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Evaluation of $^{50}Cr(n,\gamma)^{51}Cr$, $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$, and $^{68}Zn(n,x)^{67}Cu$ reaction cross sections for the IRDFF library

Progress Report on Research Contract

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Obninsk, Russia

August 2019

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1. INTRODUCTION

Cross-section data for the $^{50}Cr(n,\gamma)^{51}Cr$, $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$, and $^{68}Zn(n,x)^{67}Cu$ reactions are needed to solve a wide spectrum of scientific and technical tasks. The listed reactions are not used in practice as activation detectors in the reactor and fusion dosimetry. Evaluation of cross sections for listed reactions is needed first of all to create the initial files.

In the existent version of International Reactor Dosimetry and Fusion File – IRDFF-v1.05 [1.1] data for the $^{50}Cr(n,\gamma)^{51}Cr$, $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$, and $^{68}Zn(n,x)^{67}Cu$ reaction excitation functions are absent.

Cross section data for $^{50}Cr(n,\gamma)^{51}Cr$ reaction are given in all well-known libraries. The more representative data with covariance matrices of uncertainty are given in the ENDF/B-VII.1 [1.2], TENDL-2014 [1.4] and TENDL-2015 [1.5] libraries.

In the process of neutrons interaction with ^{56}Fe tree reactions leads to production of the ^{54}Mn. They are $^{56}Fe(n,t)^{54}Mn$, $^{56}Fe(n,n+d)^{54}Mn$ and $^{56}Fe(n,2n+p)^{54}Mn$. Cross section data for $^{56}Fe(n,t)^{54}Mn$ reaction are given in all well known libraries. Data for all tree reactions with covariance matrices of uncertainty are given in the libraries EAF-2010 (up to 60 MeV) [1.3], TENDL-2014 (up to 60 MeV), TENDL-2015 (up to 60 MeV) and TENDL-2017 (up to 30 MeV) [1.6].

The isotope ^{56}Mn is produced in interaction neutrons with ^{57}Fe via reactions $^{57}Fe(n,d)^{56}Mn$, $^{57}Fe(n,n+p)^{56}Mn$ and $^{57}Fe(n,p+n)^{56}Mn$. Cross section data for $^{57}Fe(n,d)^{56}Mn$ reaction are given in all well known libraries. Data for these reactions with covariance matrices of uncertainty are given in the libraries EAF-2010 (up to 60 MeV), TENDL-2014 (up to 60 MeV), TENDL-2015 (up to 60 MeV) and TENDL-217 (up to 30 MeV).

The isotope ^{67}Cu is produced in interaction neutrons with ^{68}Zn via reactions $^{68}Zn(n,d)^{67}Cu$, $^{68}Zn(n,n+p)^{67}Cu$ and $^{68}Zn(n,p+n)^{67}Cu$. Cross section data for $^{68}Zn(n,d)^{67}Cu$ reaction are given in all well known libraries. Data for (n,d), (n,n+p), (n,p+n) reactions with covariance matrices of uncertainty are given in the libraries EAF-2010 (up to 60 MeV), TENDL-2014 (up to 60 MeV), TENDL-2015 (up to 60 MeV) and TENDL-2017 (up to 30 MeV).

Modern method used in nuclear data evaluation of TENDL data files with the TALYS code system is described in Ref. [1.7].

The main aim of this work was the evaluation of the cross section data and related covariance matrices of uncertainty for $^{50}Cr(n,\gamma)^{51}Cr$, $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$, and $^{68}Zn(n,x)^{67}Cu$ reactions. Excitation function for the $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$, and $^{68}Zn(n,x)^{67}Cu$ reactions needs to be evaluated with extension to higher neutron energies up to 60 MeV. New evaluations were performed and corrected to the new standards of all available experimental data and data obtained from consistent theoretical model calculations.

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2. METHOD OF EVALUATION OF THE REACTION EXCITATION FUNCTIONS

2.1. Sources of information used in the evaluation

In the process of evaluating cross sections and their uncertainties two common information sources were used for reactions ^{50}Cr(n,γ)^{51}Cr, ^{56}Fe(n,x)^{54}Mn, ^{57}Fe(n,x)^{56}Mn, and ^{68}Zn(n,x)^{67}Cu: available differential and integral experimental data. Differential and integral experimental data were taken mainly from EXFOR Library (Version June 2018). In those cases where the necessary information was absent in the EXFOR, the information was taken from the original publications.

2.2. Analysis of experimental data

As the first step of evaluation all experimental data were analysed. During this procedure all experimental data, where possible, were corrected to the new recommended cross section data for monitor reactions used in the measurements and to the new recommended decay data.

Correction of experimental data to the new standards, in general, leads to decreasing of discrepancies in the experimental data and thus to decreasing of uncertainty in the evaluated cross section values.

The needed information regarding standards used for correction of microscopic experimental data under investigation is given in the Table 2.1.

Table 2.1. Data used as standards for correction of microscopic experimental cross sections.

Monitor reaction	Cross section used as standard	Half-life of residual nuclei	Radiation mode and energy, keV	Emission Probability per decay
^{1}H(n,n)^{1}H	Carlson+ [2.1]			
^{6}Li(n,t)^{4}He	Carlson+ [2.1]			
^{27}Al(n,α)^{24}Na	Zolotarev [2.2]	14.997 (12) h	Gamma 1368.63 Gamma 2754.01	0.999936 (15) [2.12] 0.99855 (5) [2.12]
^{27}Al(n,p)^{27}Mg	Zolotarev+ [2.3]	9.458 (12) m	Gamma 843.76 Gamma 1014.44	0.718 (4) [2.13] 0.280 (4) [2.13]
^{54}Fe(n,p)^{54}Mn	Zolotarev+ [2.4]	312.05 (4) d	Gamma 834.848	0.99976 (1) [2.14]
^{56}Fe(n,p)^{56}Mn	Zolotarev [2.5]	2.5789 (1) h	Gamma 846.76 Gamma 1810.73	0.9885(3) [2.15] 0.2719 (79) [2.15]
^{63}Cu(n,2n)^{62}Cu	Zolotarev [2.6]	9.67 (3) m	Beta+ 2936.9 Gamma 511 Gamma 1172.97	0.9760 (3) [2.16] 1.9566 (5) [2.16] 0.00342 (5) [2.16]
^{65}Cu(n,2n)^{64}Cu	Zolotarev [2.6]	12.700 (2) h	Beta+ 653.1 Beta- 578.7 Gamma 511 Gamma 1345.77	0.1740 (22) [2.16] 0.390 (4) [2.16] 0.348 (4) [2.16] 0.00473 (10) [2.16]
^{75}As(n,2n)^{74}As	Zolotarev [2.7]	17.77 (2) d	Gamma 511	0.580 (60) [2.17]
^{93}Nb(n,2n)^{92m}Nb	Zolotarev [2.8]	10.15 (2) d	Gamma 934.44	0.9907 (4) [2.13]
^{115}In(n,γ) ^{116m}In	Zolotarev+ [2.4]	54.29 (17) m	Gamma 416.90 Gamma 1097.28 Gamma 1293.56	0.272 (4) [2.18] 0.585 (8) [2.18] 0.848 (12) [2.18]
^{127}I(n,γ)^{128}I	Zolotarev [2.9]	24.99 (2) m	Gamma 442.90	0.169 (17) [2.13]
^{141}Pr(n,2n)^{140}Pr	Zolotarev [2.10]	3.39 (1) m	Gamma 511	1.020 (6) [2.20]
^{197}Au(n,2n)^{196}Au	Zolotarev [2.6]	6.183 (10) d	Gamma 333.03 Gamma 355.73 Gamma 426.10	0.229 (6) [2.13] 0.870 (4) [2.13] 0.066 (4) [2.13]
^{197}Au(n,γ)^{198}Au	Carlson+ [2.1]	2.6947 (3) d	Gamma 411.802	0.9562 (4) [2.20]
^{235}U(n,f)	Carlson+ [2.1]			

Comment for Table 2.1: for beta transition the end-point value of energy is given.

Recommended thermal neutron cross sections at 0.0253 eV were taken mainly from works [2.1] and [2.21]. Recommended value for the $^{50}Cr(n,\gamma)^{51}Cr$ reaction cross sections at 0.0253 eV is discussed in this work.

Recommended cross section and decay data for monitor reactions used in the measurements of integral cross sections in ^{235}U thermal fission neutron spectrum and ^{252}Cf spontaneous fission neutron spectrum are given below in Table 2.2.

Table 2.2. Data used as standards for correction of integral experimental cross sections measured in ^{235}U thermal fission and ^{252}Cf spontaneous fission neutron spectra.

Monitor Reaction	Cross section used as standard, mb	Half-life for residual nuclei	Radiation mode and energy, keV	Emission Probability per decay
$^{27}Al(n,\alpha)^{24}Na$	0.7007±1.28% [2.22] U 1.016±1.28% [2.23] Cf	14.997 (12) h	Gamma 1368.63 Gamma 2754.01	0.999936(15) [2.12] 0.99855 (5) [2.12]
$^{54}Fe(n,p)^{54}Mn$	78.09±1.50% [2.4] U	312.05 (4) d	Gamma 834.848	0.999760(10) [2.14]
$^{56}Fe(n,p)^{56}Mn$	1.079±1.54% [2.22] U	2.5789 (1) h	Gamma 846.754 Gamma 1810.72	0.9887 (3) [2.15] 0.2719 (79) [2.15]
$^{58}Ni(n,p)^{58}Co$	108.2±1.30% [2.22] U	70.86 (6) d	Gamma 511 Gamma 810.78	0.298 (4) [2.24] 0.99450 (10) [2.24]
$^{115}In(n,n')^{115m}In$	187.8±1.23% [2.22] U 197.4±1.37% [2.23] Cf	4.486 (4) h	Gamma 336.24	0.458 (22) [2.25]
$^{238}U(n,f)$	325.7±1.64% [2.23] Cf			

Comments for Table 1.2: Symbol "U" – means ^{235}U thermal fission neutron spectrum,
Symbol "Cf" – means ^{252}Cf spontaneous fission neutron spectrum.

Digital data for ^{235}U thermal fission and ^{252}Cf spontaneous fission neutron spectra were taken from IRDFF-v1.05 neutron spectra data file material numbers MAT=9228 and MAT=9861, respectively. Neutron spectra data files were prepared by A. Trkov. Both spectra were taken from ENDF/B-VII decay data library and extrapolated to 30 MeV. The interpolation laws were refined to avoid bumps in the spectra (A. Trkov, November 2013).
Information about isotopic compositions of the elements was taken from Ref. [2.26].

2.3. Theoretical model calculation cross section values for dosimetry reactions

The theoretical model calculation was used as additional source of cross section information for reactions with poor experimental data. In our case, the theoretical model calculation was carried out for the determination of the relative shape $^{50}Cr(n,\gamma)^{51}Cr$ reaction excitation functions above 0.7 MeV.

For theoretical description of the excitation functions optical-statistical method was used while taking into account consistently the contribution of the direct, preequilibrium and statistical equilibrium processes in the different outgoing channels.

The practical calculations of cross sections were made by means of a modified version of the GNASH code [2.27]. The modified GNASH code is differing in general from the original GNASH code [2.28]. The modified version includes subroutine which permits to take into account the neutron width fluctuation. Furthermore, the modified GNASH code has a mode which permits to calculate cross section of population of individual levels excited in the investigated reaction. This capability is very important to calculate, for example, the $^{27}Al(n,2n)^{26g}Al$ and $^{27}Al(n,2n)^{26m}Al$ reactions cross sections.

The calculation of penetrability coefficients for neutrons was made on the basis of a generalized optical model, which permits estimation of cross sections for the direct excitations of collective low-lying levels. The ECIS coupled channel deformed optical model code [2.29] was used for these calculations. The optical coefficients of proton and alpha particle penetrability's were determined by means of the SCAT2 code [2.30].

The data file used by GNASH code on the discrete levels parameters of residual nuclei was formed on the basis data given in Ref. [2.13] and permanently corrected. 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 in accordance with the radiation strength functions recommended in Ref. [2.31].

