International Atomic Energy Agency

INDC(CCP)-414
Distr. J+HE

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

Development and Testing of Helium Production Data Base for Main Structural Materials

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September 1998

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

Printed by the IAEA in Austria
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Abstract

The report describes the evaluation of helium production cross sections for reactions induced by neutrons with energy in the range up to 20 MeV on nuclei of stable isotopes, Mn, Co and Cu. The covariance matrix of the uncertainty of cross section was also evaluated for each reaction. The computerized evaluated data files in ENDF-6 format are being prepared.

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DEVELOPMENT AND TESTING OF HELIUM PRODUCTION DATA BASE FOR MAIN STRUCTURAL MATERIALS

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Progress Report on Research Contract No 8716/RB/R1

Obninsk
1997

1. Introduction

Structural materials in fission and fusion reactors are designed to withstand great radiation doses during long period of time.

Radiation damage (high temperature embrittlement, swelling and so on) in structural materials caused by irradiation are mainly due to the helium production as a result of the following reactions: (n,α), (n,nα), (n,pα), (n,2α), (n,He3), (n,nHe3) and so on.

For reliable prediction of helium production and behavior of structural materials under irradiation by a great radiation dose during long period of time and it is necessary to have reliable evaluated excitation functions for the all reactions producing helium in order to calculate total helium production cross sections. The uncertainty of calculation of helium production rate depends significantly on the accuracy of nuclear data used.

The analysis of helium production excitation functions from the existing data libraries ADL−3 [1], BROND−2 [2], CENDL−2 [3], JENDL−3.2 [4], JEF−2 [5], EAF−2 [6], ENDF/B−VI [7] shows that there are large discrepancies among the data of different libraries even for such important structural materials as Ti, Cr, Fe and Ni.

As far as the libraries above mentioned were developed as of activation and general purpose libraries, there are no data in its for total helium production cross sections.

The first specialized gas production library, containing the data on total helium production cross sections for 18 elements and isotopes was developed in 1985 on the base of partial reaction cross sections of ENDF/B−V. In 1991 the gas production cross section library was formed on the base of JENDL−3.1 library. This library contains the data for 23 elements and its isotopes [8].

However, the both libraries are based on the data files of general purpose and does not take into account some peculiarities of the problem of interest. Besides these evaluated data files are produced many years ago, obsolete to some extent and does not contain the data for the following additions and some admixtures in structural materials: P, S, Zn, Sn, Gd, Ta, W, Pb and Bi.

That is why new evaluated excitation functions are needed for the all helium producing reactions with taking into account the recent experimental data, theoretical calculations and systematics of reaction cross sections.

The starter file of HElium PRoduction neutron cross section data Library (HEPRL−96) was created under IAEA Research Contract No. 8716/RB in 1996. The evaluations of helium production cross section data were prepared for Mg, Ti,Cr,Fe,Ni, and its stable isotopes. For the first time prepared evaluations were supplemented by covariance matrixes which were constructed on the basis of analysis of available theoretical and experimental information. In the framework of renewed RC No.8716/R1 the starter file HEPRL−96 was expanded to include new evaluations for V, Mn, Co, Cu structural materials and its stable isotopes again together with covariance matrixes. The text below describes method of evaluation and shows comparison results of new evaluations (HEPRL−97) with ENDF/B−VI data and available experimental data.

2. Method of evaluation of the helium producing reaction cross section.

In the process of creation of the helium producing reaction cross section library (HEPRL−97) the following information sources were used: available experimental data, results of theoretical model calculations, predictions of (n,α) cross section systematics at the maximum of the excitation functions, the data on energy dependence of (n,α) cross sections for target−nuclei with the same neutron excess (N−Z), where N and Z − the numbers of neutrons and protons, respectively. As it is noted earlier the isotopes of He−3 and He−4 under neutron irradiation are produced as a result of the following reactions: (n,He3), (n,n'He3), (n,α), (n,n'α) and so on. On the light mass nuclei in addition to these reactions the helium can be produced in other reactions. For example, the helium is produced on the ^{9}Be in the ^{9}Be(n,2n) reaction. In this reaction the yield of α−particles at the neutron energy above 3 MeV is significantly higher than in the ^{9}Be(n,α)^{6}He reaction. As far as ^{10}B is concerned the ^{10}B(n,t)2α (above 2 MeV) and ^{10}B(n,n'α)2α (above 10 MeV) reactions can essentially contribute to helium production.

For nuclei since Z≥8 and in the energy range up to 20 MeV the essential effect on helium production process can mainly occur only two reactions: (n,α) and (n,n'α).

At the present time there are experimental data for (n,α) reaction cross section in the energy region of 14−15 MeV practically for all the elements and isotopes which are components of structural materials used in nuclear and thermonuclear reactors.

For Mg−26, Si−30, Ti−48, Ti−50, Cr−54, Fe−56, Ni−58, Ni−62, Ni−64, Cu−65, Zn−68, As−75 and some others there are also experimental data in other energy regions. However, this information is too incomplete for reliable evaluation of (n,α) reaction excitation function in the whole energy region from the threshold up to 20 MeV.

The (n,α) reaction cross sections for B−10, Al−27, P−31, V−51, Mn−55, Fe−54, Co−59, Cu−63 are measured in many experiments in detail in the energy region up to 20 MeV.

There are scanty experimental measurements on the (n,n'α) reaction cross sections. Besides these measurements are made on small number of isotopes and the data obtained give an information about the excitation functions only in separate energy points. One should note, that the same situation with experimental data are observed in the case of (n,He3) and (n,n'He3) reactions.

Simultaneously with measurements of partial reaction cross sections the intensive experimental investigations were under way to determine the total helium production cross section. At the present time these types of measurements are made for the great number of elements and isotopes which are components of structural materials used in nuclear and thermonuclear reactors [1−9]. However only for four isotopes (^{56}Fe, ^{59}Co, ^{58}Ni and ^{60}Ni) the total helium production cross sections are measured in the whole neutron energy region. Sterbenz et al. were investigated in detail the energy dependence of ^{56}Fe(n,x)^{4}He reaction cross section in the neutron energy region from 1 MeV up to 30 MeV [8]. The data for ^{59}Co(n,x)He , ^{58}Ni(n,x)He , ^{60}Ni(n,x)He excitation functions, obtained by Haight et al., comprise the neutron energy region of 5−50 MeV [9].

In the process of preparation of the input data for evaluation of the helium producing reactions the all experimental data used for the evaluation were thoroughly analyzed. In those cases, where it was possible, the experimental data were corrected taking into account new recommended monitor cross sections and new recommended decay data for residual nuclei. The experimental data which contradict to the group of consistent measurements of cross sections and result of theoretical calculations did not included, as a rule, into the data base used for evaluation of excitation function.

The theoretical calculations of the neutron reactions leading to helium productions were made in the framework of statistical theory with using Hauser−Feschbach−Moldauer formalism and taking into account pre−equilibrium process contribution [10,11]. The calculations are made by STAPRE−0 code [12]. As input data the model parameters, scheme of discrete levels and binding energies were taken from the work [13]. The transmission coefficients for output channels and other parameters of optical models were calculated by SCAT−2 code [14].

In evaluation of the data for HEPRL−97 library the predictions of (n,α) reaction systematics were widely used. The detailed description of thise systematics is given in the work [15]. The present paper gives brief description only.

The analysis of the experimental data base allowed to reveal a number of trends in behaviour of the (n,α) reaction excitation functions:

1. The (n,α) reaction cross section at the maximum of the excitation functions for isotopes of the same element (Z=const) decreases exponentionally with the increase of mass number A. Within the uncertainties of the cross sections the dependence of $\ln\sigma^{max}_{n,\alpha}$ on A can be approximated by linear function.
2. For isotopes with the same neutron excess (N−Z) the values of the $\ln\sigma^{max}_{n,\alpha}$ increase practically linearly with increase of Z. One should note that in comparison with similar dependence for maximum (n,p) reaction cross section the maximum (n,α) cross sections are changed against A and (N−Z) more slow.
3. For elements with close values of Z the dependences of $\ln\sigma^{max}_{n,\alpha}$ as a function of A are practically parallel and equidistant. For isotopes with close values of (N−Z) the dependences of $\ln\sigma^{max}_{n,\alpha}$ as a function of (N−Z) are also practically parallel and equidistant.
4. The shapes of (n,α) reaction excitation functions for the isotopes with the same (N−Z) and close values of $(Q_{n,n\alpha} - Q_{n,\alpha})$ are similar. $Q_{n,n\alpha}$ and $Q_{n,\alpha}$ are reaction energies of (n,α) and (n,nα) reaction, respectively.

The predictions of the (n,α) systematics at the maximum of the excitation functions were used in those cases where the experimental data were absent or scanty and discrepant. The predictions of the systematics concerning the shape of (n,α) excitation functions were used in any case where there were reliable experimental data for one of reactions (we call it "reference") from the set of (n,α) reactions on isotopes with same (N−Z) and close values of $(Q_{n,n\alpha} - Q_{n,\alpha})$.

Input data base for an evaluation of the (n,n'α) reaction excitation function was formed on the base of theoretical calculations mainly. Experimental investigation of (n,n'α) reaction excitation function were carried out only for V−51 and Cu−65 isotopes. For testing calculations the data of Kneff et al. on the total helium production cross sections at the energy 14,8 MeV were mainly used. This does not allow to evaluate the (n,n'α) reaction excitation functions above 16−17 MeV with accuracy better than 20−30 %. By similar way the data base was formed for evaluation of (n,He3) excitation function. As far as the thresholds of this reactions are relatively high and the cross sections are negligebly small in comparison with the (n,α) and (n,n'α) reaction cross section the accuracy of these data was not taken into account.

Preparation the total helium production cross sections for vanadium, manganese, cobalt and copper was done on the basis of the evaluated partial excitation functions.The summing of partial cross sections was made by FIXUP code [16].

As a final procedure of evaluation of the helium producing reactions the statistical analysis of the created data base of reaction cross section was performed.

The calculations were made by PADE−2 code [17], where rational function was used as a model function [18]. These calculations allowed together with the excitation function evaluation to obtain covariance matrices of uncertainties as well.

Integral experimental data for V−51, Cu−63, Cu−65, Co−59 received on U−235 thermal fission and Cf−252 spontaneous fission neutron spectra were used for testing evaluated α−emission excitation functions for above mentioned isotopes. Calculations of spectra averaged cross sections were carried out with using ENDF/B−VI data [19] for U−235 thermal fission neutron spectrum and Mannhart data [20] for Cf−252 spontaneous fission neutron spectrum.

3. Evaluation of cross section data for VANADIUM

Natural vanadium consists of two stable isotopes V−50 and V−51 with abundances 0.25% and 99.75%, respectively.

Below 20 MeV the (n,α), (n,nα) and (n,He3) reactions produce helium from neutron interaction in vanadium. reactions. Energies and thresholds for above reactions in vanadium isotopes are given in Table 3.1 below.

Table 3.1

Energies and thresholds of (n,α), (n,nα) and (n,He3) reactions for vanadium isotopes

Isotope	(n,α)		(n,nα)		(n,He3)	
	Q, MeV	E_{th}, MeV	Q, MeV	E_{th}, MeV	Q, MeV	E_{th}, MeV
V−50	0.760		−9.880	10.078	−11.589	11.821
V−51	−2.06	2.10	−10.290	10.492	−12.499	12.744

Contribution to helium production from (n,α) and (n,nα) reactions in vanadium dominates for all kind of fission reactors and fusion designs. Contribution of (n,He3) reaction to the total production of helium is negligible due to high threshold and low cross sections. Because of low isotopic abundance in natural vanadium contribution of all helium production reactions in V−51 is also negligible.

