6.6] VOS, R., GHORAI, S.K., GILCHRIST, R.D., ALFORD, W.L., The (n,2n) Cross Section of ^{169}Tm, J. Bul. American Phys. Soc. **18** (1973) 775 (EB6).

[6.7] QAIM, S.M., STOECKLIN, G., Total (n,2n) Cross Sections and Isomeric Cross-Section Ratios at 14.7 MeV in the Region Rare Earths, Nucl. Phys. A **224** (1974) 319.

[6.8] BAYHURST, B.P., GILMORE, J.S., PRESTWOOD, R.J., WILHELMY, J.B., JARMIE, N., ERKKILA, B.H., HARDEKOPF, R.A., Cross-sections for (n,xn) Reactions Between 7.5 and 28 MeV, Phys. Rev. C **12** (1975) 451-467.

[6.9] VEESER, L.R., ARTHUR, E.D., YOUNG, P.G., Cross Sections for (n,2n) and (n,3n) Reactions Above 14 MeV, Phys. Rev. C **16** (1977) 1792-1802.

[6.10] FREHAUT, J., BERTIN, A., BOIS, R., JARY, J., Status of (n,2n) Cross-section Measurements at Bruyéres-le-Châtel, pp. 399-411 in Proc. Symp. on Neutron Cross Sections from 10-50 MeV, 12-14 May 1980, Upton, USA, Bhat, M.R. and Pearlstein, S. (Eds), BNL-NCS-51245, 1980.

[6.11] LAUREC, J, ADAM, A., De Bruyne, T., Measurement of the (n,2n) Reaction Cross Sections of the Nuclei ^{89}Y, ^{93}Nb, ^{103}Rh, ^{107}Ag, ^{169}Tm, ^{175}Lu, and ^{197}Au at 14.1 and 14.8 MeV, Report CEA-R-5109, June 1981 (in French).

[6.12] GREENWOOD, L.R., Recent Research in Neutron Dosimetry and Damage Analysis for Materials Irradiations, ASTM-STP-956 (1987) 743-749.

[6.13] ZHAO WENRONG, LU HANLIN, YU WEIXIANG, YUAN XIALIN, Compilation of Measurements and Evaluations of Nuclear Activation Cross Sections for Nuclear Data Applications, Report INDC(CPR)-16, IAEA, Vienna, Austria, 1989.

[6.14] WANG XIUYUAN, HAO FANHUA, LI ZHENGTONG, HUANG RUILIANG, Measurements of Activation Cross Section, Private communication by WANG XIUYUAN, July 1989, EXFOR 30935004.

[6.15] KONNO, C., IKEDA, Y., OISHI, K., KAWADE, K., YAMAMOTO, H., MAEKAWA, H., Activation Cross Section Measurements at Neutron Energy from 13.3 to 14.9 MeV Using FNS Facility, Report JAERI 1329, October 1993.

[6.16] IWASAKI, S., MATSUYAMA, S., OHKUBO, T., FUKUDA, H., SAKUMA, M, KITAMURA, M., Measurement of activation cross-sections for several elements between 12 and 20 MeV, in: Proc. Int. Conf. Nuclear Data for Science and Technology, 9-13 May 1994, Gatlinburg, USA, Dickens, J.K. (Ed.), Vol. 1, American Nuclear Society, USA, 1994, p.305.

[6.17] VALLIS, D.G., Cross Sections for (n,2n) Reaction at 14.7 MeV of Some ODD-proton Nuclei, Report AWRE-0-76/66, Atomic Weapons Research Establishment, Aldermaston, UK, December 1966.

[6.18] BARI, A., 14.8 Mev Neutron Activation Cross Sections of Rubidium, Strontium, Zirconium, Niobium and Rare-Earth Nuclides, Dissertation Abstracts, Section B **32** (1972) 5091.

[6.19] LEVIS, R.E., Progress Report ORDNL-CF-66-12-9, p.6, 1966.

[6.20] BRODSKAJA, A.K., IVANOVA, N.I., NASYROV, F.K., Cross Sections of (n,α), (n,p), (n,2n), (n,n') Reactions Averaged in Fission Neutron Spectrum for Some Elements., Voprocy Atomnoj Nauki i Techniki, Ser.: Yadernye Konstanty **4** (1976) 4-5 (in Russian).

[6.21] MANNHART, W., Validation of Differential Cross Sections with Integral Data., pp. 59-64 in Summary Report of the Technical Meeting on International Reactor Dosimetry File IRDF-2002, Greenwood, L.R. and Paviotti-Corcuera, R. (Eds), Report INDC(NDS)-435, IAEA, Vienna, Austria, September 2002.