Continuum level densities were represented with the Gilbert-Cameron [2.32] model using the Cook parameters [2.33] (mode IBSF=1 in the GNASH code). The calculation of gamma-ray transition probabilities in the continuum region of excited states of all nuclei under consideration was made in the frame of hypothesis of domination of giant dipole resonance with parameters of radiative strength function from Kopecky-Uhl systematic [2.34]. Recommended parameters of giant dipole resonances were taken from Ref. [2.35].

2.4. Statistical analysis of cross sections from the database

The method of statistical analysis of correlated data used to evaluate the excitation functions of $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$, and $^{68}Zn(n,x)^{67}Cu$ reactions from threshold to 60 MeV and $^{50}Cr(n,\gamma)^{51}Cr$ reaction in the energies range 783 keV – 20 MeV was described in the IAEA NDS Reports [2.2-2.4], [2.6], [2.8]. Detailed description of the method and PADE-2 code may be found in Refs. [2.36-2.38].

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3. RE-EVALUATION OF THE ^{50}Cr(n,γ) ^{51}CR REACTION EXCITATION FUNCTION

Currently in the nature four stable chromium isotopes are known: ^{50}Cr, ^{52}Cr, ^{53}Cr and ^{54}Cr. The abundance of isotopes in natural chromium is ^{50}Cr – 4.345 (13), ^{52}Cr - 83.789 (18), ^{53}Cr - 9.501 (17), ^{54}Cr - 2.365 (7) atom percents.
The (J_{π}=7/2-) ground level of ^{51}Cr obtained in the (n,γ) reaction undergoes 100% via EC-decay mode with a half-life of (27.704 ± 0.003) days. The EC-decay is accompanying with emission of electrons gamma and X-ray radiation. The gamma-line with energy 320.0824 (4) keV with intensity of I_{γ} = 0.09910 (10) is normally used to determine the ^{50}Cr(n,γ)^{51}Cr reaction rate. Recommended decay data for the half-life and emission probability, I_{γ} per decay of ^{51}Cr were taken from Ref. [3.18].
Microscopic experimental data for the ^{50}Cr(n,γ)^{51}Cr reaction excitation function is given in the works [3.1-3.14]. The most part of cross section measurements was carried out in a region of thermal neutrons [3.1-3.3], [3.5], [3.7], [3.10-3.12], [3.14]. The rest works [3.4], [3.6], [3.8-3.9], [3.13] gives experimental information about cross section from 29 eV to 1.05 MeV. Experimental data of works [3.2-3.3], [3.5], [3.7], [3.10-3.12], and [3.14] in the process of analysis were corrected to the new standards for the relevant monitor reactions (see Table 2.1) and for the recommended decay data for ^{51}Cr.

The high precision measurements of ^{50}Cr(n,γ), ^{50}Cr(n,el) and ^{50}Cr(n,tot) reaction cross sections in thermal region and first of all at 0.0253 eV neutron energy are necessary and are very important for true determination parameters of the negative resonance.
Unfortunately, experimental data for (n,tot) and (n,el) cross sections in the region of thermal neutrons are absent.
As mentioned above the ^{50}Cr(n,γ)^{51}Cr thermal cross section was determined in 9 works. Cross section data at thermal region were measured by using 3 methods: pile oscillator method, classical activation method, and k_0- activation method.
The k_0- method was developed especially for reactor neutron activation analysis (NAA). This method permitted standardized NAA measurements at reactor spectra with different ratio of the thermal neutron flux to epithermal flux. Thermal cross sections at 0.0253 eV are determined from measured $k_{0,m}$, $Q_{0,m}$ and $Q_{0,x}$ - factors, where $Q_{0,m}$ and $Q_{0,x}$ are resonance integral to 2200 ms^{-1} cross-section ratio for monitor reaction and investigated reaction, respectively. Usually in k_0- activation method ^{197}Au(n,γ)^{198}Au reaction is used as monitor .

The ^{50}Cr(n,γ)^{51}Cr experimental data obtained in the region thermal neutrons are compared below in Table 3.1.
Thermal cross sections of ^{50}Cr(n,γ)^{51}Cr reaction presented in the Table 3.1 ranged from (11.0 ± 4.4) b [3.1] to (16.93 ± 1.35) b [3.2]. Data of works [3.1], [3.2], [3.3], [3.7] and [3.10] may be omitted from analysis due to incomplete description of experimental information.

Table 3.1. Comparison of $^{50}Cr(n,\gamma)^{51}Cr$ experimental cross section data obtained in the region thermal neutrons.

Author	Neutron source	Method	Monitor reaction and ref to standardization value	Cross section, b
Seren+ [3.1]	Reactor at ANL, thermal spectrum	Activation		11.0 ± 4.4
Pomerance [3.2]	thermal spectrum	Pile oscillator	$^{197}Au(n,\gamma)^{198}Au$ [2.1]	16.93 ± 1.35
Lyon [3.3]	ORNL graphite reactor	Activation	$^{59}Co(n,\gamma)^{60}Co$ [2.22]	16.82 ± 1.68
Sims+ [3.5]	Reactor at Chalk River	Activation	$^{59}Co(n,\gamma)^{60}Co$ [2.22]	14.32 ± 0.09
Gleason [3.7]	Graphite-moderated Cf-252 facility	Activation	$^{197}Au(n,\gamma)^{198}Au$ [2.1] $^{55}Mn(n,\gamma)^{56}Mn$ [2.22]	15.78 ± 0.20
Heft [3.10]	LPTR Research reactor facility at LRL	Activation	$^{45}Sc(n,\gamma)^{46}Sc$ [2.22]	15.66 ± 0.10
Simonits+ [3.11]	WWR-M thermal reactor at Budapest, TETIS reactor at Gent	K_0 - method	$^{197}Au(n,\gamma)^{198}Au$ [2.1]	15.12 ± 0.20
Venturini+ [3.12]	IEA-R1 research 2 MV reactor	Activation	$^{14}N(n,\gamma)^{15}N$ [2.22]	14.72 ± 0.37
Farina Arb+ [3.14]	BR1 reactor at SCK-CEN, Iradiation at 4 positions	K_0 - method	$^{197}Au(n,\gamma)^{198}Au$ [2.1]	14.42 ± 0.13

In the EXFOR library only data of Simonits et al. [3.11] and Farina Arbocco et al. [3.14] are qualified as $^{50}Cr(n,\gamma)^{51}Cr$ cross section at 0.0253 eV.
Comparison of experimental data by Simonits et al. and Farina Arbocco et al. show its inconsistency (15.12 ± 0.20) b and (14.42 ± 0.13) b, respectively.

Cross section presented by Simonits et al. is a result of analysis of theoretical and experimental $k_{0,Au}$ – factors for ^{51}Cr gamma-line with energy 320.0824 (4) keV (I_γ = 0.09910 ± 0.00010) obtained at two reactors. One independent run was performed at WWR-M thermal reactor of Central Research Institute of Physics, Budapest, Hungary. A second independent run was performed at THETIS reactor of Institute for Nuclear Science, Gent, Belgium. Cr samples used at WWR-M and THETIS measurements were different. Method used by Simonits et al. to determined cross section at 0.0253 eV is based on assumption that theoretical and experimental $k_{0,Au}$ – factors for ^{51}Cr gamma-line with energy 320.0824 keV are equivalent. How this assumption is realized in the experiment is a question.

Measurements by Farina Arbocco et al. were carried out at the BR1 reactor at SCK-CEN, Belgium. Irradiation was performed at 4 positions: channels S84, Y4, X26 and Cavity. Ratio of the thermal neutron flux to epithermal flux – **f** and slope parameter – **a** of the epithermal spectrum (~1/(E**(1+a)) at the irradiation positions were following: channel S84 (**f**=16.4±0.4, **a**=0.066±0.003), channel Y4 (**f**=38.2±0.5, **a**=-0.003±0.005), channel X26 (**f**=95±5,

a=0.11±0.01), Cavity (**f**=70000 , pure thermal). Value of $^{50}Cr(n,\gamma)^{51}Cr$ 2200 m/s cross section was determined directly from measurements at Cavity.

Experimental data by Sims [3.5] and Venturini et al. [3.12] are agreed in the limit of declared uncertainties with cross section value measured by Farina Arbocco et al. [3.14]. This fact support opinion that $^{50}Cr(n,\gamma)^{51}Cr$ 2200 m/s cross section measured by Farina Arbocco et al. [3.14] is currently the best representative.

Recommended by S.F. Mughabghab $^{50}Cr(n,\gamma)^{51}Cr$ reaction cross section at 0.0253 eV is equal to (15.4 ± 0.2) barns. Recommendation of S.F. Mughabghab doesn't take into account the resent experimental data by Farina Arbocco et al. [3.14].

In the evaluation description of $^{50}Cr(n,\gamma)^{51}Cr$ reaction excitation function cross section in the energy range 1.0000E-05 eV – 783 keV is given via the Reich-Moore (RM) resonance parameters.

Parameters of the negative S-resonance: energy of resonance - E_r = -5.300E+2 eV, spin of resonance – J = 0.5, neutron width - Γ_n = 7.61260E+0 eV, radiative width - Γ_γ = 1.23736E+0 eV were adopted to obtain the $^{50}Cr(n,el)$ and $^{50}Cr(n,\gamma)$ cross sections at 0.0253 eV equal to (2.42±0.12) barns [2.22] and (14.41±0.13) barns [3.14], respectively.

Parameters of the first S-resonance were taken equal to: Er= 5.6210E+3 eV, J= 0.5, GN=1.5600E+3 eV and GG= 3.2500E+0 eV. Parameters of this resonance and parameters of S-resonances at Er= 2.8438E+4 eV, 3.7480E+4 eV, 5.5170E+4 eV, 6.4860E+4 eV and parameters of P-resonance at Er= 7.7900E+4 eV were taken from experimental data obtained by Brusegan et. al [3.15]. Measurements had been carried out at linear accelerator Gelina at IRMM, Geel, Belgium. Samples in the form of oxide powder enriched to 95.9 % of Cr-50 were used. Neutron flux was determined by TOF method. The flight path in capture experiments was 58.0 m. The flight path in transmission experiments was 48.9, 197.5 and 387.7 m, respectively.

Parameters of S-resonances (l=0), P-resonances (l=1) and D-resonances (l=2) for ^{50}Cr above 90 keV were taken from evaluation carried out by Leal et al. [3.16]. Resolved resonance parameter evaluation was done with the computer code SAMMY and based on transmission measurement for ^{50}Cr performed by Harvey [3.17]. The transmission measurement was done at the Oak Ridge Electron Linear Accelerator (ORELA) of the Oak Ridge National Laboratory, USA. The transmission data were measured at the 201-meter flight-path in the neutrons energy range of 90-800 KeV with using a 95.98% enriched to ^{50}Cr sample.
Values of resonance parameters evaluated by Leal above 90 keV were taken from the ENDF/B-VII.1 library.

RM parameters evaluated for 393 resonances of 3 l-values are used for reconstruction of $^{50}Cr(n,\gamma)$, $^{50}Cr(n,el)$ and $^{50}Cr(n,tot)$, cross sections from 1.000E-5 eV to 7.830E+5 eV.
The scattering radius was taken equal to 5.24 fermi in according to the Atlas of Neutron Resonances [2.22].

2200 m/sec cross sections and resonance integrals calculated from RM parameters are as follows:

Table 3.2. Average parameters from INTER (***T=300K)***

Reaction	2200 m/s cross section, barns	Resonance integral, barns
$^{50}Cr(n,\gamma)$	14.4273	6.8027
$^{50}Cr(n,el)$	2.4224	234.857
$^{50}Cr(n,tot)$	16.8496	241.661

Excitation function for the $^{50}Cr(n,\gamma)^{51}Cr$ reaction in the energy region from 0.783 MeV to 20 MeV was evaluated by means of statistical analysis of experimental cross section data [3.13] and data obtained from theoretical model calculation carried out by GNASH code. Evaluation of the $^{50}Cr(n,\gamma)^{51}Cr$ reaction cross section and related uncertainties were performed by means of PADE-2 code.

Uncertainties in the re-evaluated $^{50}Cr(n,\gamma)^{51}Cr$ reaction excitation function are given via two independent matrixes.