Excitation function for the V−51(n,nα)Sc−47 reaction in the energy region from threshold to 20 MeV was evaluated by means of statistical analysis of experimental cross section data [1−3] and data from STAPRE calculation. All analised microscopic experimental data [1−7] were renormalized to the new recommended standards for monitor reactions cross sections and decay data. Experimental data of Bormann et al. [4], Bramlitt and Fink [5], Pepelnik et al. [6], Qaim [7] were rejected due to their big contradiction to the total alpha−emission cross section measured Kheff et al. [8] and data from theoretical model calculation

Excitation function for the V−51(n,He3)Sc−49 reaction in the energy region from threshold to 20 MeV was receaved from STAPRE calculation.

Excitation function for the V−51(n,α)Sc−48 reaction in the energy region from threshold to 20 MeV was evaluated by means of statistical analysis of experimental cross section data [1,6,9−29] and data from STAPRE calculation.

All analised microscopic experimental data [1,6,9−39] and integral experimental data [40−44] were renormalized to the new recommended standards for monitor reactions cross sections and decay data. Cross section data measured by Bormann et al.[9] were renormalized to the preliminary evaluated integral of excitation function in the energy range 13 − 15 MeV. Experimental cross section data from ref. [5] , [30−39] were rejected due to their big discrepancy with the main bulk of experimental data [1,6,9−39], data from theoretical model calculation and data from (n,a) cross section systematics.

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

Table 3.2

Calculated and measured average cross sections for reaction V51(n,α)Sc48 in the U−235 thermal fission neutron spectrum

Average cross section, mb			C/E	90% − Responce range, MeV
Library	calculated	measured		
HEPRL−97	0.024467	0.0235 ± 0.0015 [41] 0.0213 ± 0.0012 [42]	1.0152	7.40 − 13.80
ENDF/B−VI	0.024595	0.0241 ± 0.0009 [43]	1.0205	7.40 − 13.80

C/E values given in the table 3.2 were calculated with using experimental data [43].

Table 3.3

Calculated and measured average cross sections for reaction V51(n,α)Sc48 in the Cf−252 spontaneous fission neutron spectrum

Average cross section, mb			C/E	90% − Responce range, MeV
Library	calculated	measured		
HEPRL−97	0.03865	0.0388 ± 0.0012 [43]	0.9961	7.500 − 14.500
ENDF/B−VI	0.03872		0.9980	7.500 − 14.500

Excitation function for the V−51(n,pα)Ca−47 reaction in the energy region from threshold to 20 MeV was receaved from STAPRE calculation

Total helium−3 and helium−4 emission excitation function was determined by summing the cross section data for (n,n'α), (n,α), (n,He3), (n,pα) reactions., for a given element or isotope.

The covarience matrix of cross section uncertainties for V−51 were obtained simultaneously with excitation functions by means of PADE−2 code in the LB=5 representation.

Evaluated excitation functions for V−51(n,α)Sc−48, V−51(n,nα)Sc−47 and V−51(n,x)He reactions are given on the Fig.1−3, respectively. HEPRL−97

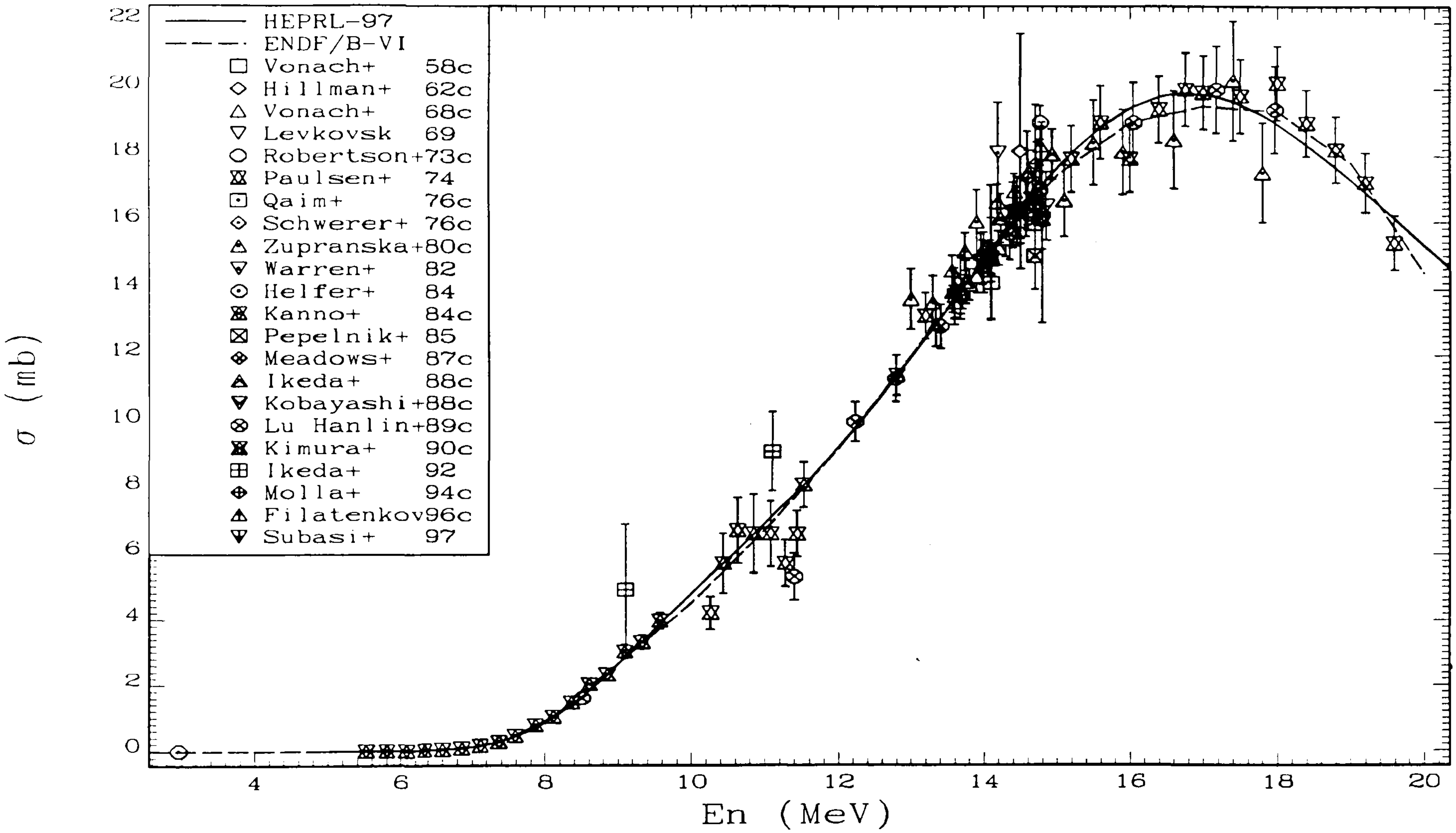

Fig.1. Evaluated excitation function for the reaction $^{51}V(n,\alpha)^{48}Sc$ in comparison with ENDF/B-6 and experimental data.

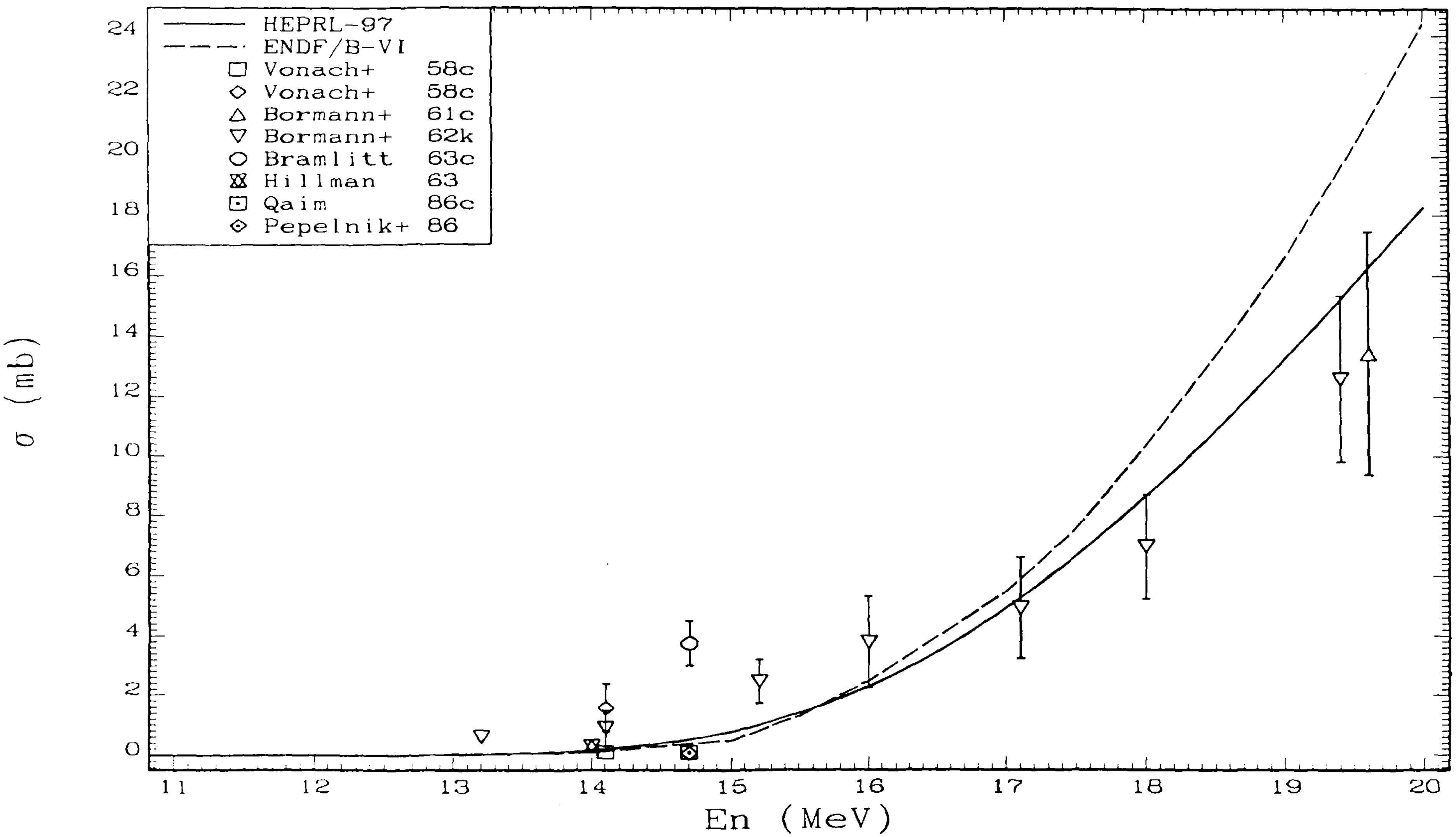

Fig.2. Evaluated excitation function for the reaction $^{51}V(n,n\alpha)^{47}Sc$ in comparison with ENDF/B-6 and experimental data.