7. EVALUATION OF THE EXCITATION FUNCTION OF THE $^{209}Bi(n,3n)^{207}Bi$ REACTION

The isotopic abundance of ^{209}Bi in natural bismuth is 100 atom percent. The ground (J_π = 9/2-) state of ^{207}Bi obtained via the (n,3n) reaction undergoes 100% ε capture decay with a half-life of (32.9 ± 1.4) years.
The 569.698-keV gamma radiation (I_γ = 0.9776 ± 0.0003), 1063.656-keV gamma radiation (I_γ = 0.746 ± 0.005) and 1770.228-keV gamma radiation (I_γ = 0.0687 ± 0.0003) may be used to determine the $^{209}Bi(n,3n)^{207}Bi$ reaction rate. Recommended decay data for the half-life and gamma-ray emission probabilities per decay of ^{207}Bi were taken from Ref. [2.8] of Section 2.

Microscopic experimental data [7.1-7.6] were analyzed in the preparation of the input database for the evaluation of the cross sections and uncertainties of the $^{209}Bi(n,3n)^{207}Bi$ reaction. During this procedure, the experimental data of Ref. [7.2] and Refs. [7.4-7.6] were corrected with respect to the newly recommended cross-section standards and decay data (see Table 2.1).

The Eun Joo Kim *et al.* experimental data [7.4] at 21.8 MeV and 27.6 MeV were not taken into account in the evaluation due to significant contradiction with experimental data of Veeser *et al.* [7.1] and data from the GNASH calculation. Cross-section data obtained in Refs. [7.2] and [7.6] were rejected completely due to their significant overestimation in the $^{209}Bi(n,3n)^{207}Bi$ reaction cross-section near threshold.

The excitation function for the $^{209}Bi(n,3n)^{207}Bi$ reaction in the energy range from threshold to 45 MeV was evaluated by means of a comprehensive statistical analysis of the experimental cross-section data [7.1], [7.3-7.5] and data obtained from theoretical model calculation. Uncertainties in the evaluated excitation function are given in the form of a relative covariance matrix for 42-neutron energy groups (LB = 5). This covariance matrix was calculated simultaneously with the recommended cross-section data by means of the PADE-2 code.

The resulting six-digit eigenvalues for the relative covariance matrix of File-33 are as follows:

```
4.30642E-06    4.35518E-06    4.43850E-06    4.54985E-06
4.70282E-06    4.88332E-06    5.13505E-06    5.48985E-06
5.90356E-06    6.38084E-06    7.14243E-06    8.28912E-06
9.39733E-06    1.12639E-05    1.41149E-05    1.67921E-05
2.18950E-05    2.75176E-05    3.27436E-05    4.29064E-05
5.38157E-05    6.08243E-05    7.12168E-05    8.56898E-05
1.01859E-04    1.19537E-04    1.38719E-04    1.57775E-04
1.69009E-04    1.89220E-04    5.98933E-04    1.36933E-03
2.46051E-03    2.81904E-03    3.56622E-03    5.00042E-03
5.45379E-03    6.71757E-03    1.48123E-02    2.25297E-02
2.80584E-01    3.74512E-01
```

All of these eigenvalues are positive.

Evaluated group cross sections and their uncertainties for the $^{209}Bi(n,3n)^{207}Bi$ reaction are listed in Table 7.1. Group boundaries are the same as in File-33. While the lowest uncertainties in the evaluated cross sections of 4.72% to 4.96% are observed in the neutron energy range from 20.0 to 24.5 MeV, the significant uncertainty of 59.55% occurs from threshold to 15.5 MeV due to the large uncertainties and discrepancies between experimental data in this region. Experimental cross-section data for the neutron energies above 25 MeV are presented only in one work (Ref. [7.4]). These experimental data have a significant uncertainty. Due to the uncertainty in the input parameters, theoretical model calculations do not permit determination of the ^{209}Bi(n,3n)^{207}Bi reaction cross sections for the incident neutron energies 25 - 45 MeV better than 5-17%. Furthermore, the relatively higher uncertainty in the evaluated excitation function is due to a significant current uncertainty of 4.26% in the half-life value of ^{207}Bi.