In the RRR range 1.000E-5 - 7.830E+5 eV uncertainties are presented in the form of relative covariance matrix for the 34 neutron energy groups (LB=5). Covariance matrix was generated by the PADE-2 code. Eigenvalues of the 6-th digits relative covariance matrix given in the 33-file are the following:

```
2.58781E-08     4.26657E-08     6.70679E-08     3.59993E-07
3.49483E-06     2.79938E-05     5.58492E-05     7.21507E-05
1.97799E-04     2.60641E-04     5.28239E-04     7.60984E-04
8.01516E-04     1.56235E-03     1.80513E-03     1.92138E-03
2.04248E-03     2.48700E-03     3.37688E-03     3.58054E-03
3.81186E-03     4.79592E-03     5.80916E-03     7.45054E-03
9.76742E-03     1.13877E-02     1.22678E-02     1.40584E-02
1.70204E-02     2.31911E-02     3.27065E-02     5.87933E-02
1.29126E-01     1.52516E-01
```

In the energy range 783.0 keV - 20 MeV uncertainties are presented in the form of relative covariance matrix for the 32 neutron energy groups (LB=5). Covariance matrix was generated also by the PADE-2 code. Eigenvalues of the 6-th digits relative covariance matrix given in the 33-file are the following:

```
1.78549E-06     2.23147E-06     2.40064E-06     2.82289E-06
3.09425E-06     3.22114E-06     5.24945E-06     8.53408E-06
1.27268E-05     1.72666E-05     1.84226E-05     1.87762E-05
1.94836E-05     2.07700E-05     2.14607E-05     2.28505E-05
2.49743E-05     2.58866E-05     2.69973E-05     2.81777E-05
2.89818E-05     3.41528E-05     3.00631E-03     1.95919E-02
2.94498E-02     3.66629E-02     3.90725E-02     7.03630E-02
7.49466E-02     9.33232E-02     1.49928E-01     7.49537E-01
1.33695E-02     1.54593E-02     1.76644E-02     1.90960E-02
```

Eigenvalues of the covariance sub-matrixes were tested in addition by COVEIG code [3.xx]. Some differences in the eigenvalues determined by PADE-2 code and COVEIG code occured only for the lowest eigenvalues. The highest of the eigenvalues are equivalent. Group cross sections and their uncertainties for the evaluated $^{50}Cr(n,\gamma)^{51}Cr$ reaction excitation function from 1.000E-05 eV to 20MeV are given in Table 3.3. Group boundaries are the same as in File-33.

Table 3.3. Evaluated cross sections and their uncertainties for the $^{50}Cr(n,\gamma)^{51}Cr$ reaction in the neutron energy range from 1.000E-5 eV to 20 MeV.

Neutron energy (eV) from - to	Cross section (barns)	Uncer-tainty (%)	Neutron energy (eV) from - to	Cross section (barns)	Uncer-tainty (%)
1.000E-05 - 1.000E-04	3.488E+2	4.41	4.000E+05 - 7.830E+05	4. 081E-3	39.03
1.000E-04 - 1.000E-03	1.109E+2	4.65	7.830E+05 - 9.000E+05	4. 306E-3	8.71
1.000E-03 - 1.000E-02	3.488E+1	3.78	9.000E+05 - 1.000E+06	3.477E-3	9.10
1.000E-02 - 2.000E-02	1.902E+1	2.87	1.000E+06 - 1.250E+06	2.958E-3	9.78
2.000E-02 - 3.000E-02	1.459E+1	2.20	1.250E+06 - 1.500E+06	2.627E-3	10.89
3.000E-02 - 5.000E-02	1.157E+1	2.65	1.500E+06 - 1.750E+06	2.544E-3	12.35
5.000E-02 - 7.000E-02	9.405E+0	3.28	1.750E+06 - 2.000E+06	2.614E-3	14.07
7.000E-02 - 1.000E-01	7.904E+0	3.63	2.000E+06 - 2.500E+06	2.866E-3	15.43
1.000E-01 - 5.000E-01	4.485E+0	4.79	2.500E+06 - 3.000E+06	3.131E-3	16.12
5.000E-01 - 1.000E+00	2.687E+0	6.30	3.000E+06 - 3.500E+06	3.038E-3	16.33
1.000E+00 - 5.000E+00	1.414E+0	4.97	3.500E+06 - 4.000E+06	2.650E-3	16.84
5.000E+00 - 1.000E+01	8.435E-1	5.71	4.000E+06 - 4.500E+06	2.190E-3	17.81
1.000E+01 - 5.000E+01	4.360E-1	4.64	4.500E+06 - 5.000E+06	1.785E-3	18.14
5.000E+01 - 1.000E+02	2.512E-1	4.74	5.000E+06 - 5.500E+06	1.479E-3	18.21
1.000E+02 - 5.000E+02	1.236E-1	4.55	5.500E+06 - 6.000E+06	1.238E-3	18.50
5.000E+02 - 1.000E+03	7.710E-2	4.57	6.000E+06 - 6.500E+06	1.073E-3	18.92
1.000E+03 - 2.000E+03	7.178E-2	4.89	6.500E+06 - 7.000E+06	9.603E-4	19.17
2.000E+03 - 3.000E+03	9.321E-2	4.51	7.000E+06 - 7.500E+06	8.880E-4	19.20
3.000E+03 - 4.000E+03	1.621E-1	3.91	7.500E+06 - 8.000E+06	8.469E-4	19.21
4.000E+03 - 5.000E+03	4.039E-1	4.16	8.000E+06 - 8.500E+06	8.296E-4	19.36
5.000E+03 - 6.000E+03	9.031E-1	4.20	8.500E+06 - 9.000E+06	8.305E-4	19.63
6.000E+03 - 7.000E+03	4.338E-1	4.50	9.000E+06 - 1.000E+07	8.570E-4	19.81
7.000E+03 - 8.000E+03	1.337E-1	5.87	1.000E+07 - 1.100E+07	9.143E-4	19.76
8.000E+03 - 1.000E+04	4.869E-2	9.57	1.100E+07 - 1.200E+07	9.778E-4	20.07
1.000E+04 - 1.600E+04	9.348E-3	15.01	1.200E+07 - 1.300E+07	1.029E-3	20.79
1.600E+04 - 2.000E+04	6.258E-2	17.20	1.300E+07 - 1.400E+07	1.056E-3	21.31
2.000E+04 - 3.000E+04	1.419E-2	17.36	1.400E+07 - 1.450E+07	1.057E-3	21.93
3.000E+04 - 4.000E+04	5.638E-2	17.11	1.450E+07 - 1.500E+07	1.047E-3	22.68
4.000E+04 - 6.000E+04	2.241E-2	16.76	1.500E+07 - 1.600E+07	1.018E-3	24.43
6.000E+04 - 9.000E+04	1.435E-2	16.62	1.600E+07 - 1.700E+07	9.578E-4	27.35
9.000E+04 - 1.500E+05	1.952E-2	17.35	1.700E+07 - 1.800E+07	8.872E-4	29.52
1.500E+05 - 2.000E+05	1.449E-2	19.23	1.800E+07 - 1.900E+07	7.852E-4	30.71
2.000E+05 - 4.000E+05	9.290E-3	24.65	1.900E+07 - 2.000E+07	6.848E-4	33.47

Uncertainties in the evaluated the $^{50}Cr(n,\gamma)^{51}Cr$ excitation function range from 2.20% to 39.03%. The smallest uncertainties in the evaluated cross sections of 2.20% are observed in the neutron energy interval 2.000E-02 - 3.000E-02 eV and reflect the knowledge of 2200 m/sec capture cross section. Uncertainties observed in the $^{50}Cr(n,\gamma)^{51}Cr$ reaction cross sections exceed 10% in the resonance range between 1.000E+04 - 7.830E+05 eV and in the energy range 1.25 - 20 MeV.

The evaluated excitation function for the $^{50}Cr(n,\gamma)^{51}Cr$ reaction in the neutron energy range 1.000E-08 - 20 MeV shown in Fig. 3.1 compares with the equivalent data from ENDF/B-VII.1 and TENDL-2015 libraries and corrected experimental data. The same information but in the narrow neutron energy range 2.000E-02 - 20 MeV is shown in Fig. 3.2. It is necessary to note, that in the resonance range 1.000E-5 - 7.830E+5 eV, ENDF/B-VII.1 and TENDL-2015 data are similar. They differ above 7.830E+5 eV.

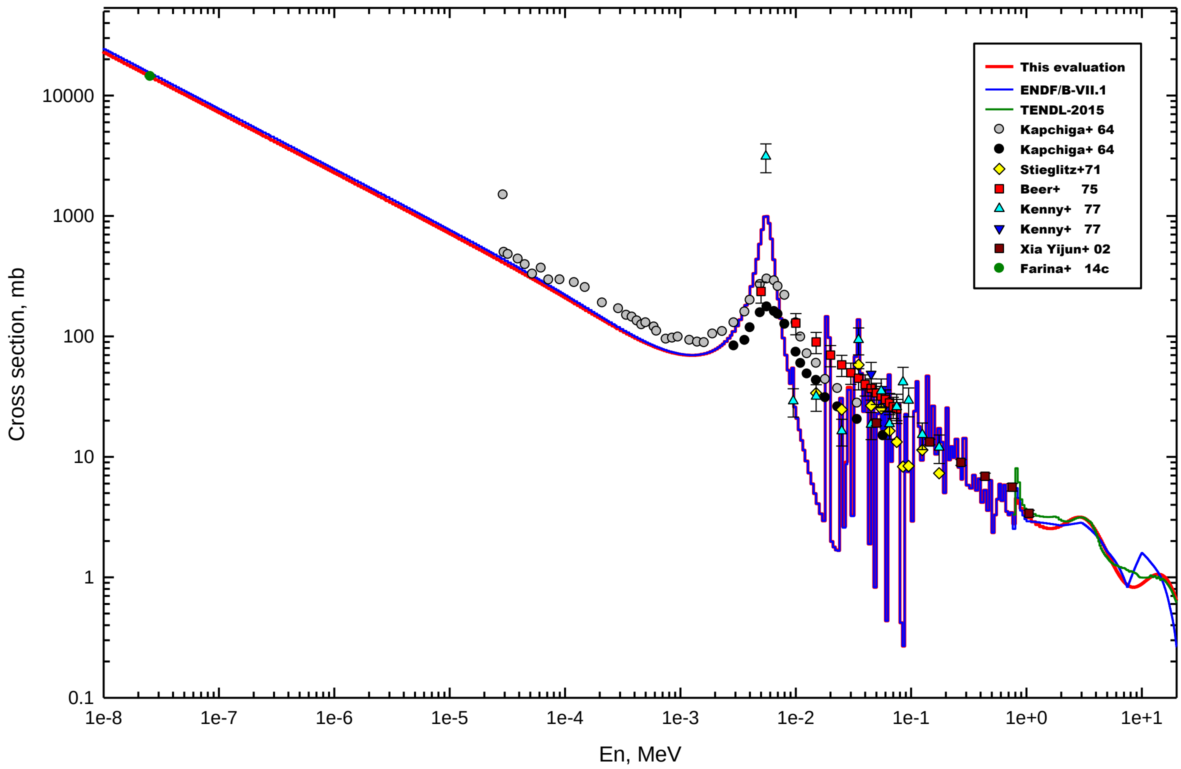

Fig. 3.1 Evaluated $^{50}Cr(n,\gamma)^{51}Cr$ reaction excitation function in the energy range 1.0E-8 – 20 MeV in comparison with equivalent data from ENDF/B-VII.1 and TENDL-2015 libraries and corrected experimental data.