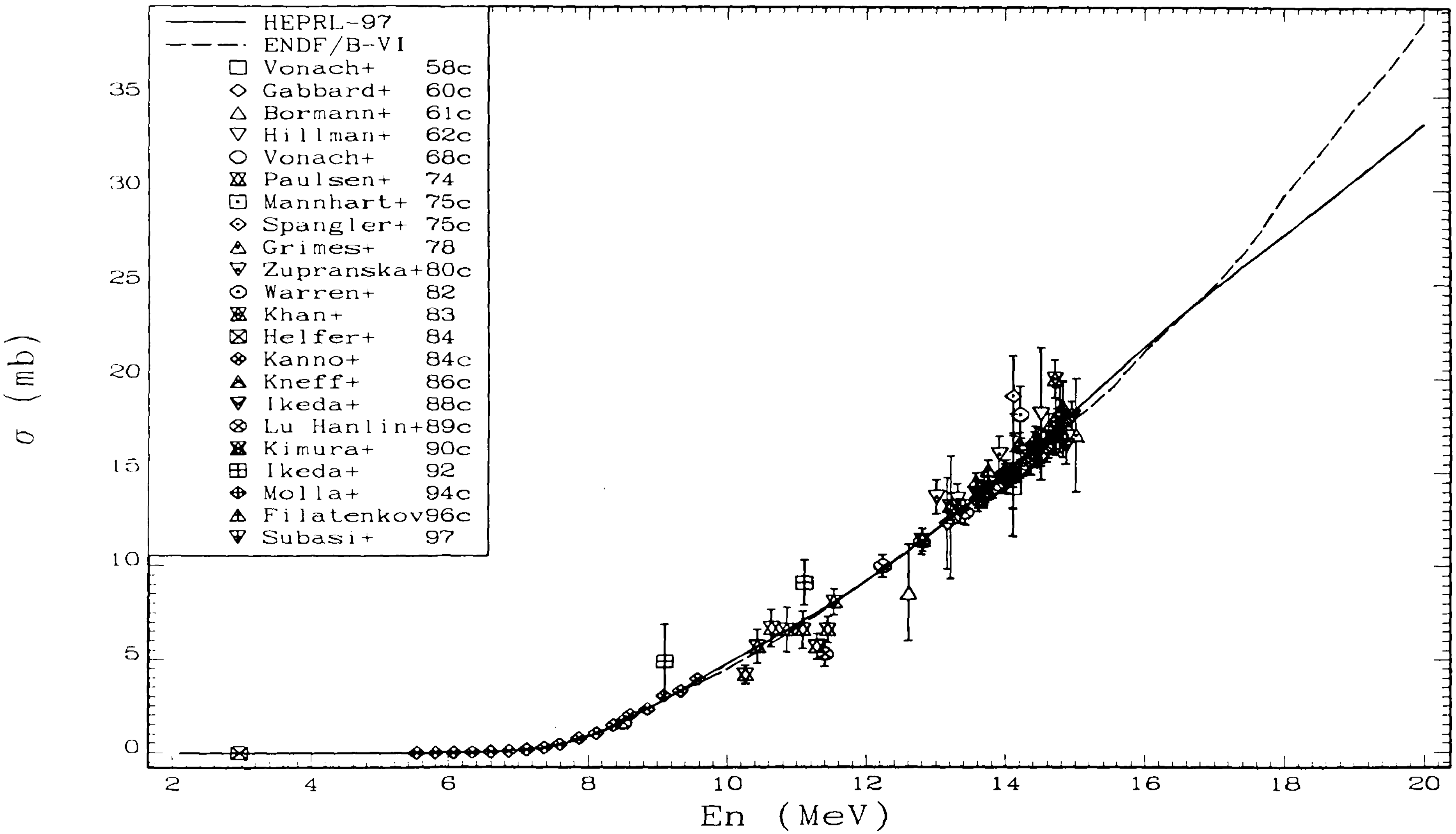

Fig.3. Evaluated excitation function for the reaction $^{51}V(n,x)He$ in comparison with ENDF/B-6 and experimental data.

data are compare with ENDF/B−VI evaluated data and available experimental data.

4. Evaluation of cross section data for MANGANESE

Natural manganese consists of one stable isotope Mn−55.

For neutrons with energies below 20 MeV the most significant ^{3}He and ^{4}He production channels in manganese are (n,α), (n,n'α) and (n,He3) reactions. Energies and thresholds for above reactions in Mn−55 are given in Table 4.1 below.

Table 4.1

Energies and thresholds of (n,α), (n,n'α) and (n,He3) reactions for manganese

Isotope	(n,α)		(n,n'α)		(n,He3)	
	Q, MeV	E_{th}, MeV	Q, MeV	E_{th}, MeV	Q, MeV	E_{th}, MeV
Mn−55	−0.624	0.636	−7.936	8.082	−12.707	12.940

Contribution to helium production from (n,α) and (n,n'α) reactions in manganese dominates for all kind of fission reactors and fusion designs. Contribution of (n,He3) reaction to the total production of helium is negligible due to high threshold and low cross sections.

Excitation function for the Mn−55(n,n'α)V−51 reaction in the energy region from threshold to 20 MeV was receaved from STAPRE calculation. Parameters for theoretical model calculation were selected with taking into account the total alpha−emission cross section measured by Kheff et al. [1].

Evaluation of excitation function for the Mn−55(n,He3)V−53 reaction in the energy range from threshold to 20 MeV is based on the data from STAPRE calculation and experimental data [2],[3]

Excitation function for the Mn−55(n,α)V−52 reaction in the energy region from threshold to 20 MeV was evaluated by means of statistical analysis of experimental cross section data [4−15], data from STAPRE calculation, data from (n,α) cross section systematics at the maximum of the excitation function and the data on energy dependens of (n,α) cross sections for target−nuclei with the same neutron excess.

All experimental data were renormalized to the new standards for monitor reactions cross sections and decay data.

Cross section data measured by Nix et al. [16], Gabbard and Kern [17], Strain and Ross [18], Frevert [2], Bahal and Pepelnik [19], Helfer et al. [20] were rejected due to their big discrepancy with the main bulk of experimental data [4−15], data from theoretical model calculation and data from (n,α) cross section systematics.

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

Total helium−3 and helium−4 emission excitation function was receaved from summing of cross section data for (n,n'a), (n,a), (n,He3) reactions. Evaluated excitation function in the energy range 14−15 Mev agree well with total helium production cross sections measured by Kheff et al. [1] and Fischer et al. [21].

The covarience matrix of cross section uncertainties were obtained simultaneously with excitation functions by means of PADE−2 code in the LB=5 representation.

Evaluated excitation functions for Mn−55(n,α)V−52, Mn−55(n,n'α)V−51 and Mn−55(n,x)He reactions are given on the Fig.4−6, respectively. HEPRL−97 data are compare with ENDF/B−VI evaluated data and available experimental data.

5. Evaluation of cross section data for COPPER

Natural copper consists of two stable isotopes Cu−63 and Cu−65 with abundances 69.2% and 30.8%, respectively.

Below 20 MeV the main channals of produsig helium in copper are (n,α), (n,n'α) and (n,He3) reactions. Energies and thresholds for above reactions in copper isotopes are given in Table 4.1 below.

Table 5.1

Energies and thresholds of (n,α), (n,n'α) and (n,He3) reactions for copper isotopes

Isotope	(n,α)		(n,n'α)		(n,He3)	
	Q, MeV	E_{th}, MeV	Q, MeV	E_{th}, MeV	Q, MeV	E_{th}, MeV
Cu−63	1.720		−5.480	5.872	−9.544	9.696
Cu−65	−0.180	0.183	−6.790	6.895	−12.284	12.473

Contribution to helium production from (n,α) and (n,n'α) reactions in copper dominates for all kind of fission reactors and fusion designs. Contribution of (n,He3) reaction to the total production of helium is negligible due to high threshold and low cross sections.

Excitation function for the Cu−63(n,n'α)Co−59 reaction in the energy region from threshold to 20 MeV was receaved from STAPRE calculation. Parameters for theoretical model calculation were selected with taking into account the total alpha−emission cross section measured by Kheff et al. [1].

Excitation function for the Cu−63(n,He3)Co−61 reaction in the energy region from threshold to 20 MeV was receaved from STAPRE calculation with taking into account experimental data [2].

Evaluation of Cu63(n,α)Co60m+g − excitation function was carried out by means of statistical analisis of cr oss sections from data base prepared in the energy range 2 − 20 Mev. In the energy range 3.56 − 19.55 MeV input data base was formed with using of experimental data from ref. [3−20]. Cross section data in the interval 2.0 − 3.5 MeV were taken from theoretical model calculation.

Experimental data included in the input data base were renormalized using new cross sections standards for monitor reactions.

The special correction was applied to the experimental data [4],[5],[14],[15]. Cross section data of A.Paulsen and H.Liskien [4−5] measured in the energy region 12.09 − 19.55 MeV with using T(d,n)He4 neutron source were multiplied to the factor 1.20805 . Experimental data of Lu Hanlin et al. [14] and Wang Yongchag et al. [15] were multiplied to the factors 0.88110 and 0.84377, respectively. The correction factors were derived from preliminary evaluated cross sections integral in the energy interval 13 − 15 MeV.

Data of A.Paulsen and H.Liskien [4] in the energy range 5.76 − 11.48 MeV measured with using D(d,n)He3 , Be9(α,n)C12 , C14(d,n)N15 , N15(d,n)O16 neutron sources were rejected due to their inconsistency with precision

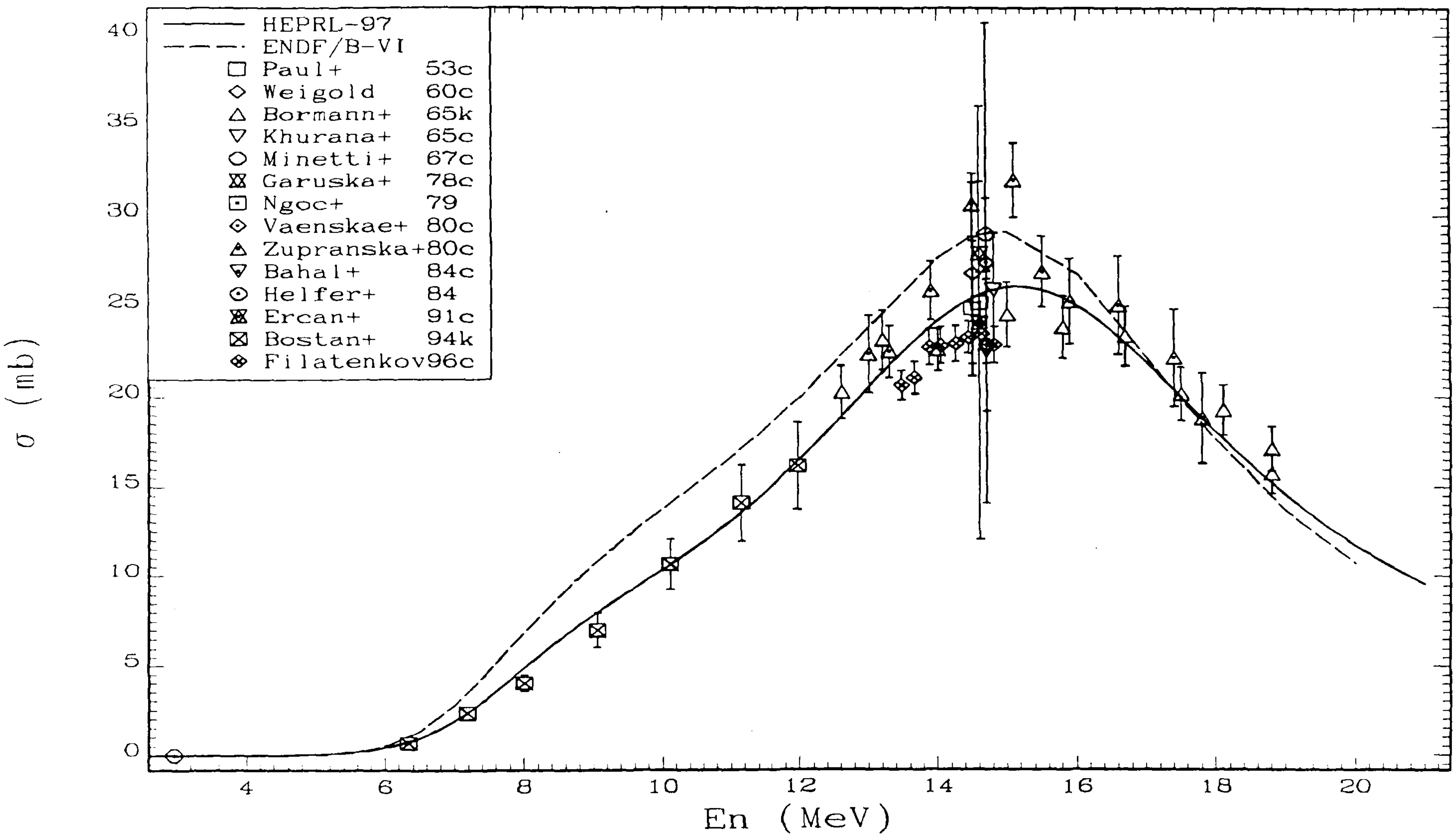

Fig.4. Evaluated excitation function for the reaction $^{55}Mn(n,\alpha)^{52}V$ in comparison with ENDF/B-6 and experimental data.