TABLE 7.1. EVALUATED CROSS SECTIONS AND THEIR UNCERTAINTIES FOR THE ^{209}Bi(n,3n)^{207}Bi REACTION IN THE NEUTRON ENERGY RANGE FROM THRESHOLD TO 45 MeV

Neutron energy (MeV) From to	**Cross section (mb)**	**Uncer-tainty (%)**	**Neutron energy (MeV) from to**	**Cross section (mb)**	**Uncer-tainty (%)**
14.416 - 15.500	6.692	59.55	25.500 - 26.000	1874.090	5.78
15.500 - 16.000	50.178	10.58	26.000 - 26.500	1834.960	6.14
16.000 - 16.500	119.994	7.89	26.500 - 27.000	1774.360	6.46
16.500 - 17.000	226.490	7.06	27.000 - 28.000	1643.090	6.81
17.000 - 17.500	367.773	6.55	28.000 - 29.000	1427.780	7.16
17.500 - 18.000	535.663	6.28	29.000 - 30.000	1206.490	7.42
18.000 - 18.500	717.192	6.06	30.000 - 31.000	1012.290	7.78
18.500 - 19.000	898.089	5.76	31.000 - 32.000	856.084	8.44
19.000 - 19.500	1066.560	5.42	32.000 - 33.000	735.160	9.31
19.500 - 20.000	1215.530	5.13	33.000 - 34.000	642.272	10.22
20.000 - 20.500	1342.710	4.94	34.000 - 35.000	570.240	11.05
20.500 - 21.000	1449.370	4.83	35.000 - 36.000	513.355	11.83
21.000 - 21.500	1538.660	4.76	36.000 - 37.000	467.443	12.59
21.500 - 22.000	1614.240	4.72	37.000 - 38.000	429.554	13.36
22.000 - 22.500	1679.330	4.72	38.000 - 39.000	397.618	14.14
22.500 - 23.000	1736.250	4.74	39.000 - 40.000	370.176	14.88
23.000 - 23.500	1786.080	4.78	40.000 - 41.000	346.192	15.57
23.500 - 24.000	1828.530	4.84	41.000 - 42.000	324.918	16.16
24.000 - 24.500	1861.890	4.96	42.000 - 43.000	305.808	16.63
24.500 - 25.000	1883.190	5.15	43.000 - 44.000	288.455	16.99
25.000 - 25.500	1888.560	5.44	44.000 - 45.000	272.552	17.27

In Fig. 7.1 the evaluated excitation function for the ^{209}Bi(n,3n)^{207}Bi reaction in the neutron energy range from threshold to 45 MeV is shown in comparison with the equivalent data from ENDF/B-VII, TENDL-2009, MENDL-2 and experimental data. Above 20 MeV the evaluated excitation function is equivalent to the results of the GNASH theoretical model calculation. The ENDF/B-VII library in comparison with other evaluations gives systematically lower cross section data from threshold to 20 MeV. In comparison with the present evaluation, TENDL-2009 and MENDL-2 libraries give systematically higher cross section values in the energy range from threshold to 25 MeV. Behaviour of the ^{209}Bi(n,3n)^{207}Bi reaction excitation above 26 MeV given in TENDL-2009 library contradicts the current work, the MENDL-2 evaluation and the Eun Joo Kim *et al.* experimental data [7.4] at 32.8 MeV and 38.3 MeV.

Unfortunately, there are no available integral experimental data for the ^{209}Bi(n,3n)^{207}Bi reaction. Calculated from four different excitation functions averaged cross sections over the ^{235}U thermal fission neutron spectrum are compared in Table 7.2. The 90%-response energy range given in Table 7.2 indicates that the ^{209}Bi(n,3n)^{207}Bi reaction excitation function can be tested using experimental data measured in the ^{235}U thermal fission neutron spectrum. Calculation of the average cross sections for ^{252}Cf spontaneous fission neutron spectrum was not carried out because this reference spectrum is evaluated only up to 20 MeV.

TABLE 7.2. CALCULATED INTEGRAL CROSS SECTIONS FOR THE $^{209}Bi(n,3n)^{207}Bi$ REACTION IN ^{235}U THERMAL FISSION NEUTRON SPECTRUM

Library	Calculated integral cross section, mb	90%-Response range, MeV
Present evaluation	5.3415E-03	15.8 – 21.4
ENDF/B-VII	3.7015E-03	15.4 – 19.6
MENDL-2	7.4226E-03	15.7 – 21.1
TENDL-2009	6.7370E-05	15.6 – 21.2

The averaged cross sections calculated from ENDF/B-VII data are not quite correctly determined because of microscopic cross sections for the $^{209}Bi(n,3n)^{207}Bi$ reaction in this library given only up to 20 MeV. Due to this fact ENDF/B-VII data produce the lowest value of the calculated integral cross section.