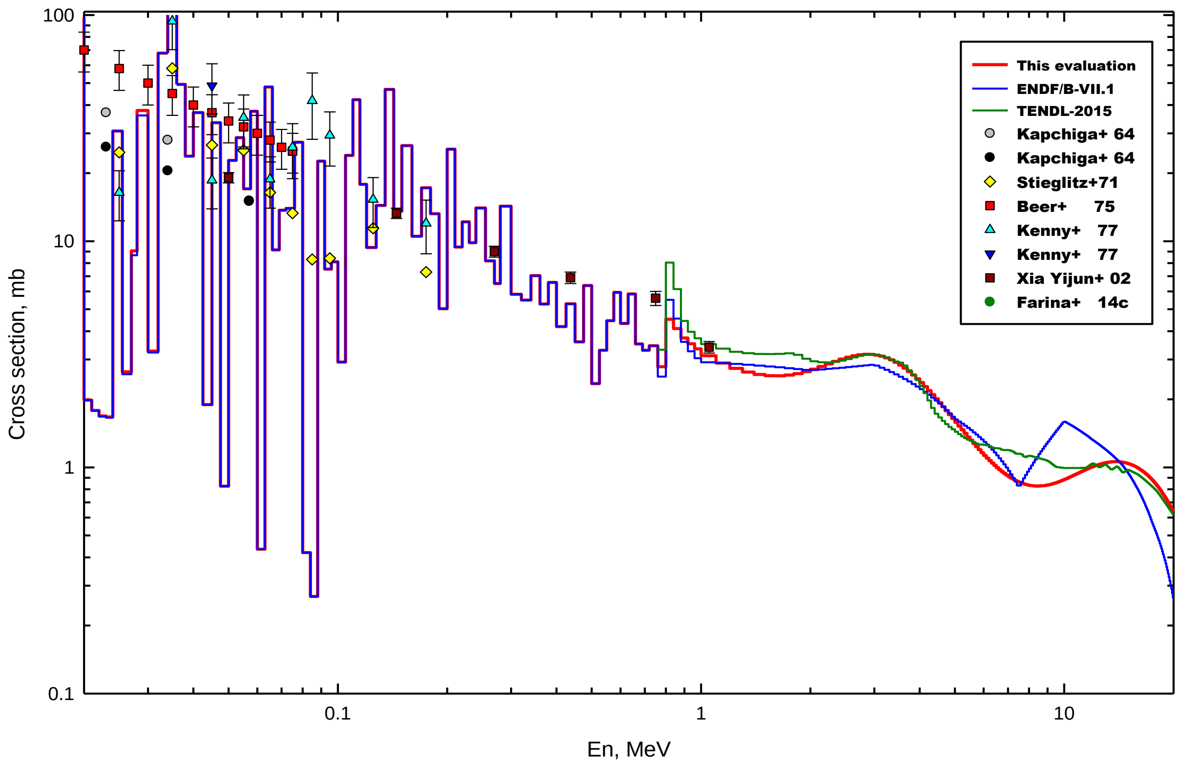

Fig. 3.2 Evaluated $^{50}Cr(n,\gamma)^{51}Cr$ reaction excitation function in the energy range 2.0E-2 – 20 MeV in comparison with equivalent data from ENDF/B-VII.1 and TENDL-2015 libraries and corrected experimental data.

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4. EVALUATION OF THE $^{56}Fe(n,x)^{54}Mn$ REACTION EXCITATION FUNCTION

In the process of neutrons interaction with ^{56}Fe 3 reactions lead to production of the ^{56}Mn. They are $^{56}Fe(n,t)^{54}Mn$, $^{56}Fe(n,n+d)^{54}Mn$ and $^{56}Fe(n,2n+p)^{54}Mn$. Threshold of the $^{56}Fe(n,t)^{54}Mn$ reaction equals to Eth=12.14309 (0.00108) MeV. Threshold of the $^{56}Fe(n,n+d)^{54}Mn$ reaction is equal to Eth=18.51319 (0.00108) MeV and threshold of the $^{56}Fe(n,2n+p)^{54}Mn$ reaction is equal to Eth=20.77788 (0.00112) MeV. For a short representation this tree reactions will be written as $^{56}Fe(n,x)^{54}Mn$.

Experimental data for the $^{56}Fe(n,x)^{54}Mn$ reaction excitation function are given only in works [4.1] and [4.2]. In the work [4.1] Qaim and Stoecklin give $^{56}Fe(n,t)^{54}Mn$ cross section measured at 14.6 MeV . Integral of the $^{56}Fe(n,x)^{54}Mn$ cross section measured at Be(d,n) neutron spectrum is presented in the work [4.2]. Measurements were carried out at Juelich isochronous cyclotron. 53- MeV deuterons were bombarded on a 1 cm thick Be target. Generated neutron spectrum extended from 11.5 to 43.5 MeV with maximum intensity at 22.5 MeV and FWHM of 15.8 MeV. 80 % of neutrons from integration lie within the range 14-30 MeV. Average of neutron spectrum cross section of $^{56}Fe(n,t)^{54}Mn$, $^{56}Fe(n,n+d)^{54}Mn$ and $^{56}Fe(n,2n+p)^{54}Mn$ reactions was measured by activation method. Iron sample in the form Fe2O3 powder, with isotopic composition ^{54}Fe - 0.03%, ^{56}Fe - 99.93%, ^{57}Fe - 0.03%, ^{58}Fe - 0.02%, was used in measurements. Target material was sealed in quartz ampoule and wrapped in an Au monitor foil. For gamma spectroscopic analysis sample was wrapped in a polyethylene foil. Gamma activity of ^{54}Mn was measured by Ge(Li) detector.

Microscopic data for the $^{56}Fe(n,x)^{54}Mn$ reaction excitation function in neutron energies range from 12.14309 to 60.0 MeV were extracted from experimental cross section data for $^{nat}Fe(n,x)^{54}Mn$ reaction [4.4 – 4.5] .
In a cooperation of seven institutes R. Michel et al. measured $^{nat}Fe(n,x)^{54}Mn$ excitation function up to 180 MeV [4.4]. Irradiation of ^{nat}Fe samples was performed at Louvain and Uppsala cyclotrons. Reaction $^{7}Li(p,n)$ served as neutron source. Li-target was enriched 99.984% to ^{7}Li. Neutron spectra were determined experimentally by time of-flight method. Gamma activity of ^{54}Mn was measured by Ge(Li) and HP Ge detectors.
M. Majerle et al. at the Nuclear Physic Institute (NPI), Rez, Czech Republic, measured $^{nat}Fe(n,x)^{54}Mn$ excitation function at neutron energies 17.125, 19.625, 22.750, 25.000, 27.250, 30.000 and 32.500 MeV [4.5]. Measurements were carried out at quasi-monoenergetic neutron generator. Neutron spectra were determined experimentally by time of-flight method.

Radionuclide ^{54}Mn is produced on ^{nat}Fe via ten neutron-induced reactions: $^{54}Fe(n,p)^{54}Mn$, $^{56}Fe(n,t)^{54}Mn$, $^{56}Fe(n,n+d)^{54}Mn$, $^{56}Fe(n,2n+p)^{54}Mn$, $^{57}Fe(n,n+t)^{54}Mn$, $^{57}Fe(n,2n+d)^{54}Mn$, $^{57}Fe(n,3n+p)^{54}Mn$, $^{58}Fe(n,2n+t)^{54}Mn$, $^{58}Fe(n,3n+d)^{54}Mn$, $^{58}Fe(n,4n+p)^{54}Mn$. As for ^{56}Fe isotope reactions on ^{57}Fe and ^{58}Fe for a short representation will be written as $^{57}Fe(n,x)^{54}Mn$ and $^{58}Fe(n,x)^{54}Mn$. The $^{56}Fe(n,x)^{54}Mn$ reaction cross-sections were extracted from relation:

$CS_{fenatnx}(E)=A_{54}*CS_{fe54np}(E) + A_{56}*CS_{fe56nx}(E) + A_{57}*CS_{fe57nx}(E) + A_{58}*CS_{fe58nx}(E)$, where A_{54}, A_{56}, A_{57}, A_{58} – abundance of ^{54}Fe, ^{56}Fe, ^{57}Fe and ^{58}Fe isotopes in natural iron.

The abundances of isotopes in natural iron were taken equal to: ^{54}Fe – 5.845 (35), ^{56}Fe - 91.754 (36), ^{57}Fe - 2.119 (10), ^{58}Fe - 0.282 (4) atom percents.

Needed for subtraction procedure $^{54}Fe(n,p)^{54}Mn$ cross section data were taken from IRDFF-V1.05 dosimetry file. Data for $^{57}Fe(n,x)^{54}Mn$ and $^{58}Fe(n,x)^{54}Mn$ reactions were taken from EAF-2010 library. It is necessary to note, that using data for $^{57}Fe(n,x)^{54}Mn$ and $^{58}Fe(n,x)^{54}Mn$

reactions from TENDL-2014 and TENDL-2015 libraries do not significantly influence the extracted values of the $^{56}Fe(n,x)^{54}Mn$ cross sections.
Cross section data in the IRDFF-V1.05, EAF-2010, TENDL-2014 and TENDL-2015 libraries is given up to 60 MeV. Due to this reason data of R. Michel et al. obtained above 60 MeV and data by J.M. Sisterson and M.B. Chadwick which measured $^{nat}Fe(n,x)^{54}Mn$ excitation function at 112.2 and 151.6 MeV [4.6] can't be used for extraction of $^{56}Fe(n,x)^{54}Mn$ cross sections.

As the first step of analysis, microscopic and integral experimental data [4.1-4.5] were corrected to the new standards. Recommended decay data for ^{54}Mn were taken from Ref. [2.14].

Excitation function for the $^{56}Fe(n,x)^{54}Mn$ reaction in the energy region from threshold to 60 MeV was evaluated by means of statistical analysis of experimental cross section data [4.1], [4.4], [4.5] and data from EAF-2010 library. Cross section data from EAF-2010 library were taken for neutron energies 14-15 MeV.
Statistical analysis of input cross section data was carried out by means of PADE-2 code. Rational function was used as model function.
Uncertainties in the re-evaluated $^{56}Fe(n,x)^{54}Mn$ reaction excitation function are given via two independent matrixes.
In the energy range 12.143-20 MeV there reaction $^{56}Fe(n,t)^{54}Mn$ is dominant uncertainties are presented in the form of relative covariance matrix for the 5 neutron energy groups (LB=5). Eigenvalues of the 6-th digits relative covariance matrix given in the 33-file is the following:

6.87680E-08	6.07310E-05	1.31147E-03	3.84013E-02
1.55038E-01			

In the energies range 20-60 MeV uncertainties are presented also in the form of relative covariance matrix for the 40 neutron energy groups (LB=5). Eigenvalues of the 6-th digits relative covariance matrix given in the 33-file is the following:

2.42743E-07	2.48765E-07	2.58804E-07	2.71823E-07
2.89210E-07	3.13366E-07	3.37814E-07	3.73894E-07
4.15987E-07	4.55032E-07	5.12316E-07	5.85028E-07
6.59534E-07	7.26690E-07	8.14078E-07	9.25683E-07
1.05184E-06	1.19202E-06	1.34170E-06	1.49739E-06
1.64690E-06	1.78569E-06	1.94487E-06	2.13303E-06
2.34181E-06	2.56748E-06	2.80260E-06	3.08152E-06
8.00798E-06	6.53309E-05	5.15636E-04	2.26931E-03
2.19435E-02	2.40841E-02	2.68467E-02	3.13230E-02
3.42471E-02	4.22999E-02	5.22641E-02	2.06360E-01

Covariance matrixes were generated by means of the PADE-2 code and tested by COVEIG code.

Group cross sections and their uncertainties for the evaluated $^{56}Fe(n,x)^{54}Mn$ reaction excitation function 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 $^{56}Fe(n,x)^{54}Mn$ reaction in the neutron energy range from threshold to 60 MeV.