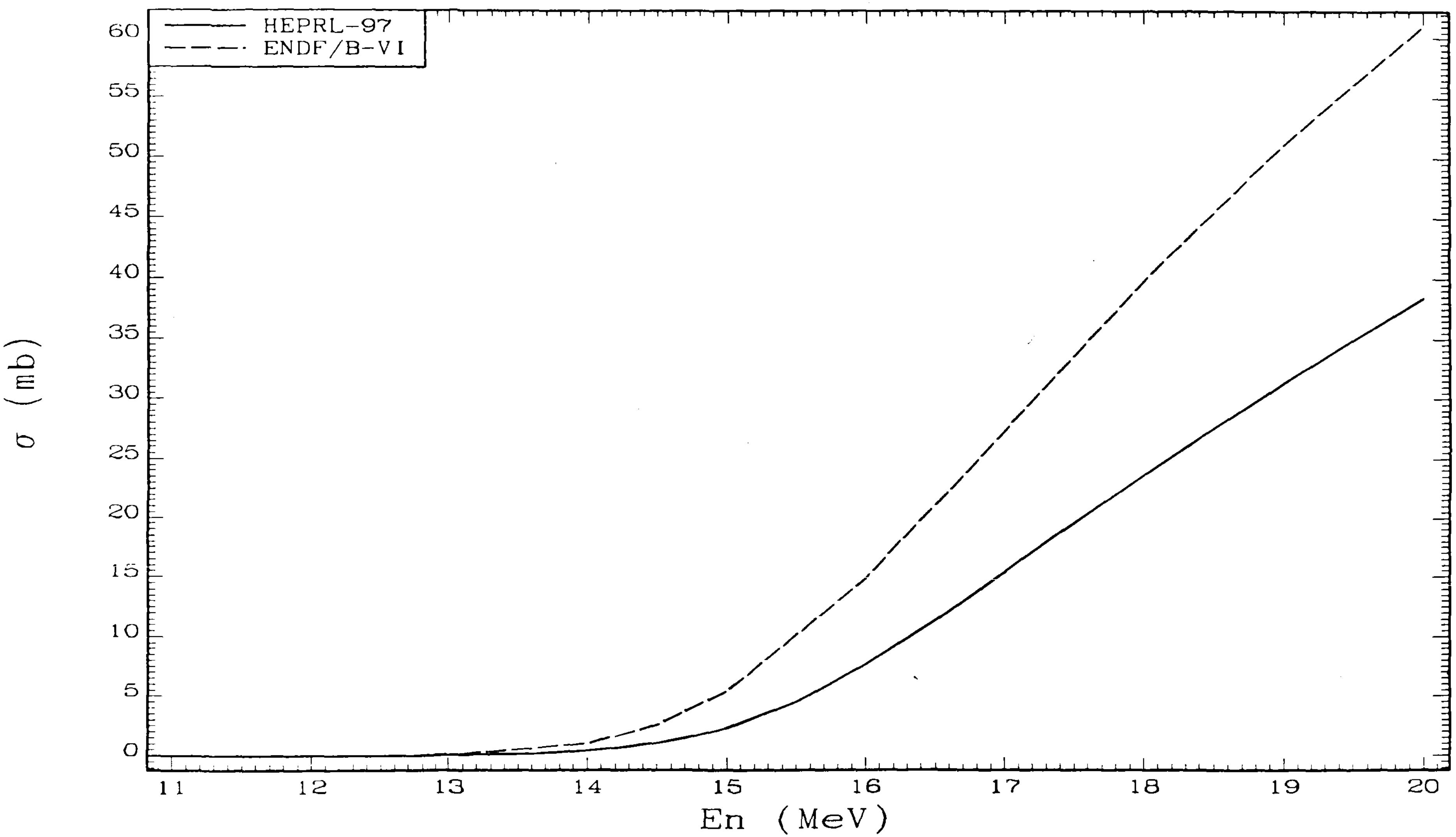

Fig.5. Evaluated excitation function for the reaction $^{55}Mn(n,n\alpha)^{51}V$ in comparison with ENDF/B-6.

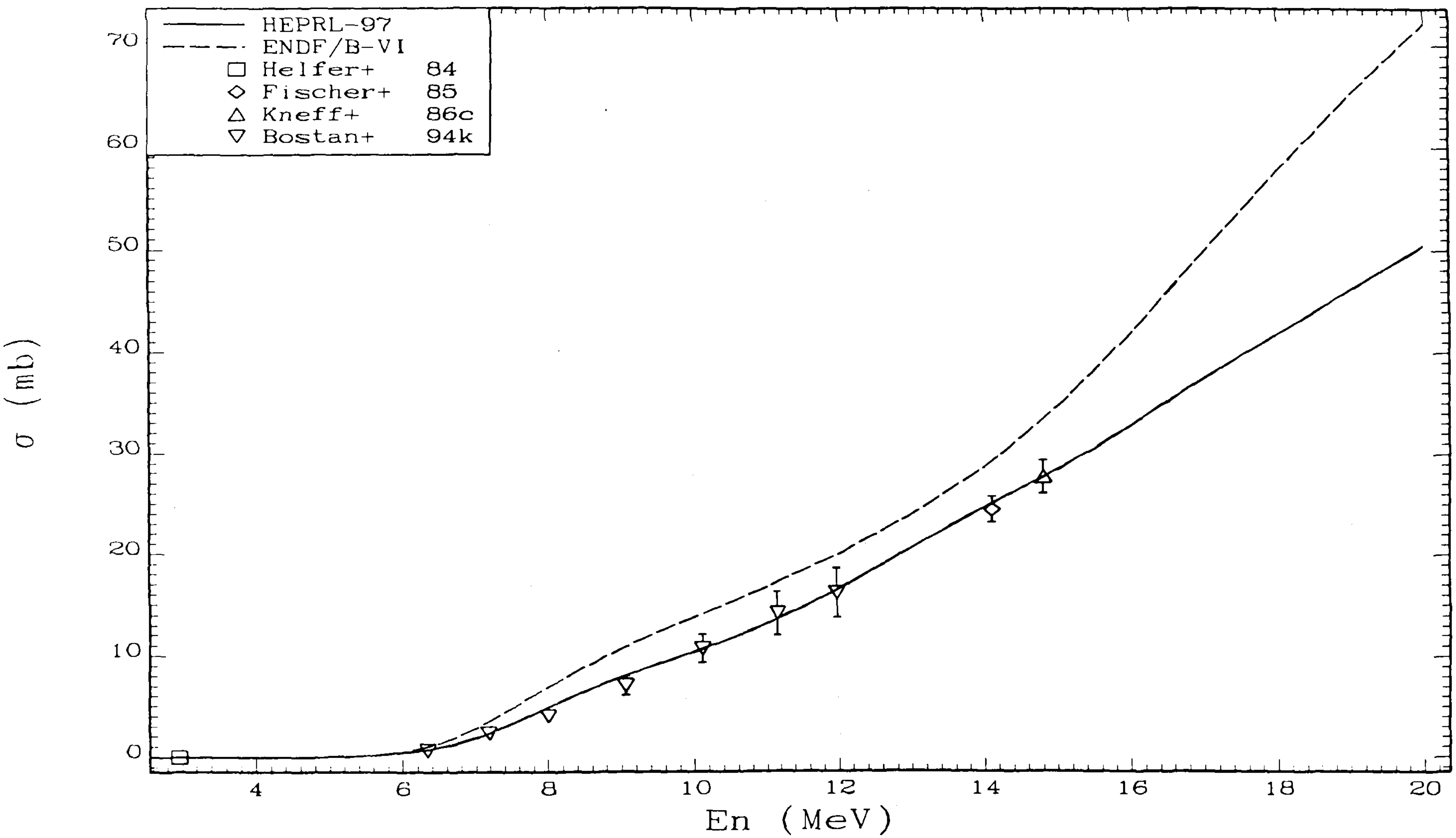

Fig.6. Evaluated excitation function for the reaction ^{55}Mn(n,x)He in comparison with ENDF/B-6 and experimental data.

easurements of G.Winkler et al. [10] and integral experimental data for U−235 fission neutron spectrum [21−26] and Cf−252 spontaneous fission neutron spectrum [27−28]. Cross sections measured by M.Bormann et al. [29] were also rejected due to the big discrepancy with the main bulk expimental data.

The final procedure evaluation of (n,α) excitation function was carried out by means of Pade−2 code.

Evaluated excitation function for the reaction Cu63(n,α)Co60m+g was tested with using integral experimental data [21−26] for U−235 thermal fission neutron spectrum and evaluated integral experimental data [31] for Cf−252 spontaeous fission neutron spectrum. Calculated and measured average cross section values for U−235 thermal fission neutron spectrum and Cf−252 spontaneous fission neutron spectrum are given in the table 5.2

Table 5.2

Calculated and measured average cross sections for reaction Cu63(n,α)Co60m+g in the U−235 thermal fission neutron spectrum

Average cross section, mb			C/E	90%−Responce range,
Library	calculated	measured		MeV
HEPRL−97	0.52280		0.9918	7.40 − 13.80
		0.5271 ± 0.0139 [*]		
ENDF/B−VI	0.52145		0.9893	7.40 − 13.80

*) average weighted cross section from experimental data [21−26]

Table 5.3

Calculated and measured average cross sections for reaction Cu63(n,α)Co60m+g in the Cf−252 spontaneous fission neutron spectrum

Average cross section, mb			C/E	90%−Responce range,
Library	calculated	measured		MeV
HEPRL−97	0.68029		0.98636	7.500 − 14.500
		0.6897 ± 0.0130 [30]		
ENDF/B−VI	0.67780		0.98275	7.500 − 14.500

From the cross sections averaged in the U−235 neutron thermal fission spectrum and Cf−252 spontaneous fission neutron spectrum one can see (see Tables 5.2 and 5.3) that the data obtained on the base of our evaluated Cu−63(n,α)Co−60 reaction excitation function are in better agreement with the measured average cross sections than ENDF/B−VI data.

Total helium−3 and helium−4 emission excitation function for Cu−63 was receaved from summing of cross section data for (n,n'a), (n,a), (n,He3) reactions. Evaluated excitation function in the energy range 14−15 Mev agree well with total helium production cross section measured by Kheff et al. [1].

The covarience matrix of cross section uncertainties for Cu−63 were obtained simultaneously with excitation functions by means of PADE−2 code in the LB=5 representation.

Evaluated excitation functions for Cu−63(n,α)Co−60m+g , Cu−63(n,n'α)Co−59 and Cu−63(n,x)He reactions are given on the Fig. 7 − 9, respectively. HEPRL−97 data are compare with ENDF/B−VI evaluated data and available experimental data.