Precise measurements of the integral cross section of the $^{209}Bi(n,3n)^{207}Bi$ reaction are required for ^{235}U thermal fission neutron spectrum for a final testing of the evaluated excitation function.

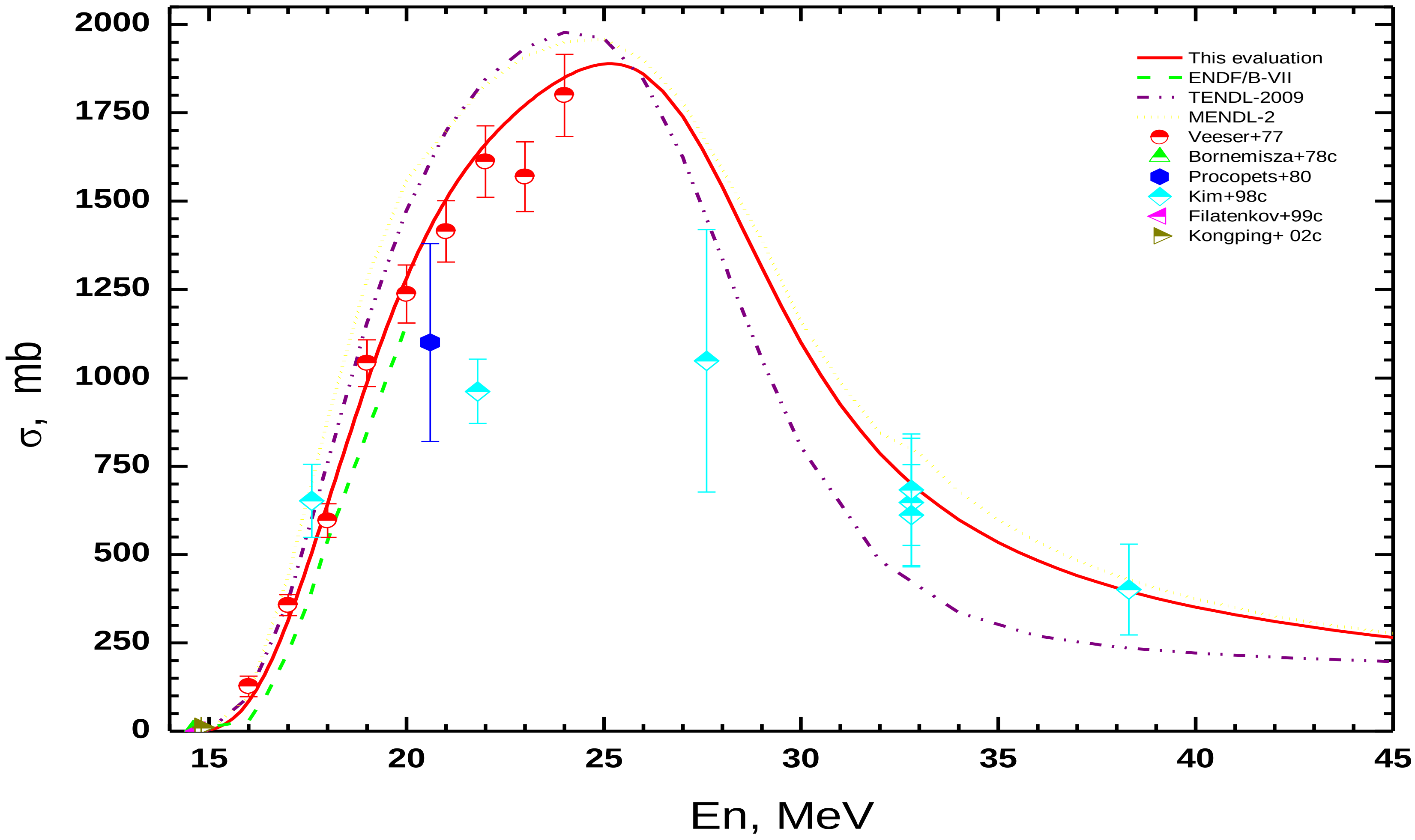

FIG. 7.1. Evaluated excitation function of the $^{209}Bi(n,3n)^{207}Bi$ reaction in the energy range from threshold to 45 MeV in comparison with ENDF/B-VII, TENDL-2009, MENDL-2 and experimental data

REFERENCES TO SECTION 7

[7.1] VEESER, L.R., ARTHUR, E.D., YOUNG, P.G., Cross Sections for (n,2n) and (n,3n) Reactions Above 14 MeV, Phys. Rev. C **16** (1977) 1792-1802.