Neutron energy (MeV) from - to	Cross section (mb)	Uncer tainty (%)	Neutron energy (MeV) from - to	Cross section (mb)	Uncer-tainty (%)
1.214E+01 - 1.600E+01	4.911E-2	27.14	3.800E+01 - 3.900E+01	2.800E+2	7.33
1.600E+01 - 1.700E+01	3. 308E-1	25.69	3.900E+01 - 4.000E+01	2.646E+2	7.45
1.700E+01 - 1.800E+01	5.865E-1	23.76	4.000E+01 - 4.100E+01	2.484E+2	7.67
1.800E+01 - 1.900E+01	9.144E-1	21.90	4.100E+01 - 4.200E+01	2.322E+2	7.94
1.900E+01 - 2.000E+01	1.328E+0	20.96	4.200E+01 - 4.300E+01	2.167E+2	8.22
2.000E+01 - 2.100E+01	1.905E+0	16.87	4.300E+01 - 4.400E+01	2.021E+2	8.46
2.100E+01 - 2.200E+01	2.896E+0	14.88	4.400E+01 - 4.500E+01	1.886E+2	8.66
2.200E+01 - 2.300E+01	5.057E+0	14.80	4.500E+01 - 4.600E+01	1.762E+2	8.82
2.300E+01 - 2.400E+01	1.007E+1	13.41	4.600E+01 - 4.700E+01	1.650E+2	8.96
2.400E+01 - 2.500E+01	2.207E+1	13.48	4.700E+01 - 4.800E+01	1.548E+2	9.09
2.500E+01 - 2.600E+01	4.743E+1	12.69	4.800E+01 - 4.900E+01	1.455E+2	9.24
2.600E+01 - 2.700E+01	8.751E+1	11.64	4.900E+01 - 5.000E+01	1.371E+2	9.43
2.700E+01 - 2.800E+01	1.340E+2	10.40	5.000E+01 - 5.100E+01	1.296E+2	9.67
2.800E+01 - 2.900E+01	1.772E+2	9.26	5.100E+01 - 5.200E+01	1.227E+2	9.97
2.900E+01 - 3.000E+01	2.137E+2	8.72	5.200E+01 - 5.300E+01	1.165E+2	10.36
3.000E+01 - 3.100E+01	2.439E+2	8.31	5.300E+01 - 5.400E+01	1.108E+2	10.82
3.100E+01 - 3.200E+01	2.691E+2	7.82	5.400E+01 - 5.500E+01	1.056E+2	11.36
3.200E+01 - 3.300E+01	2.889E+2	7.47	5.500E+01 - 5.600E+01	1.009E+2	11.96
3.300E+01 - 3.400E+01	3.025E+2	7.37	5.600E+01 - 5.700E+01	9.661E+1	12.63
3.400E+01 - 3.500E+01	3.093E+2	7.42	5.700E+01 - 5.800E+01	9.265E+1	13.36
3.500E+01 - 3.600E+01	3.096E+2	7.44	5.800E+01 - 5.900E+01	8.901E+1	14.13
3.600E+01 - 3.700E+01	3.039E+2	7.38	5.900E+01 - 6.000E+07	8.727E+1	14.94
3.700E+01 - 3.800E+01	2.936E+2	7.32			

Uncertainties in the evaluated the $^{56}Fe(n,x)^{54}Mn$ excitation function range from 7.32% to 27.14%. The smallest uncertainties in the evaluated cross sections 7.32 - 7.47 % are observed in the neutron energy interval 32.0 - 40.0 MeV. Uncertainties in the $^{56}Fe(n,x)^{54}Mn$ reaction cross sections exceeding 20% are observed in the energies range below 20 MeV.

The evaluated excitation function for the $^{56}Fe(n,x)^{54}Mn$ reaction in the neutron energy range 12.14 - 60 MeV is shown in Fig. 4.1 in comparison with the equivalent data from EAF-2010, TENDL-2014, TENDL-2015 libraries and corrected experimental data. The same information but in the narrow neutron energy range 12.14 - 22 MeV is shown in Fig. 4.2.

New evaluation of the $^{56}Fe(n,x)^{54}Mn$ reaction excitation function in the energy range 12.14 - 60 MeV based on microscopic experimental cross section data [4.1], [4.4], [4.5] and as the result is agree well with these data. EAF-2010 evaluation is agreed satisfactory with microscopic experimental data up to 40 MeV (see Figs 4.1-4.2). It is evident also from Figs 4.1-4.2 that TENDL-2014 and TENDL-2015 libraries give the $^{56}Fe\ (n,x)^{54}Mn$ cross section significantly lower than microscopic experimental data up to 40 MeV.

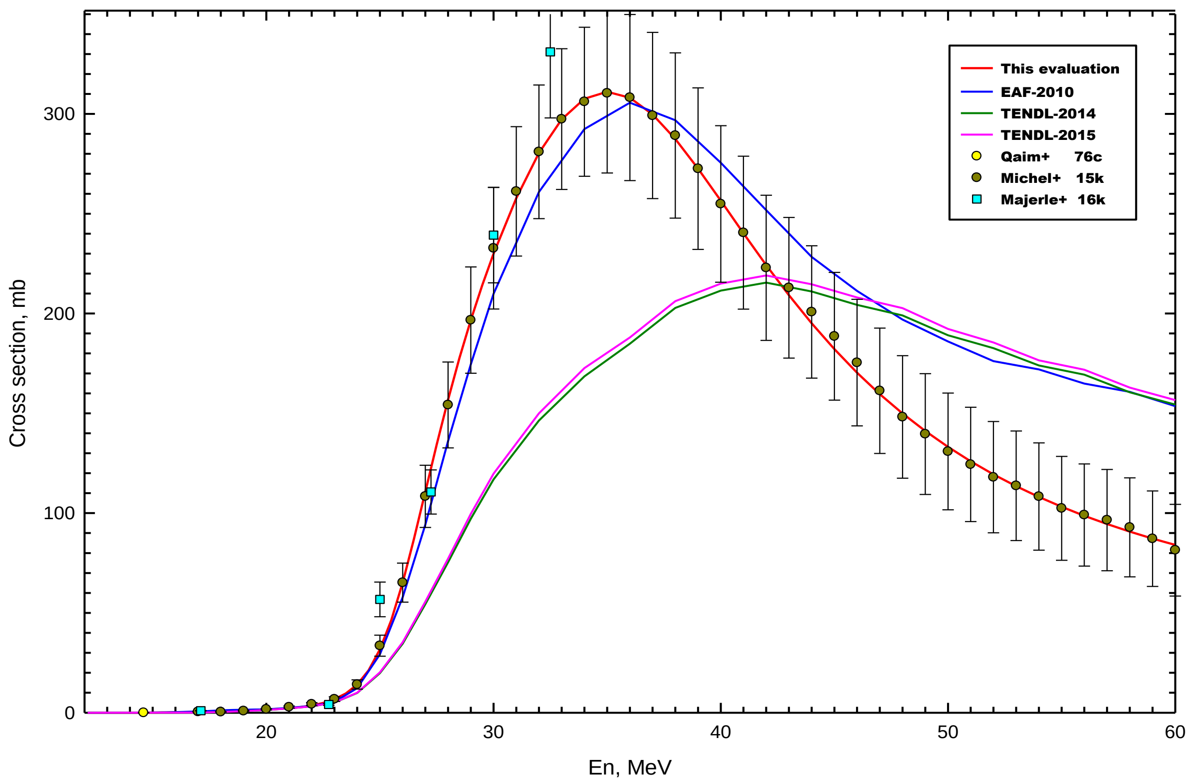

Fig. 4.1 Evaluated $^{56}Fe(n,x)^{54}Mn$ reaction excitation function in the energy range 12.14 - 60 MeV in comparison with equivalent data from EAF-2010, TENDL-2014, TENDL-2015 libraries and corrected experimental data.

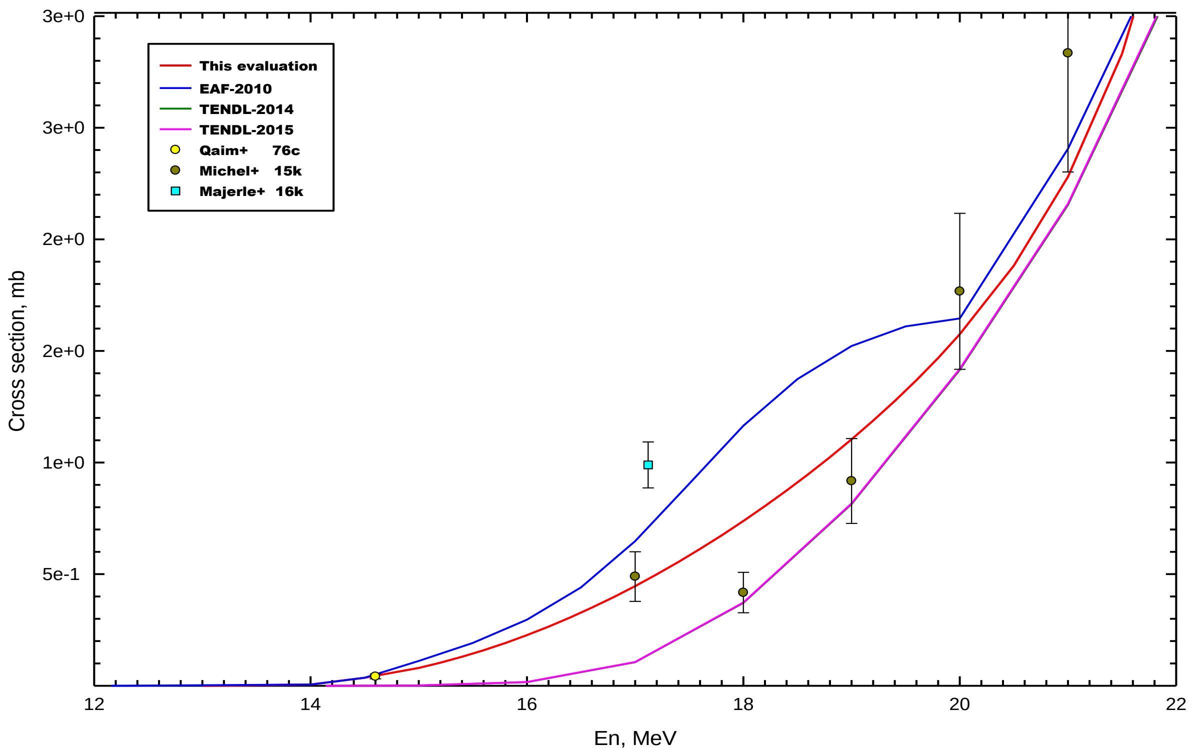

Fig. 4.2 Evaluated $^{56}Fe(n,x)^{54}Mn$ reaction excitation function in the energy range 12.14 – 22 MeV in comparison with equivalent data from EAF-2010, TENDL-2014, TENDL-2015 libraries and corrected experimental data.

The evaluated $^{56}Fe(n,x)^{54}Mn$ reaction excitation function averaged over the ^{235}U thermal fission neutron spectrum, ^{252}Cf spontaneous fission neutron spectrum and Be(d,n) neutron spectrum [4.2-4.3] gives the following integral cross-section values:

Table 4.2. Calculated and measured averaged cross sections for the $^{56}Fe(n,x)^{56}Mn$ reaction in three neutron spectra.

Type of neutron field	Averaged cross section, mb		90% response function, MeV	*C/E*
	Calculated	Measured		
^{235}U thermal fission neutron spectrum	1.1489E-5 [A] 1.5075E-5 [B] 4.2793E-6 [C] 4.3064E-6 [D]	absent	14.5 - 25.1 14.5 - 23.9 16.3 - 25.8 16.3 - 25.8	
^{252}Cf spontaneous fission neutron spectrum	4.3195E-5 [A] 5.3625E-5 [B] 1.9554E-5 [C] 1.9708E-5 [D]	absent	14.8 - 27.3 14.7 - 26.6 16.7 - 27.4 16.7 - 27.4	
Be(d,n) neutron spectrum [4.2]	74.662 [A] 70.483 [B] 43.329 [C] 44.237 [D]	39.120 ± 0.029 [4.2]	25.6 - 40.7 25.6 - 41.1 25.3 - 41.7 25.3 - 41.7	1.90854 1.80171 1.10759 1.13080
Be(d,n) neutron spectrum [4.3]	65.852 [A] 63.206 [B] 40.229 [C] 41.057 [D]	39.120 ± 0.029 [4.2]	25.8 - 43.1 25.8 - 44.0 25.6 - 45.3 25.6 - 45.3	1.68333 1.61570 1.02835 1.04951

[A] - Present evaluation,
[B] – EAF-2010
[C] – TENDL-2014
[D] – TENDL-2015

Integral experimental data for $^{56}Fe(n,x)^{54}Mn$ reaction in ^{235}U thermal fission and ^{252}Cf spontaneous fission neutron spectra are absent currently.