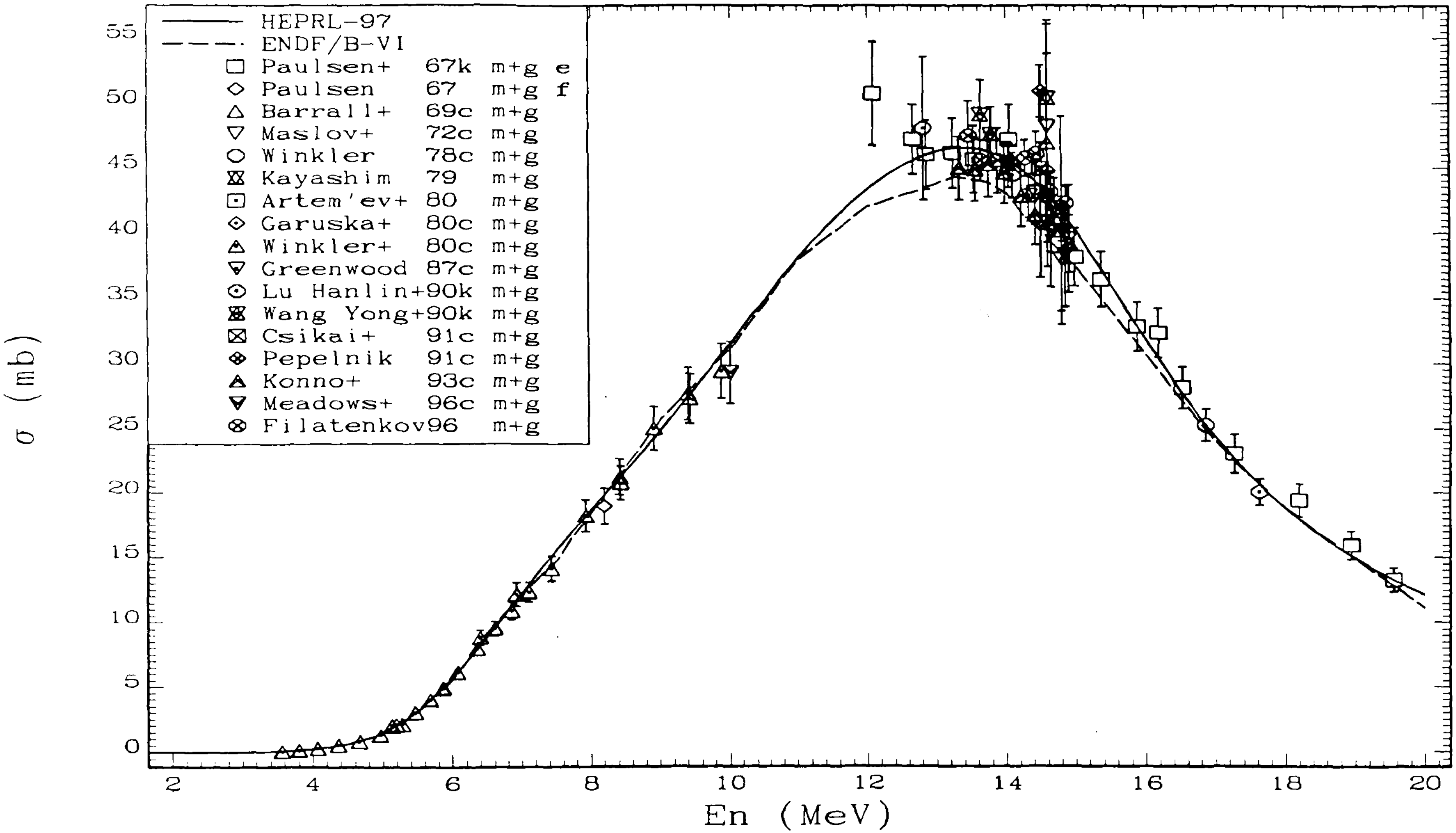

Fig.7. Evaluated excitation function for the reaction $^{63}Cu(n,\alpha)^{60m+g}Co$ in comparison with ENDF/B-6 and experimental data.

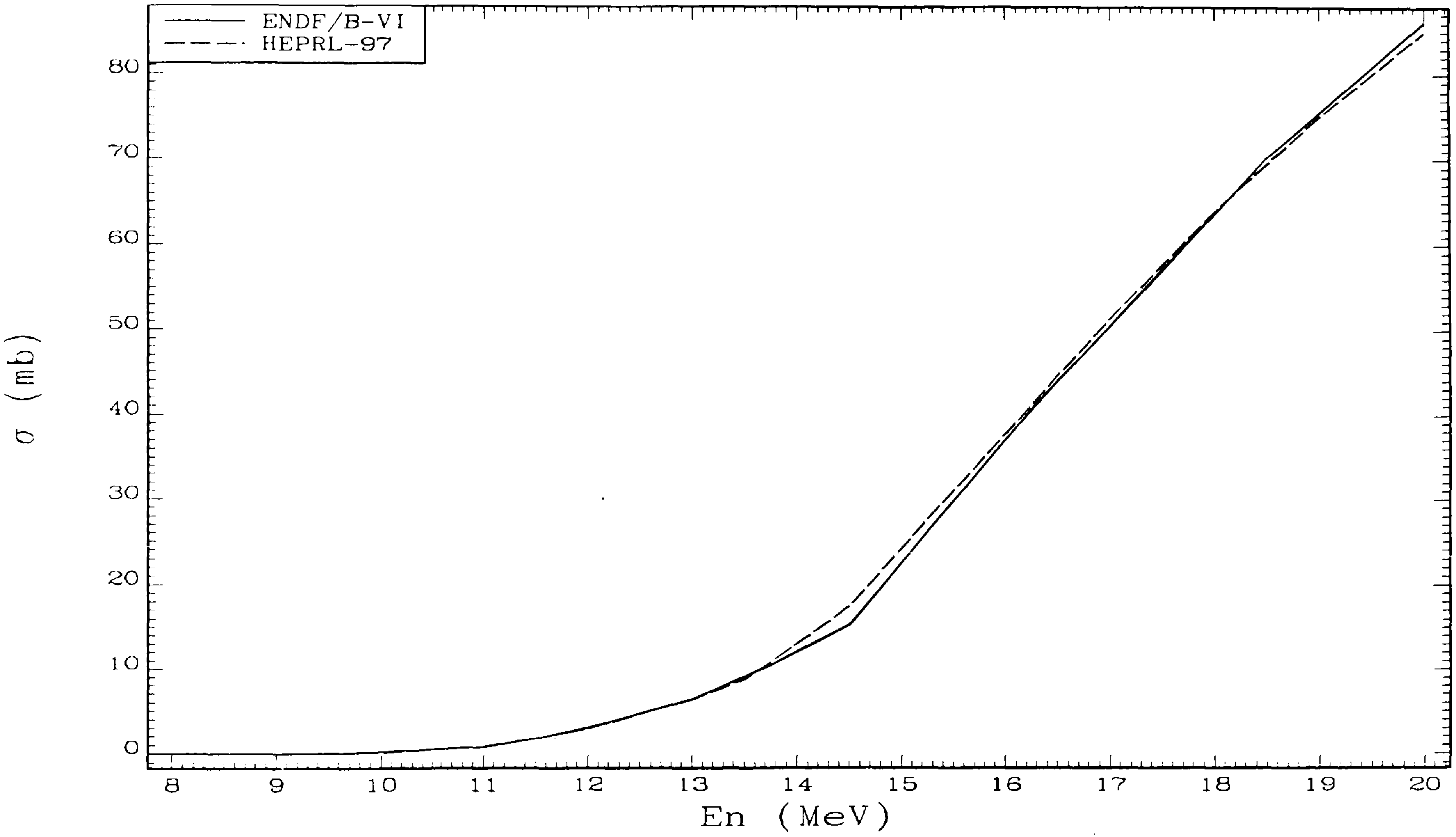

Fig.8. Evaluated excitation function for the reaction $^{63}Cu(n,n\alpha)^{59}Co$ in comparison with ENDF/B-6.

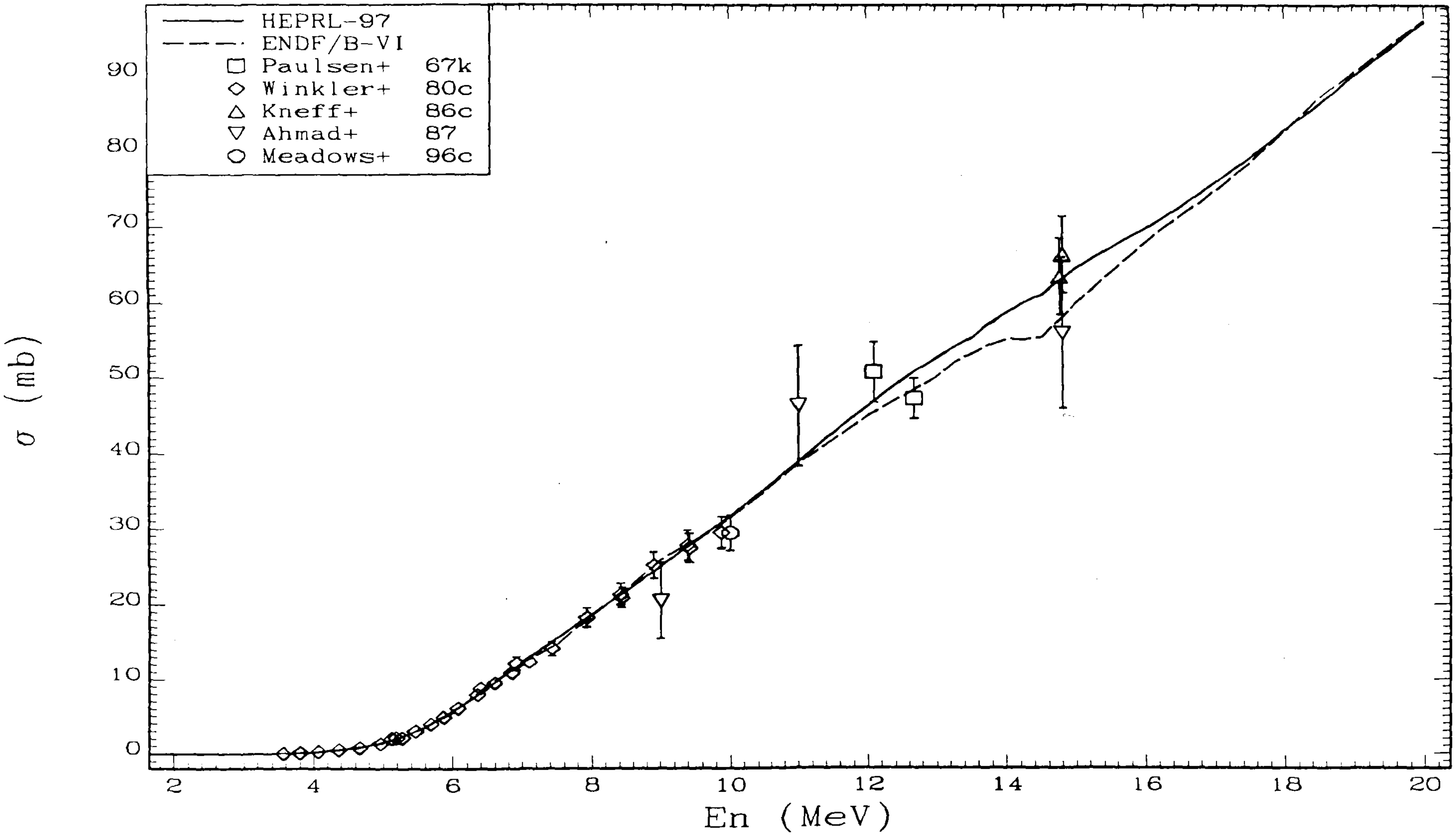

Fig.9. Evaluated excitation function for the reaction $^{63}Cu(n,x)He$ in comparison with ENDF/B-6 and experimental data.

Excitation function for the Cu−65(n,n'α)Co−61 reaction in the energy region from threshold to 20 MeV was evaluated by means of statistical analysis of experimental cross section data [1−6] and data from STAPRE calculation. Parameters for theoretical model calculation were selected with taking into account the total alpha−emission cross section measured by Kheff et al. [7].

All experimental data were renormalized to the new standards for monitor reactions cross sections and decay data. The special correction was applied to the experimental data of Santry and Butler [4]. Cross section data from ref. [4] measured in the energy range 13.58−19.80 MeV were multiplied to the factor 1.208. This correction was done to agree data of Santry and Butler with with integral experimental data of Niese [8].

Evaluated excitation function for the reaction Cu−65(n,na)Co−61 was tested with using integral experimental data [8] for U−235 thermal fission neutron spectrum. Calculated and measured average cross section values for U−235 thermal fission neutron spectrum are given in the table 5.4

Table 5.4

Calculated and measured average cross sections for reaction Cu−65(n,n'α)Co−59 in the U−235 thermal fission neutron spectrum

Average cross section, mb			C/E	90%−Responce range, MeV
Library	calculated	measured		
HEPRL−97	0.00040934	0.000438±0.000044 [8]	0.9918	13.00 − 18.90
ENDF/B−VI	0.00027707		0.9893	13.10 − 19.10

From the cross sections averaged in the U−235 neutron thermal fission spectrum one can see (see Table 5.4) that the data obtained on the base of our evaluated Cu−65(n,n'α)Co−61 reaction excitation function are in better agreement with the measured average cross section than ENDF/B−VI data.