[7.2] BORNEMISZA-PAUSPERTL P., TOEROEK I., URAY I., Some cross-sections of nuclear reactions induced by 14 MeV neutrons on Bi, Radiochemical and Radioanalytical letters **32 (**1978) 277.

[7.3] PROKOPEC, G.A., Neutron yield cross-sections for the Fe, Au, Bi nuclei at the energy 20.6 MeV, Yadernaya Fizika (Sov.) **32** issue 1 (1980) 37 (in Russian).

[7.4] EUN JOO KIM, NAKAMURA, T., KONNO, A., UWAMINO, Y., NAKANISHI, N., IMAMURA, M., NAKAO, N., SHIBATA, S., TANAKA, S., Measurements of Neutron Spallation Cross-Sections of ^{12}C and ^{209}Bi in 20 to 150 MeV Energy Range, Nucl. Sci. Eng. **129** (1998) 209.

[7.5] FILATENKOV, A.A., CHUVAEV, S.V., Systematic Activation Cross Sections Measurement at Neutron Energies around 14 MeV, Preprint RI-252, M., Atominform, 1999.

[7.6] GONGPING LI, ZHONGSHENG PU, XIANGZHONG KONG, FENG ZHANG, XUEBIN ZHU, Cross section measurements for (n,3n) reactions induced by 14.8 MeV neutrons, Appl. Rad. Isot. **56** (2002) 731.

8. CONCLUSIONS

New evaluations of cross sections and their uncertainties have been carried out for five dosimetry reactions. Excitation functions for the $^{89}Y(n,2n)^{88}Y$, $^{93}Nb(n,2n)^{92m}Nb$ and $^{169}Tm(n,2n)^{168}Tm$ reactions were re-evaluated over the neutron energy range from threshold to 40 MeV, while the excitation functions of the $^{59}Co(n,3n)^{57}Co$ and $^{209}Bi(n,3n)^{207}Bi$ reactions were evaluated in the energy ranges from thresholds to 85 MeV and to 45 MeV, respectively. Compared with IRDF-2002, the upper neutron energy boundary was increased from 20 to 40 MeV for the $^{89}Y(n,2n)^{88}Y$, $^{93}Nb(n,2n)^{92m}Nb$ and $^{169}Tm(n,2n)^{168}Tm$ reactions. Excitation functions of the $^{59}Co(n,3n)^{57}Co$ and $^{209}Bi(n,3n)^{207}Bi$ reactions were evaluated for dosimetry application. Uncertainties in the cross sections for all new evaluations are given in the form of relative covariance matrices.

Benchmark calculations performed for $^{89}Y(n,2n)^{88}Y$, $^{93}Nb(n,2n)^{92m}Nb$, $^{169}Tm(n,2n)^{168}Tm$ reactions using the ^{235}U thermal fission and ^{252}Cf spontaneous fission neutron spectra show that the integral cross sections calculated from the newly evaluated excitation functions exhibit improved agreement with related experimental data when compared with the equivalent data from the IRDF-2002, ENDF/B-VII, TENDL-2009 and MENDL-2 libraries. Newly evaluated excitation functions for the $^{59}Co(n,3n)^{57}Co$ and $^{209}Bi(n,3n)^{207}Bi$ reactions are in better agreement with related experimental data than ENDF/B-VII, TENDL-2009 and MENDL-2 libraries. Thus, the $^{59}Co(n,3n)^{57}Co$, $^{89}Y(n,2n)^{88}Y$, $^{93}Nb(n,2n)^{92m}Nb$, $^{169}Tm(n,2n)^{168}Tm$ and $^{209}Bi(n,3n)^{207}Bi$ cross-section files in ENDF-6 format should be considered as suitable candidates in the preparation of an improved version of the International Reactor Dosimetry File (IRDF).
Precise measurements of the integral cross sections of the $^{59}Co(n,3n)^{57}Co$ and $^{209}Bi(n,3n)^{207}Bi$ reactions in a well determined neutron spectra from D(Be,n) reaction are required for a final testing of the excitation functions for these reactions.

Acknowledgements

The author is grateful to the Nuclear Data Section of the International Atomic Energy Agency for their support of the project, and Dr. Roberto Capote for his close interest in this work and useful discussions.

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

e-mail: services@iaeand.iaea.org
fax: (43-1) 26007
telephone: (43-1) 2600-21710
Web: http://www-nds.iaea.org