The 90% response function shows the neutron energy range where the investigated excitation function is tested in the benchmark spectrum. Value of C/E given in the last column is the ratio of the calculated to experimental cross sections.

Two versions of neutron spectrum generated in the bombardment 53- MeV deuterons a 1 cm thick Be target (see Fig. 4.3) was used to calculate averaged cross sections for the $^{56}Fe(n,x)^{56}Mn$ reaction. Cross section data for $^{56}Fe(n,x)^{56}Mn$ reaction were taken from present evaluation, EAF-2010, TENDL-2014 and TENDL-2015 libraries.

Averaged cross section calculated from present evaluation for spectrum [4.2] is in 1.90854 times higher than experimental value (39.120 ± 0.029) mb [4.2]. Averaged cross section calculated from EAF-2010 evaluation for this spectrum is 1.80171 times higher than experimental value.
TENDL-2014 and TENDL-2015 libraries give the ^{56}Fe $(n,x)^{54}Mn$ cross section significantly lower than microscopic experimental data up to 40 MeV. Never the less averaged cross section calculated from TENDL-2014 and TENDL-2015 evaluations agree better with experimental value of Qaim and Woelfle [4.2].

Averaged cross section calculated for spectrum [4.3] from present evaluation, EAF-2010, TENDL-2014 and TENDL-2015 evaluations gives C/E values equal to 1.68333, 1.61570, 1.02835 and 1.04951, respectively.

Results of calculations show that data presented in the work [4.2] can't be used for testing of ^{56}Fe (n,x)^{54}Mn reaction excitation function because they significantly contradict microscopic experimental cross section data [4.1], [4.4], [4.5]. Results of calculations carried out with spectra [4.2] and [4.3] propose that the main problem is in the determination of neutron spectrum generated in the bombardment of 53- MeV deuterons a 1 cm thick Be target.

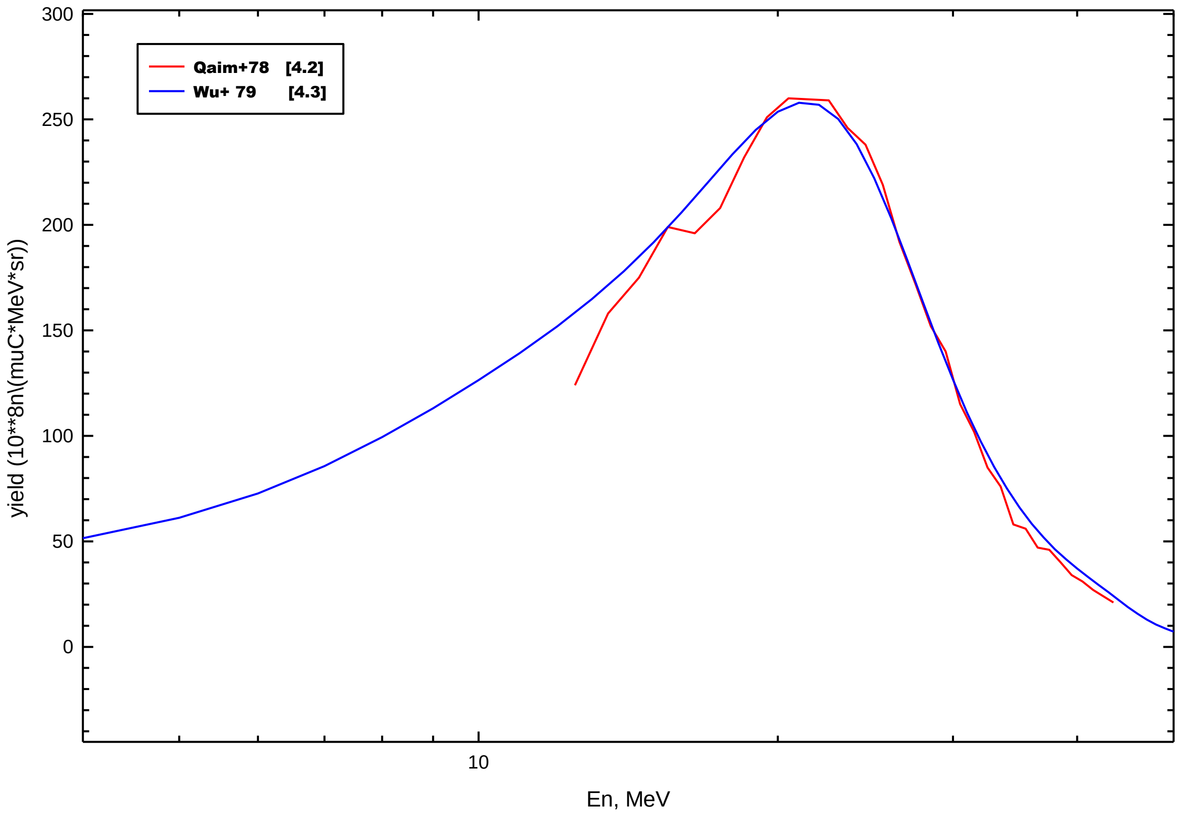

Fig. 4.3 Neutron spectrum generated in the bombardment 53-MeV deuterons a 1 cm thick Be target given in the works [4.2] and [4.3].

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5. EVALUATION OF THE $^{57}Fe(n,x)^{56}Mn$ REACTION EXCITATION FUNCTION

In the process of neutrons interaction with ^{57}Fe 3 reactions lead to production of the ^{56}Mn. These are $^{57}Fe(n,d)^{56}Mn$, $^{57}Fe(n,n+p)^{56}Mn$ and $^{57}Fe(n, p+n)^{56}Mn$. Threshold of the first reaction is equal to E_{th}=8.482397 (0.000214) MeV. Threshold of the rest of the reactions is equal to E_{th}=10.746384 (0.000214) MeV.

Microscopic experimental data for the $^{57}Fe(n,x)^{56}Mn$ reaction excitation function is given in the works [5.1-5.5] and covers neutron energies range from 13.35 MeV to 20.261 MeV.

Additional experimental information about the $^{57}Fe(n,x)^{56}Mn$ reaction excitation function is given in the work [5.6]. In this work Vrzalova et al. measured $^{nat}Fe(n,x)^{56}Mn$ reaction cross sections at 30.4 and 35.9 MeV. In the process of extraction the $^{57}Fe(n,x)^{56}Mn$ reaction cross section at 30.4 MeV and 35.9 MeV abundances of ^{56}Fe and ^{57}Fe isotopes in natural iron were taken equal to: ^{56}Fe - 91.754 (36), ^{57}Fe - 2.119 (10). The $^{56}Fe(n,p)^{56}Mn$ reaction cross section at 30.4 MeV and 35.9 MeV was taken equal 25.2 mb and 19.0 mb, respectively. Using these parameters $^{57}Fe(n,x)^{56}Mn$ reaction cross section at 30.4 MeV was obtained equal to 104.95 (15.55) mb. Obtained $^{57}Fe(n,x)^{56}Mn$ reaction cross section at 35.9 MeV is negative.

At the first step of analysis, microscopic experimental data [5.1-5.4] were corrected to the new standards. Recommended decay data for ^{56}Mn were taken from Ref. [2.40].

Cross section that had been determined in Ref. [5.1] was rejected due to inconsistency with the representative experimental data by Ikeda et al. [5.2].

Excitation function for the $^{57}Fe(n,x)^{56}Mn$ reaction in the energy region from threshold to 60 MeV was evaluated by means of statistical analysis of experimental cross section data [5.2], [5.3], [5.4], [5.5] and original data from EAF-2010 and TENDL-2014 data files. Cross section data from EAF-2010 were taken for neutron energies below 12 MeV. Data from TENDL-2014 library were used in the evaluation of $^{57}Fe(n,x)^{56}Mn$ reaction excitation function in the energy range from 18 to 60 MeV.

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

Uncertainties in the evaluated excitation function for the $^{57}Fe(n,x)^{56}Mn$ reaction are given in the form of relative covariance matrix for the 25-neutron energy groups (LB=5). Eigenvalues of the 6-th digits relative covariance matrix given in the 33-file is the following:

```
3.54106E-07     4.03022E-07     4.97615E-07     5.71339E-07
6.59332E-07     7.76799E-07     8.73647E-07     1.05401E-06
1.15532E-06     1.37425E-06     1.53682E-06     1.62925E-06
2.26722E-06     3.60551E-06     6.47818E-06     1.40292E-05
4.08486E-05     1.89243E-04     6.36423E-03     1.26892E-02
1.50909E-02     2.74594E-02     3.91197E-02     6.68996E-02
2.26164E-01
```

Covariance matrix of uncertainties was calculated simultaneously with recommended cross section data by means of PADE-2 code and tested by COVEIG code.

Group cross sections and their uncertainties for the evaluated $^{57}Fe(n,x)^{56}Mn$ reaction excitation function are listed in Table 5.1. Group boundaries are the same as in File-33.

Table 5.1. Evaluated cross sections and their uncertainties for the $^{57}Fe(n,x)^{56}Mn$ reaction in the neutron energy range from threshold to 60 MeV.

Neutron energy (MeV) from - to	Cross section (mb)	Uncer tainty (%)	Neutron energy (MeV) from - to	Cross section (mb)	Uncer- tainty (%)
8.482E+00 - 1.300E+01	1.828E-1	46.55	1.900E+01 - 1.950E+01	9.283E+1	6.79
1.300E+01 - 1.350E+01	2. 729E+0	17.25	1.950E+01 - 2.000E+01	1.008E+2	6.74
1.350E+01 - 1.400E+01	5.777E+0	11.95	2.000E+01 - 2.250E+01	1.179E+2	6.57
1.400E+01 - 1.450E+01	1.039E+1	8.80	2.250E+01 - 2.500E+01	1.282E+2	7.27
1.450E+01 - 1.500E+01	1.638E+1	6.96	2.500E+01 - 2.750E+01	1.219E+2	8.14
1.500E+01 - 1.550E+01	2.338E+1	6.45	2.750E+01 - 3.000E+01	1.107E+2	8.53
1.550E+01 - 1.600E+01	3.110E+1	6.61	3.000E+01 - 3.500E+01	9.551E+1	8.58
1.600E+01 - 1.650E+01	3.933E+1	6.81	3.500E+01 - 4.000E+01	8.074E+1	8.67
1.650E+01 - 1.700E+01	4.798E+1	6.89	4.000E+01 - 4.500E+01	7.109E+1	8.95
1.700E+01 - 1.750E+01	5.693E+1	6.89	4.500E+01 - 5.000E+01	6.454E+1	9.34
1.750E+01 - 1.800E+01	6.608E+1	6.87	5.000E+01 - 5.500E+01	5.988E+1	9.74
1.800E+01 - 1.850E+01	7. 525E+1	6.85	5.500E+01 - 6.000E+07	5.642E+1	10.13
1.850E+01 - 1.900E+01	8.425E+1	6.83			

Uncertainties in the evaluated the $^{57}Fe(n,x)^{56}Mn$ excitation function range from 6.45% to 46.55%. The smallest uncertainties in the evaluated cross sections 6.45- 6.96% are observed in the neutron energy ranges 14.5 - 22.5 MeV. The highest uuncertainty in the $^{57}Fe(n,x)^{56}Mn$ reaction cross sections is observed near threshold and exceeds 46.55%.

The evaluated excitation function for the $^{57}Fe(n,x)^{56}Mn$ reaction in the neutron energy range 12 - 60 MeV is shown in Fig. 5.1 in comparison with the equivalent data from EAF-2010, TENDL-2014, TENDL-2015 libraries and corrected experimental data. The same information but in the narrow neutron energy range 12 - 21 MeV is shown in Fig. 5.2.

The evaluated $^{57}Fe(n,x)^{56}Mn$ reaction excitation function averaged over the ^{235}U thermal fission neutron spectrum and ^{252}Cf spontaneous fission neutron spectrum gives the following integral cross section values:

Table 5.2. Calculated averaged cross sections of the 57Fe(n,x)56Mn reaction in 235U thermal fission and 252Cf spontaneous fission neutron spectra.