Cross section data for the Cu−65(n,He3)Co−63 reaction were taken from ENDF/B−VI evaluation, MAT=2931

Excitation function for the Cu−65(n,α)Co−62 reaction in the energy region from threshold to 21 MeV was evaluated by mean of statistical analysis of experimental cross section data [9−15], data from STAPRE calculation, data from (n,α) cross section systematics at the maximum of the excitation function and the data on energy dependens of (n,α) cross sections for target−nuclei with the same neutron excess.

All experimental data for the Cu−65(n,α)Co−62 reaction were renormalized to the new standards for monitor reactions cross sections and decay data.

Cross section data measured by Preiss et al.[16], Clator [17] were rejected due to their big discrepancy with the main bulk of experimental data [9−15], data from theoretical model calculation and data from (n,α) cross section systematics.

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

Total helium−3 and helium−4 emission excitation function for Cu−65 was receaved from summing of cross section data for (n,n'α), (n,α), (n,He3) reactions. Evaluated excitation function in the energy range 14−15 Mev agree well with total helium production cross sections measured by Kheff et al. [7] and Wattecamps [13].

The covarience matrix of cross section uncertainties for Cu−65 were obtained simultaneously with excitation functions by means of PADE−2 code in the LB=5 representation.

Evaluated excitation functions for Cu−65(n,α)Co−62, Cu−65(n,n'α)Co−61 and Cu−65(n,x)He reactions are given on the Fig.10−12, respectively. HEPRL−97 data are compare with ENDF/B−VI evaluated data and available experimental data.

The data file for the copper natural was obtained on the base of evaluated isotopic data taking into account its abundance. Evaluated excitation function for Cu−nat(n,x)He reactions is given on the Fig.13. HEPRL−97 data are compare with ENDF/B−VI evaluated data and available experimental data.

6. Evaluation of cross section data for COBALT

Natural cobalt consists of one stable isotope Co−59.

Below 21 MeV the main channals of produsig helium in cobalt are (n,α), (n,n'α) and (n,He3) reactions. Energies and thresholds for above reactions in cobalt are given in Table 6.1 below.

Table 6.1

Energies and thresholds of (n,α), (n,n'α) and (n,He3) reactions for cobalt

Isotope	(n,α)		(n,n'α)		(n,He3)	
	Q, MeV	E_{th}, MeV	Q, MeV	E_{th}, MeV	Q, MeV	E_{th}, MeV
Co−59	0.329		−6.942	7.060	−11.600	11.800

Contribution to helium production from (n,α) and (n,n'α) reactions in cobalt dominates for all kind of fission reactors and fusion designs. Contribution of (n,He3) reaction to the total production of helium is negligible due to high threshold and low cross sections.

Excitation function for the Co−59(n,n'α)Mn−55 reaction in the energy region from threshold to 21 MeV was receaved from STAPRE calculation. Parameters for theoretical model calculation were selected with taking into account experimental data [1−3] for the total alpha−emission cross section and experimental cross section data for (n,a) reaction.

Evaluation of excitation function for the Co−59(n,He3)Mn−57 reaction in the energy range from threshold to 21 MeV is based on the data from STAPRE calculation and experimental data [4],[5].

Excitation function for the Co−59(n,a)Mn−56 reaction in the energy region from 2.5 MeV to 21 MeV was evaluated by means of statistical analysis of experimental cross section data [6−30] and data from STAPRE calculation. All experimental data were renormalized to the new standards for monitor reactions cross sections and decay data. Uncertainty in the monitor reaction cross section was added to the total unsertainty for Santry and Butler data [10]. Cross section data measured by Huang Jianzhou et al. [23] were renormalized to the preliminary evaluated integral of excitation function in the energy range 13.0 − 15.0 MeV. Correction factor for this data was equal Kn= 1.0507 . Experimental data from

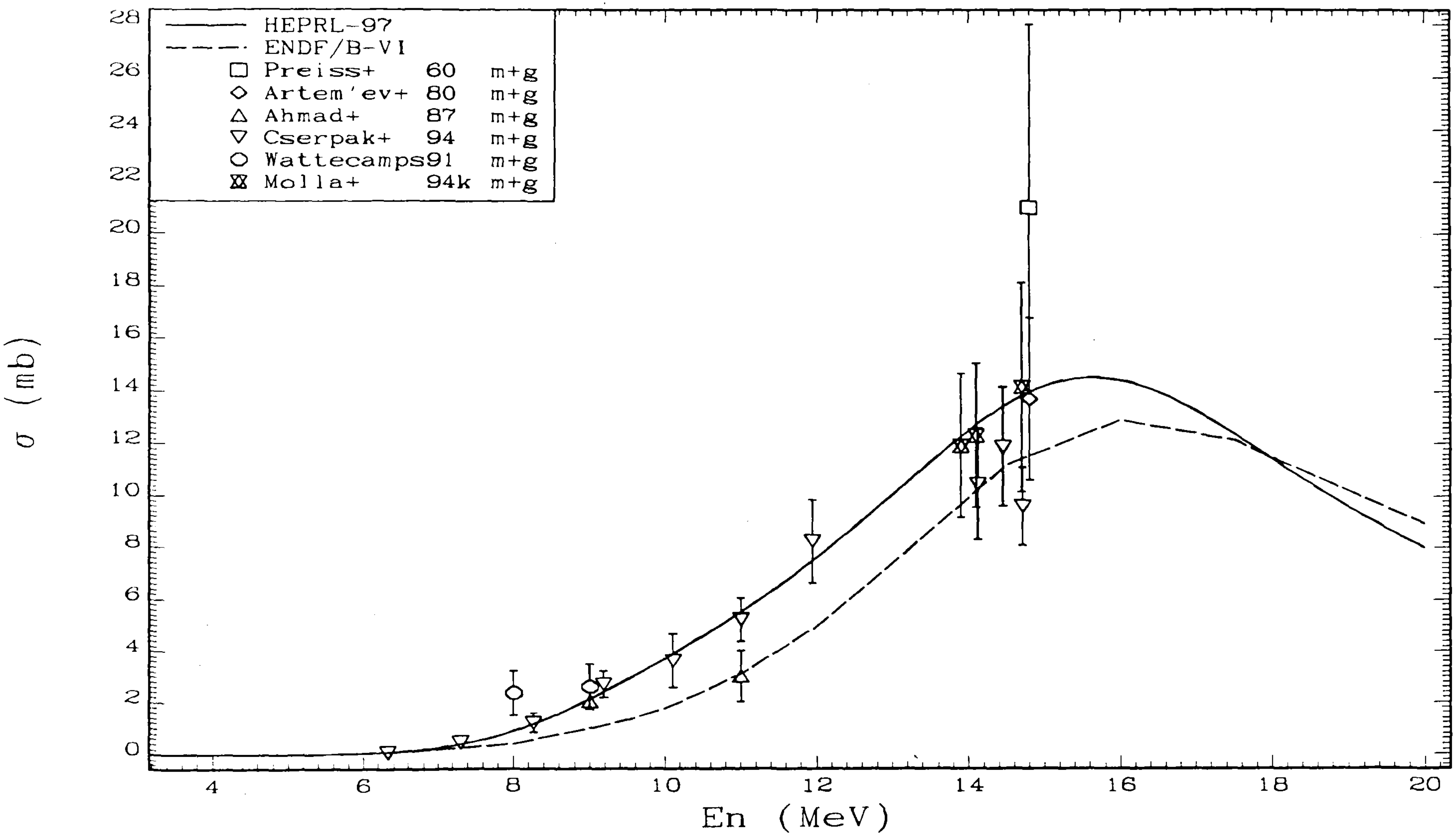

Fig.10. Evaluated excitation function for the reaction $^{65}Cu(n,\alpha)^{62m+g}Co$ in comparison with ENDF/B-6 and experimental data.

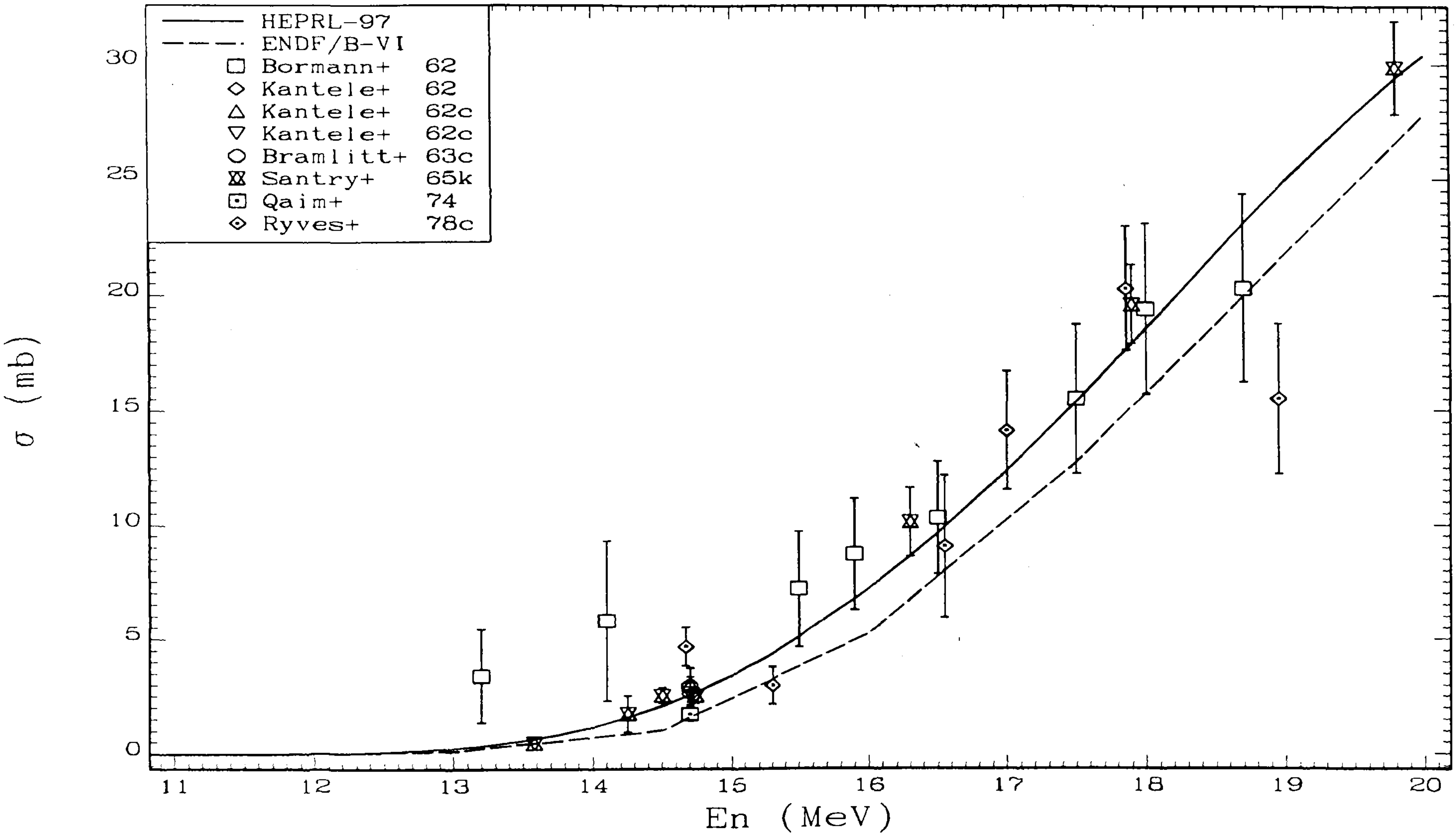

Fig.11. Evaluated excitation function for the reaction $^{65}Cu(n,n\alpha)^{61}Co$ in comparison with ENDF/B-6 and experimental data.

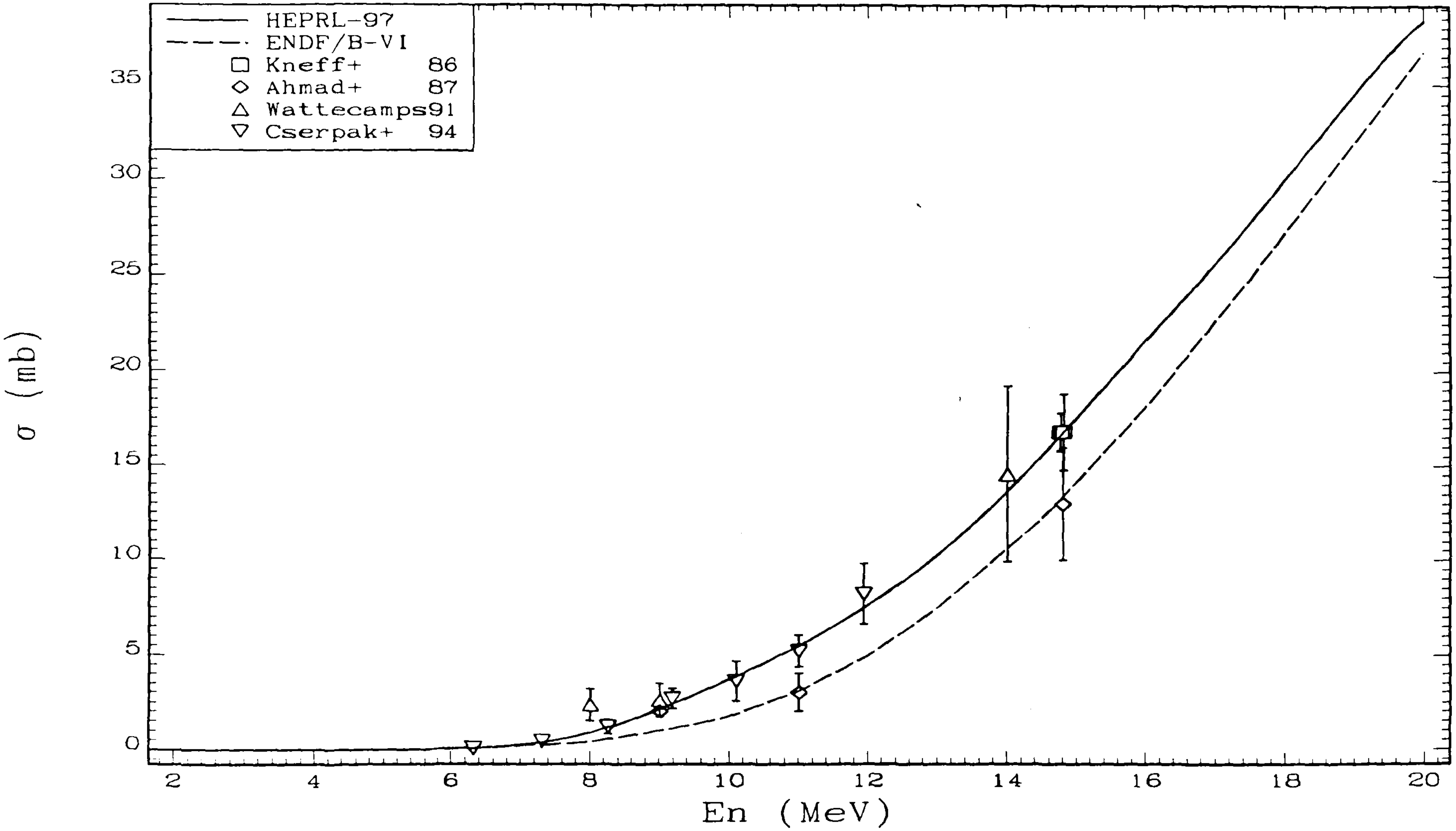

Fig.12. Evaluated excitation function for the reaction $^{65}Cu(n,x)He$ in comparison with ENDF/B-6 and experimental data.

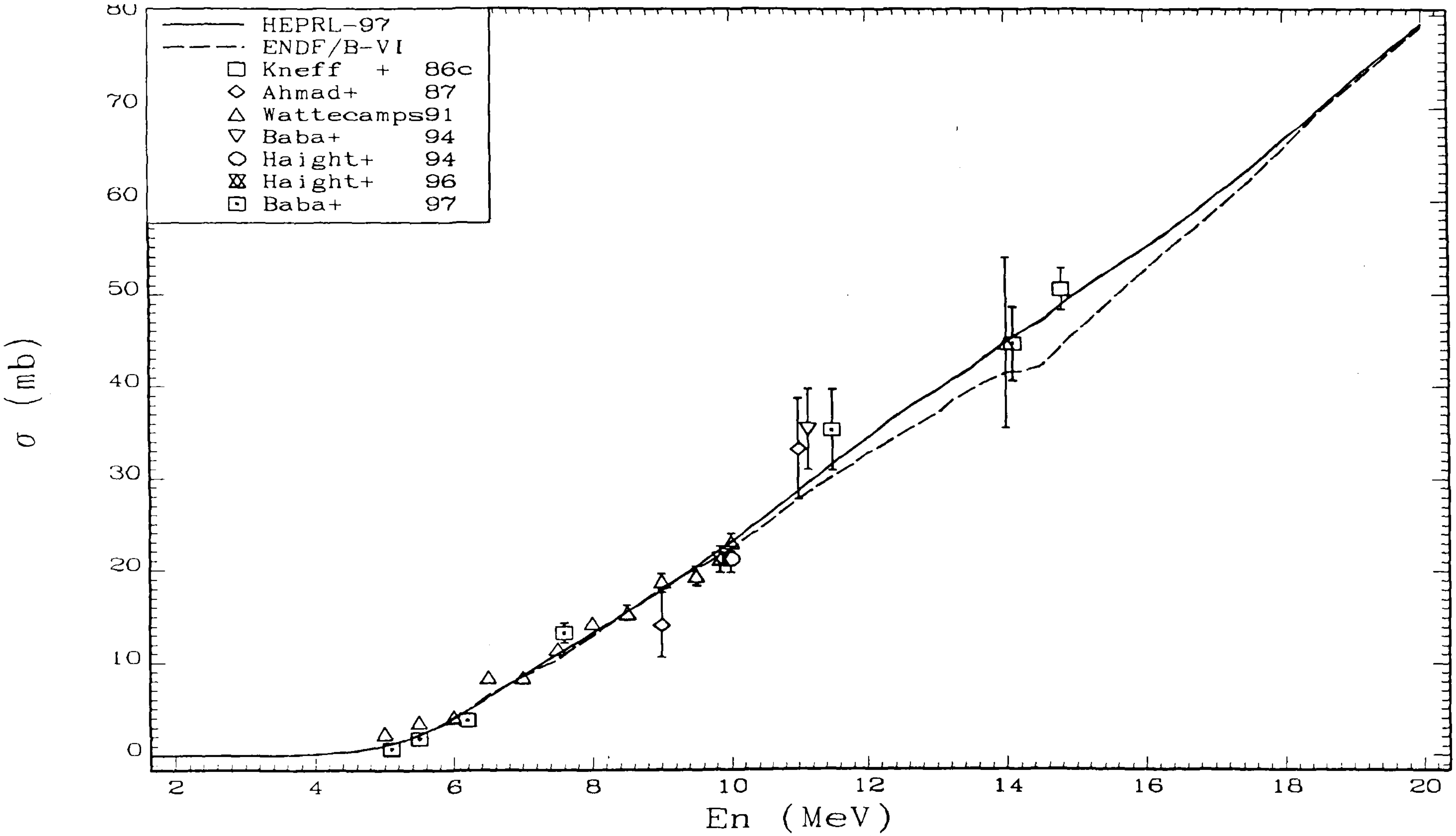

Fig.13. Evaluated excitation function for the reaction $^{nat}Cu(n,x)He$ in comparison with ENDF/B-6 and experimental data.

ref.[31 – 41] were rejected due to their discrepancy with the main bulk of experimental data [6 – 30] and data from theoretical model calculation.

Evaluated excitation function for the reaction Co59(n,a)Mn5 was tested with using integral experimental data [42 – 44] for U – 235 thermal fission neutron spectrum and evaluated integral experimental data [31] for Cf – 252 spontaeous fission neutron spectrum. Calculated and measured average cross section values for U – 235 thermal fission neutron spectrum and Cf – 252 spontaneous fission neutron spectrum are given in the tables 6.2 and 6.3, respetively.

Table 6.2

Calculated and measured average cross sections for reaction Co59(n,α)Mn56 in the U – 235 thermal fission neutron spectrum

Average cross section, mb			C/E	90% – Responce range, MeV
Library	calculated	measured		
HEPRL – 97	0.15822	0.150 ± 0.008 [42]	0.9827	5.80 – 12.10
		0.161 ± 0.007 [43]		
ENDF/B – VI	0.15486	0.170 ± 0.012 [44]	0.9619	5.80 – 12.10

Table 6.3

Calculated and measured average cross sections for reaction Co59(n,α)Mn56 in the Cf – 252 spontaneous fission neutron spectrum

Average cross section, mb			C/E	90% – Responce range, MeV
Library	calculated	measured		
HEPRL – 97	0.22094	0.2208 ± 0.0014 [45]	0.9948	5.900 – 12.700
		0.2221 ± 0.0039 [46]		
ENDF/B – VI	0.21590		0.9721	7.500 – 14.500

C/E values given in the tables 6.2 – 6.3 were calculated with using experimental data [43] and [46], respectively.

From the cross sections averaged in the U – 235 neutron thermal fission spectrum and Cf – 252 spontaneous fission neutron spectrum one can see (see Tables 6.2 and 6.3) that the data obtained on the base of our evaluated Co – 59(n,α)Mn – 56 reaction excitation function are in better agreement with the measured average cross sections than ENDF/B – VI data.

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

Total helium – 3 and helium – 4 emission excitation function for Co – 59 was receaved from summing of cross section data for (n,n'α), (n,α), (n,He3) reactions. Evaluated excitation function in the energy range 14 – 21 MeV agree well with total helium production cross sections measured by Kheff et al. [1], Fischer et al. [2] and Haight et al. [3].

The covarience matrix of cross section uncertainties for Cu – 65 were obtained simultaneously with excitation functions by means of PADE – 2 code in the LB = 5 representation.

Evaluated excitation functions for Co – 59(n,α)Mn – 56 , Co – 59(n,n'α)Mn – 55 and Co – 59(n,x)He reactions are given on the Fig. 14 – 16, respectively.