Type of neutron field	Calculated integral cross section, mb	90%-Response range, MeV
^{235}U thermal fission neutron spectrum	1.9108E-03	12.8 – 19.3
^{252}Cf spontaneous fission neutron spectrum	5.3059E-03	13.1 – 20.1

Integral experimental data for $^{57}Fe(n,x)^{56}Mn$ reaction in ^{235}U thermal fission and ^{252}Cf spontaneous fission neutron spectra are absent currently.

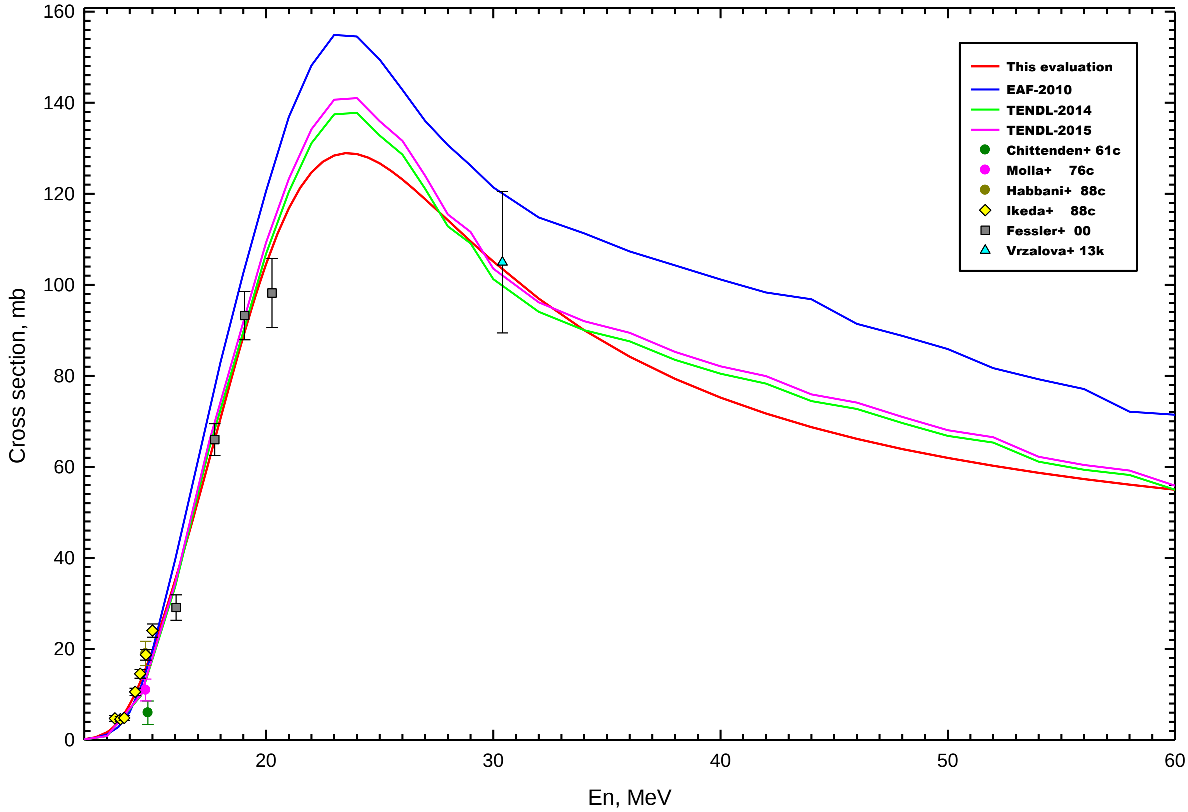

Fig. 5.1 Evaluated $^{57}Fe(n,x)^{54}Mn$ reaction excitation function in the energy range 12 - 60 MeV in comparison with equivalent data from EAF-2010, TENDL-2014, TENDL-2015 libraries and corrected experimental data.

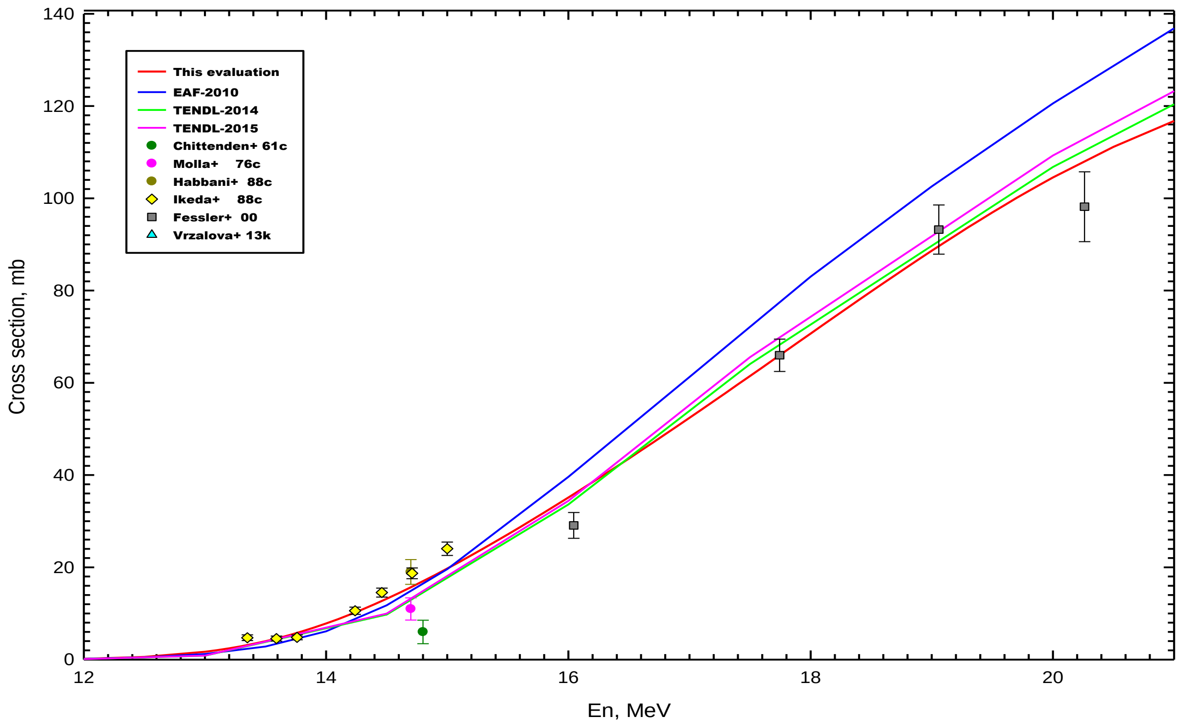

Fig. 5.2 Evaluated $^{57}Fe(n,x)^{54}Mn$ reaction excitation function in the energy range 12 – 21 MeV in comparison with equivalent data from EAF-2010, TENDL-2014, TENDL-2015 libraries and corrected experimental data.

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6. EVALUATION OF THE $^{68}Zn(n,x)^{67}Cu$ REACTION EXCITATION FUNCTION

Process of neutrons interaction with ^{68}Zn three reactions lead to production of the ^{67}Cu. These are ^{68}Zn (n,d)^{67}Cu, ^{68}Zn (n,n+p)^{67}Cu and ^{68}Zn (n, p+n)^{67}Cu. Threshold of the first reaction is equal to E_{th}=7.867126 (0.000850) MeV. Threshold of the rest reactions is equal to E_{th}=10.124734 (0.000863) MeV.

The radioactive nuclide ^{67}Cu obtained via $^{68}Zn(n,d)^{67}Cu$, $^{68}Zn(n,n+p)^{67}Cu$ and $^{68}Zn(n,p+n)^{67}Cu$ reactions undergoes 100% via β^- decay with a half-life of (61.83 ± 0.12) hours. The 184.58-keV gamma radiation (I_γ = 0.487 ± 0.003) is normally used to determine the $^{68}Zn(n,x)^{67}Zn$ reaction rate. Recommended decay data for the half-life and gamma ray emission probabilities per decay of ^{67}Cu were taken from Ref. [6.8].

Microscopic experimental data for the $^{68}Zn(n,x)^{67}Cu$ reaction excitation function is given in the works [6.1] and [6.2] and covered neutron energies range from 13.42 MeV to 14.97 MeV.

The most representative are data given by Konno et al. in Ref. [6.2]. Using T(d,n)He^4 neutron source at FNS facility at JAERI, Japan. By using activation method authors measured the $^{68}Zn(n,x)^{67}Cu$ reaction excitation function in the neutron energy interval from 13.42 - 14.97 MeV. Cross sections were measured by using Zn samples prepared from high enriched ^{68}Zn isotope ZnO powder. Content of ^{67}Zn and ^{68}Zn isotopes in the samples was equal to 0.10 and 99.36 atom percents, respectively. Activity of irradiated samples was measured with using HP Ge detector. Neutron flux was measured by $^{93}Nb(n,2n)^{92m}Nb$ monitor reaction.

Additional experimental information about the $^{68}Zn(n,x)^{67}Cu$ reaction excitation function is given in the works [6.3-6.7]. Authors of this works measured the sum of cross sections of reactions $^{67}Zn(n,p)^{67}Cu$ and $^{68}Zn(n,x)^{67}Cu$ in the neutron energies range 12.82 – 18.20 MeV by using natural zinc samples. The results of these measurements are given as values

SIG67(En)+(A68/A67)*SIG68(En), where

SIG67(En) and SIG68(En) - cross sections of $^{67}Zn(n,p)^{67}Cu$ and $^{68}Zn(n,x)^{67}Cu$ reactions, and A67 and A68 - abundance of ^{67}Zn and ^{68}Zn isotopes in natural zinc.

As the first step of analysis, microscopic experimental data [6.1-6.7] were corrected to the new standards.

As the second step of analysis, experimental data given in works [6.3-6.7] were corrected to include the contribution from the $^{67}Zn(n,p)^{67}Cu$ reaction. Cross sections for $^{67}Zn(n,p)^{67}Cu$ reaction were taken from evaluation [6.9]. The isotopic abundances of ^{67}Zn and ^{68}Zn in the natural Zn were taken equal to (4.10 ± 0.13)% and (18.75 ± 0.51)%, respectively.

After applying corrections experimental data of Viennot et al. [6.5] were renormalized to the integrals of cross section calculated from the representative measurements by Konno et al. [6.2] in the overlapping energies interval. Experimental data [6.5] were multiplied to the factor Fc= 0.448596.

Cross sections that had been determined in Refs. [6.1] and [6.3-6.4] were rejected due to inconsistency with the representative experimental data by Konno et al. [6.2]. For these reasons also experimental data of Ghorai et al. obtained at 14.2 and 15.2 MeV [6.7] were rejected.

Excitation function for the $^{68}Zn(n,x)^{67}Cu$ reaction in the energy region from threshold to 60 MeV was evaluated by means of statistical analysis of experimental cross section data [6.2], [6.5], [6.6], [6.7] and corrected data from EAF-2010 and TENDL-2015 data files. Cross section data from EAF-2010 were taken for neutron energies below 13 MeV. Data from TENDL-2015 library were renormalized at 18 MeV to a cross section value of 34.01 mb, evaluated from the experimental data. Corrected cross section data from TENDL-2015 library were used in the evaluation of $^{68}Zn(n,x)^{67}Cu$ reaction excitation function in the energy range from 18 to 60 MeV. Statistical analysis of input cross section data was carried out by means of PADE-2 code. Rational function was used as the model function.

Uncertainties in the evaluated excitation function for the $^{68}Zn(n,x)^{67}Cu$ reaction are given in the form of relative covariance matrix for the 25-neutron energy groups (LB=5). Eigenvalues of the 6-th digits relative covariance matrix given in the 33-file is the following:

```
2.44277E-06     3.16962E-06     4.37191E-06     5.31332E-06
6.64377E-06     7.70915E-06     8.79955E-06     9.39600E-06
9.71294E-06     1.11405E-05     1.72295E-05     2.80450E-05
4.73620E-05     8.25863E-05     1.48497E-04     2.75794E-04
5.31546E-04     1.07188E-03     2.29129E-03     5.30838E-03
1.15349E-01     1.84411E-01     2.89130E-01     3.71231E-01
4.39034E-01
```

Covariance matrix of uncertainties was calculated simultaneously with recommended cross section data by means of PADE-2 code and tested by COVEIG code.