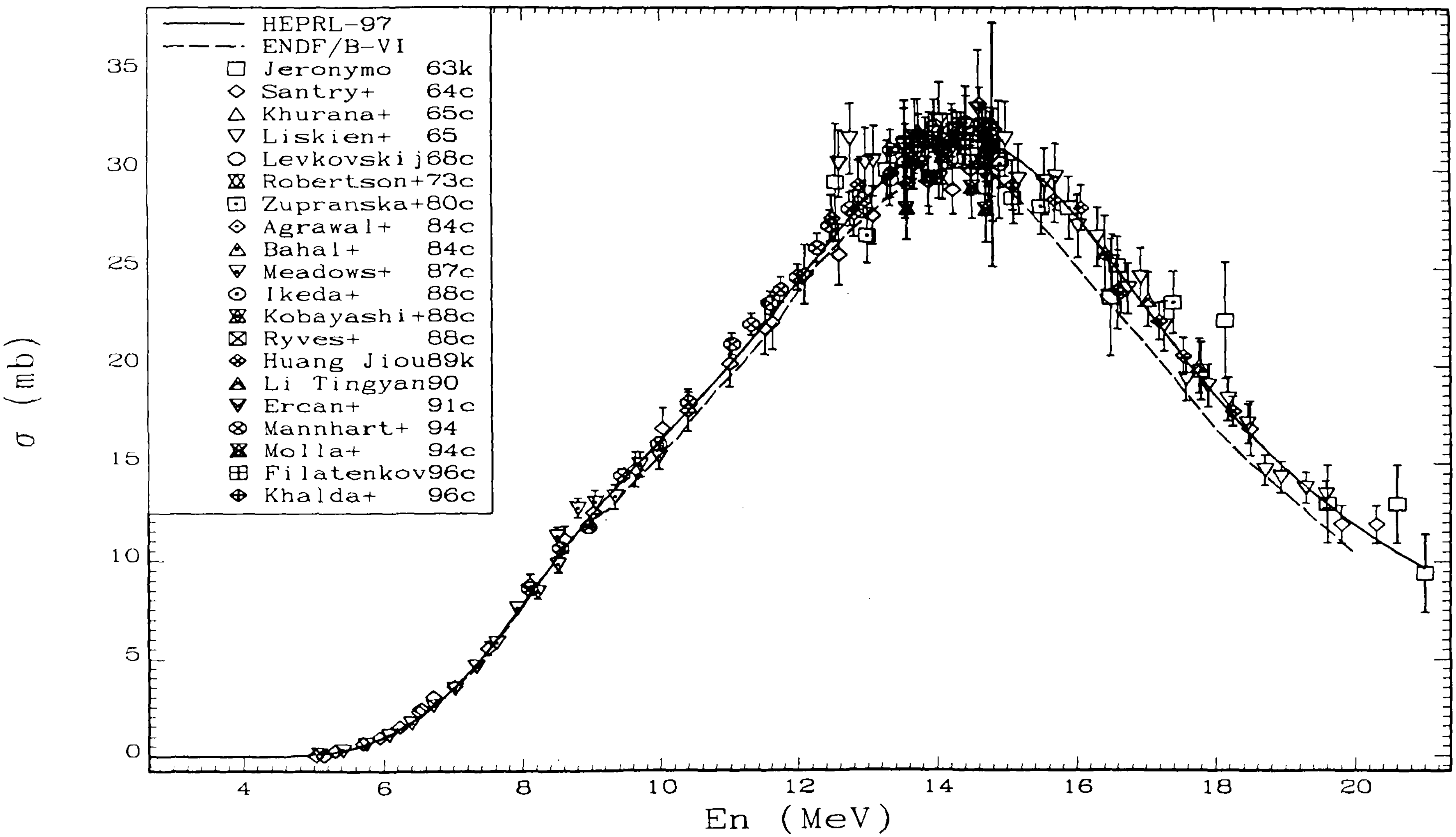

Fig.14. Evaluated excitation function for the reaction $^{59}Co(n,\alpha)^{56}Mn$ in comparison with ENDF/B-6 and experimental data.

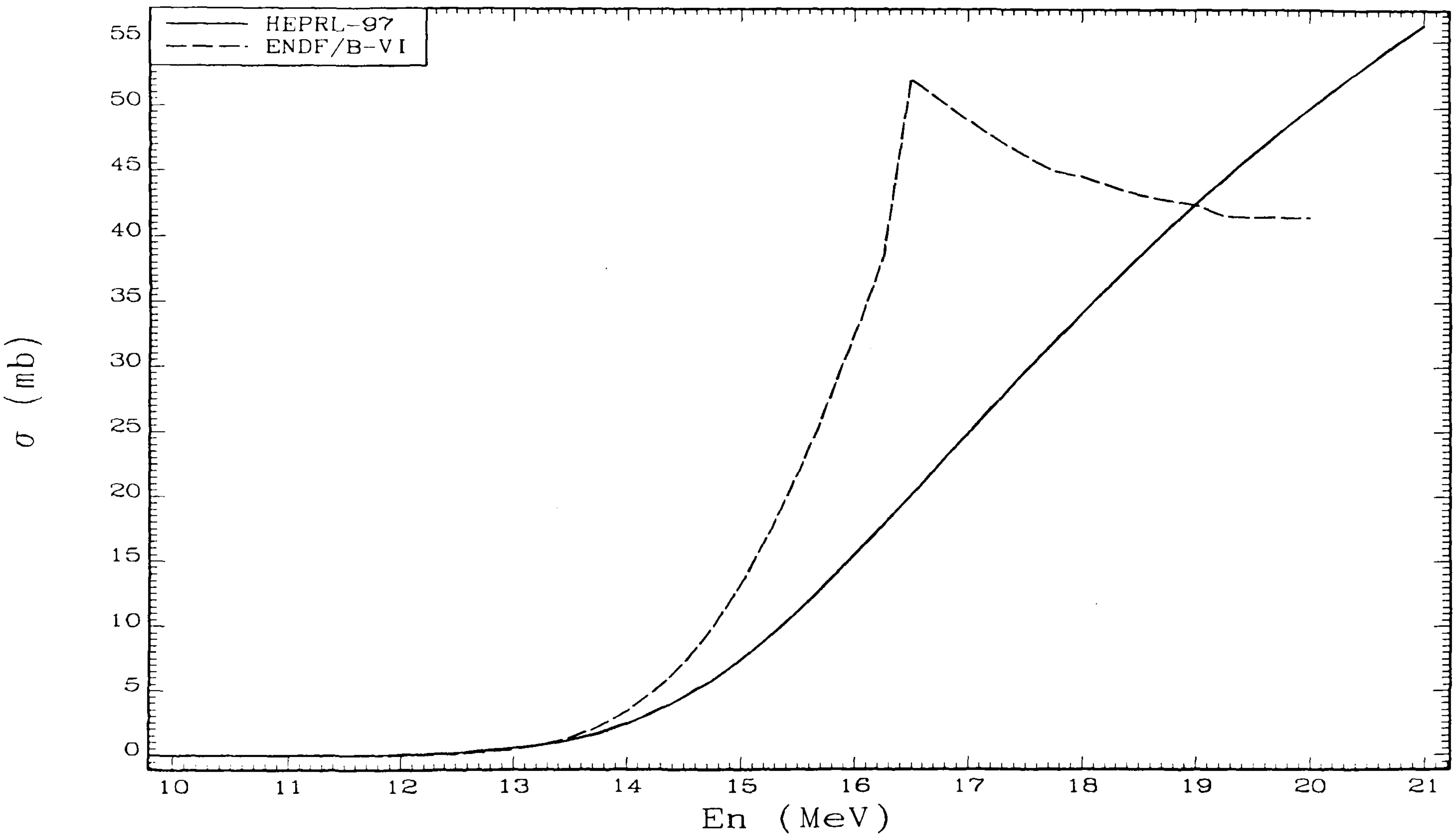

Fig.15. Evaluated excitation function for the reaction $^{59}Co(n,n\alpha)^{55}Mn$ in comparison with ENDF/B-6.

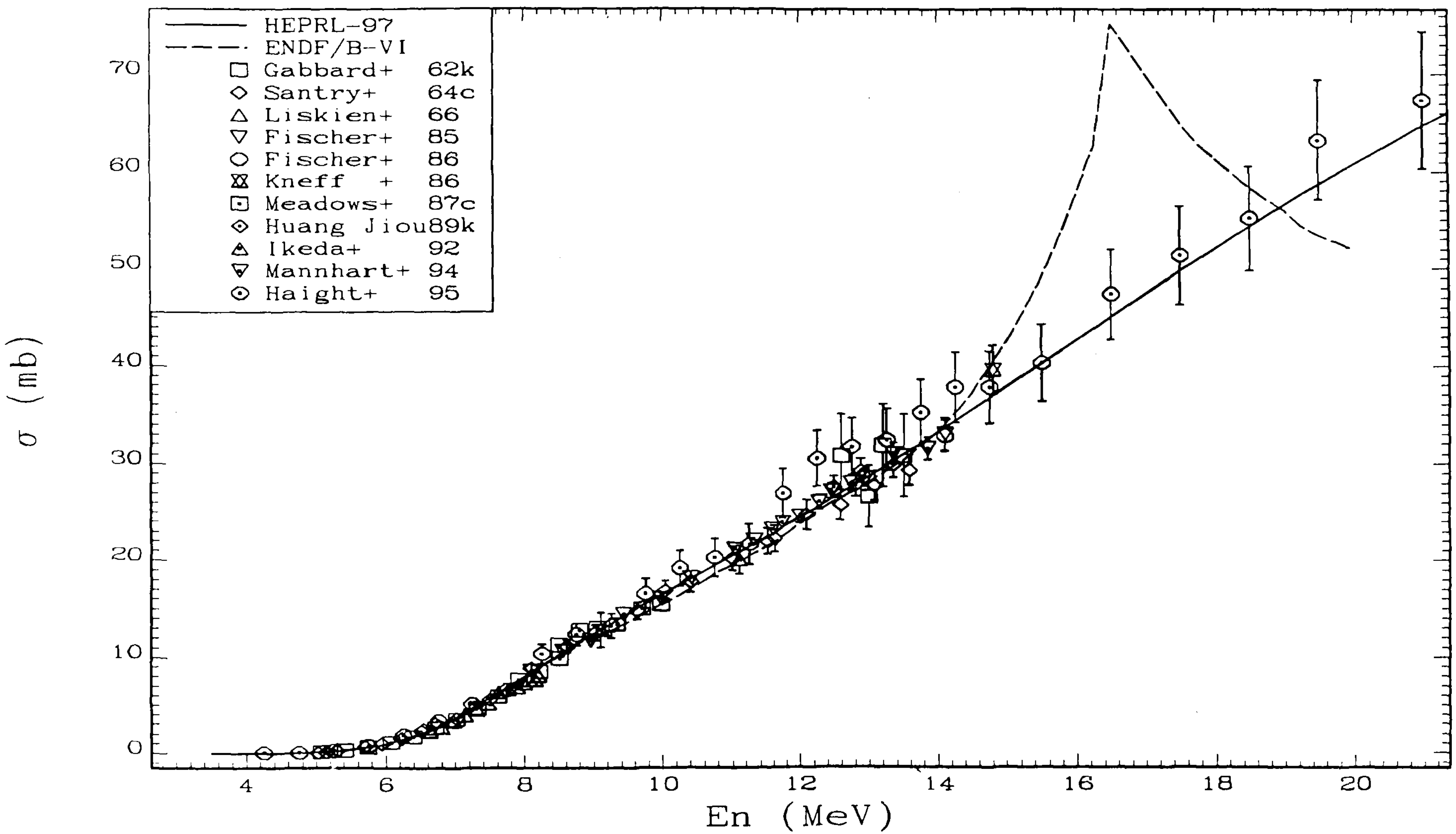

Fig. 16. Evaluated excitation function for the reaction $^{59}Co(n,x)He$ in comparison with ENDF/B-6 and experimental data.

HEPRL—97 data are compare with ENDF/B—VI evaluated data and available experimental data.

7. Conclusion.

On the basis of analysis of available experimental information, theoretical model calculations and data on systematical behavier of helium production cross sections the total helium—emission cross sections and partial cross sections of helium producing reactions were evaluated for such important structural materials of fission and fusion reactors as V, Mn, Co and Cu.

The comparison results with available evaluations from ENDF/B—VI demonstrated significant improvement of evaluated helium production data for structural materials. For the first time evaluations for V, Mn, Co, Cu and its stable isotopes contain covariance matrixes which permit make calculations of uncertainty of total helium productions. The new evaluations are prepared in ENDF—6 format in pointwize. The covariance covariance matrices of uncertainties are given under LB=5.

The data for HEPRL—97 were evaluated thoroughly in the whole energy range from threshold up to 20 – 21 MeV and can be used for calculations of helium production in various neutron spectra.

The authors are grateful to the IAEA Nuclear Data Section for support of the project and plan to continue development of the library to create evaluations for one of the most important structural material natural zirconium and his stable isotopes ZR—90, ZR—91, ZR—92, ZR—94 and ZR—96 together with covariance matrixes.

After completion of the project the Final version of validated and tested HEPRL library will be made available to the IAEA Nuclear Data Section for wide distribution to the member states.

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