Group cross sections and their uncertainties for the evaluated $^{57}Fe(n,x)^{56}Mn$ reaction excitation function are listed in Table 5.1. Group boundaries are the same as in File-33

Group cross sections and their uncertainties for the evaluated $^{68}Zn(n,x)^{67}Cu$ reaction excitation function are listed in Table 4.1. Group boundaries are the same as in File-33

Table 6.1. Evaluated cross sections and their uncertainties for the $^{68}Zn(n,x)^{67}Cu$ reaction in the neutron energy range from threshold to 60 MeV.

Neutron energy (MeV) from - to	Cross section (mb)	Uncer tainty (%)	Neutron energy (MeV) from - to	Cross section (mb)	Uncer-tainty (%)
7.867E+00 - 1.300E+01	1.288E-1	50.99	1.900E+01 - 1.950E+01	4.705E+1	23.87
1.300E+01 - 1.350E+01	1.697E+0	17.34	1.950E+01 - 2.000E+01	5.231E+1	24.57
1.350E+01 - 1.400E+01	3.191E+0	16.04	2.000E+01 - 2.250E+01	6.744E+1	23.28
1.400E+01 - 1.450E+01	5.471E+0	15.40	2.250E+01 - 2.500E+01	8.813E+1	21.37
1.450E+01 - 1.500E+01	7.998E+0	15.17	2.500E+01 - 2.750E+01	9.446E+1	22.14
1.500E+01 - 1.550E+01	1.052E+1	15.25	2.750E+01 - 3.000E+01	8.384E+1	22.38
1.550E+01 - 1.600E+01	1.358E+1	15.64	3.000E+01 - 3.500E+01	6.456E+1	21.46
1.600E+01 - 1.650E+01	1.732E+1	16.34	3.500E+01 - 4.000E+01	5.251E+1	20.43
1.650E+01 - 1.700E+01	2.162E+1	17.34	4.000E+01 - 4.500E+01	4.785E+1	21.16
1.700E+01 - 1.750E+01	2.633E+1	18.58	4.500E+01 - 5.000E+01	4.432E+1	24.61
1.750E+01 - 1.800E+01	3.133E+1	19.99	5.000E+01 - 5.500E+01	4.078E+1	31.03
1.800E+01 - 1.850E+01	3.651E+1	21.44	5.500E+01 - 6.000E+07	3.731E+1	40.48
1.850E+01 - 1.900E+01	4.177E+1	22.79			

Uncertainties in the evaluated the $^{68}Zn(n,x)^{67}Cu$ excitation function range from 15.17% to 50.99%. The smallest uncertainties in the evaluated cross sections 15.17-15.64% are observed in the neutron energy ranges 14.0 - 16.0 MeV. The highest uncertainties in the $^{68}Zn(n,x)^{67}Cu$ reaction cross sections exceeding 30% are observed near threshold and in the energy range 50 - 60 MeV.

Evaluated excitation function of the $^{68}Zn(n,x)^{67}Cu$ reaction in the neutron energy range from 10 to 60 MeV is shown in Fig. 6.1 in comparison with the equivalent data from EAF-2010, TENDL-2014, TENDL-2015 libraries and corrected experimental data. The same information but in the narrow neutron energy range 10 - 20 MeV is shown in Fig. 6.2.

Calculated from evaluated $^{68}Zn(n,x)^{67}Cu$ reaction excitation function averaged cross sections in ^{235}U thermal fission neutron spectrum and ^{252}Cf spontaneous fission neutron spectrum gives the following values:

Table 6.2. Calculated averaged cross sections of the 68Zn(n,x)67Cu reaction in 235U thermal fission and 252Cf spontaneous fission neutron spectra.

Type of neutron field	Calculated integral cross section, mb	90%-Response range, MeV
^{235}U thermal fission neutron spectrum	9.8239E-04	12.5 – 19.4
^{252}Cf spontaneous fission neutron spectrum	2.6851E-03	12.7 – 20.4

Integral experimental data for $^{68}Zn(n,x)^{67}Cu$ reaction in ^{235}U thermal fission and ^{252}Cf spontaneous fission neutron spectra are currently absent.

The 90% response function shows the neutron energy range where the investigated excitation function is tested in the benchmark spectrum.

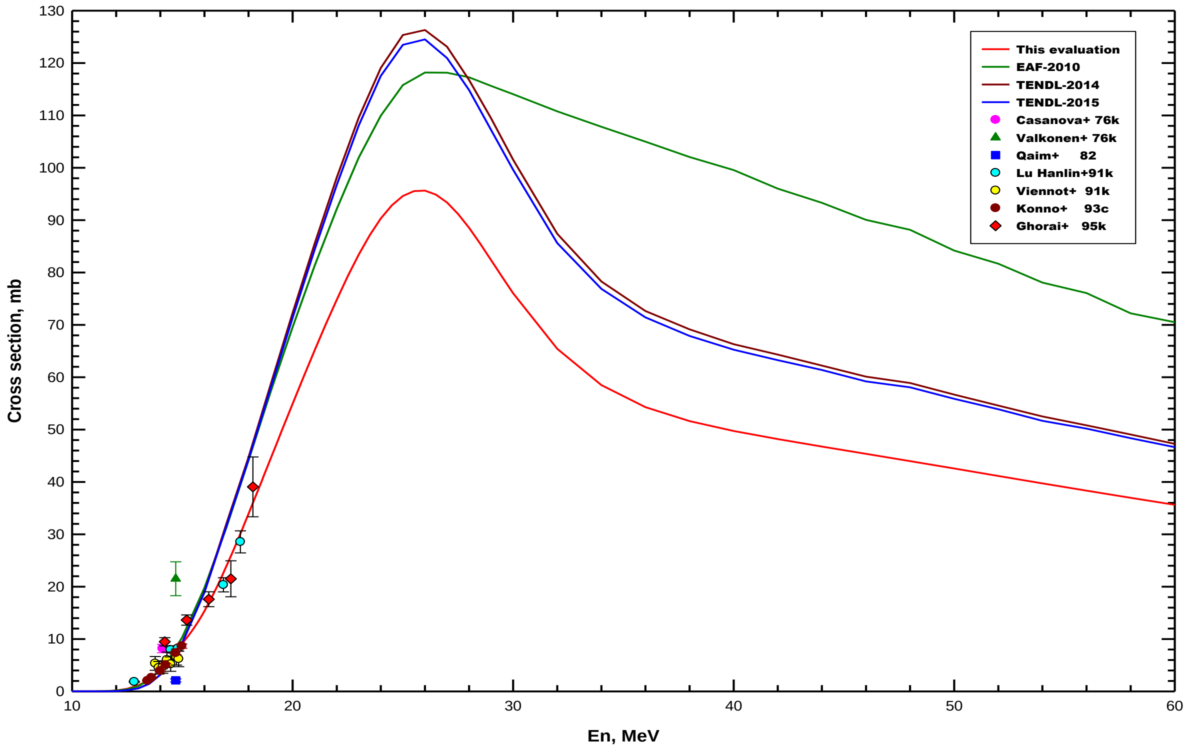

Fig. 6.1 Evaluated $^{68}Zn(n,x)^{67}Cu$ reaction excitation function in the energy range 10 - 60 MeV in comparison with equivalent data from EAF-2010, TENDL-2014, TENDL-2015 libraries and corrected experimental data.

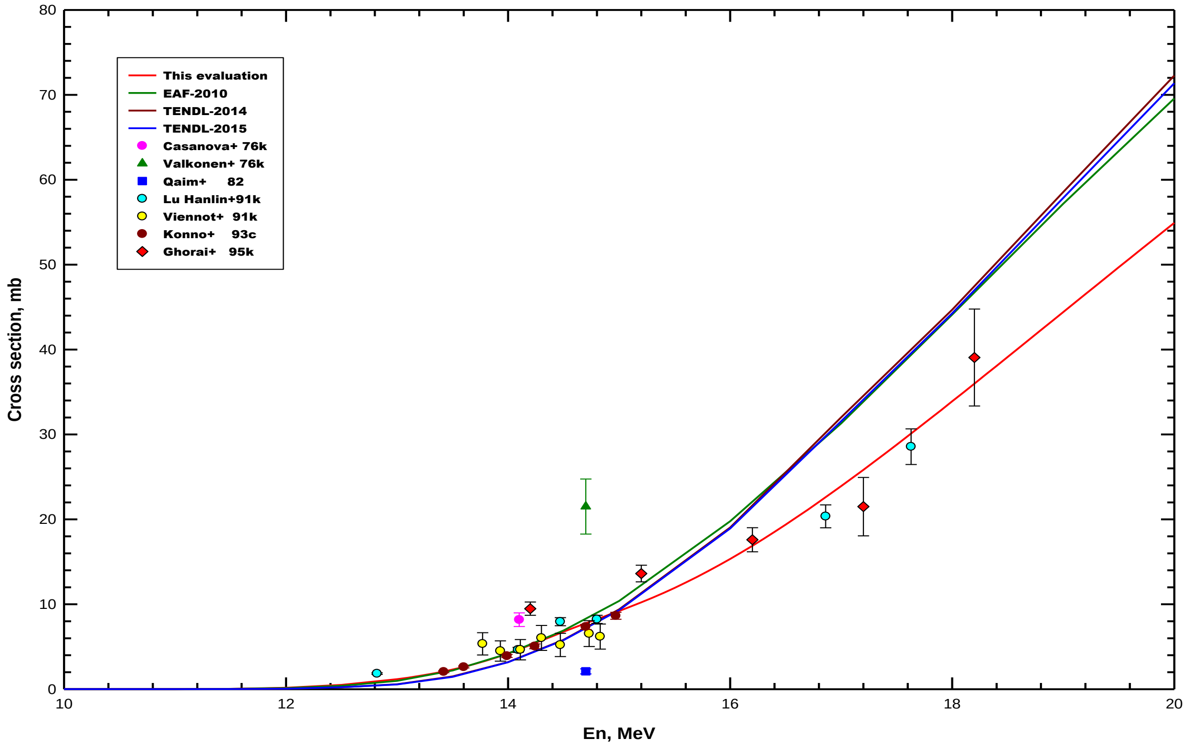

Fig. 6.2 Evaluated $^{68}Zn(n,x)^{67}Cu$ reaction excitation function in the energy range 10 – 20 MeV in comparison with equivalent data from EAF-2010, TENDL-2014, TENDL-2015 libraries and corrected experimental data.

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6. CONCLUSION

New evaluation of cross sections and their uncertainties has been carried out for four reactions: $^{50}Cr(n,\gamma)^{51}Cr$, $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$ and $^{68}Zn(n,x)^{67}Cu$. The $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$ and $^{68}Zn(n,x)^{67}Cu$ reaction excitation functions were evaluated in the energy range from threshold to 60 MeV. Cross section of the $^{50}Cr(n,\gamma)^{51}Cr$ reaction was evaluated in a wide energy region 1.000E-05 eV - 20 MeV. Uncertainty in the $^{50}Cr(n,\gamma)^{51}Cr$ reaction excitation function is given in ?? energy intervals.

Descriprion of the re-evaluation of $^{50}Cr(n,\gamma)^{51}Cr$ reaction excitation function cross section in the energy range 1.0000E-05 eV – 783 keV is given via the Reich-Moore (RM) resonance parameters. The obtained resonance parameters permit calculating the $^{50}Cr(n,tot)$, $^{50}Cr(n,el)$ and $^{50}Cr(n,\gamma)^{51}Cr$ excitation functions in the neutron energy range 1.000E-05 eV – 783 keV without any additional data (background).

Excitation function of the $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$ and $^{68}Zn(n,x)^{67}Cu$ reactions were firstly evaluated for dosimetry application.
It is recommended to include the re-evaluated $^{50}Cr(n,\gamma)^{51}Cr$ excitation function and evaluated the $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$ and $^{68}Zn(n,x)^{67}Cu$ reaction excitation functions into the new version of IRDFF library.
Measurements of integral cross sections of the $^{56}Fe(n,x)^{54}Mn$, $^{57}Fe(n,x)^{56}Mn$ and $^{68}Zn(n,x)^{67}Cu$ reactions for the ^{35}U thermal fission and ^{252}Cf spontaneous fission neutron spectra will also be useful for testing the evaluated excitation functions.

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