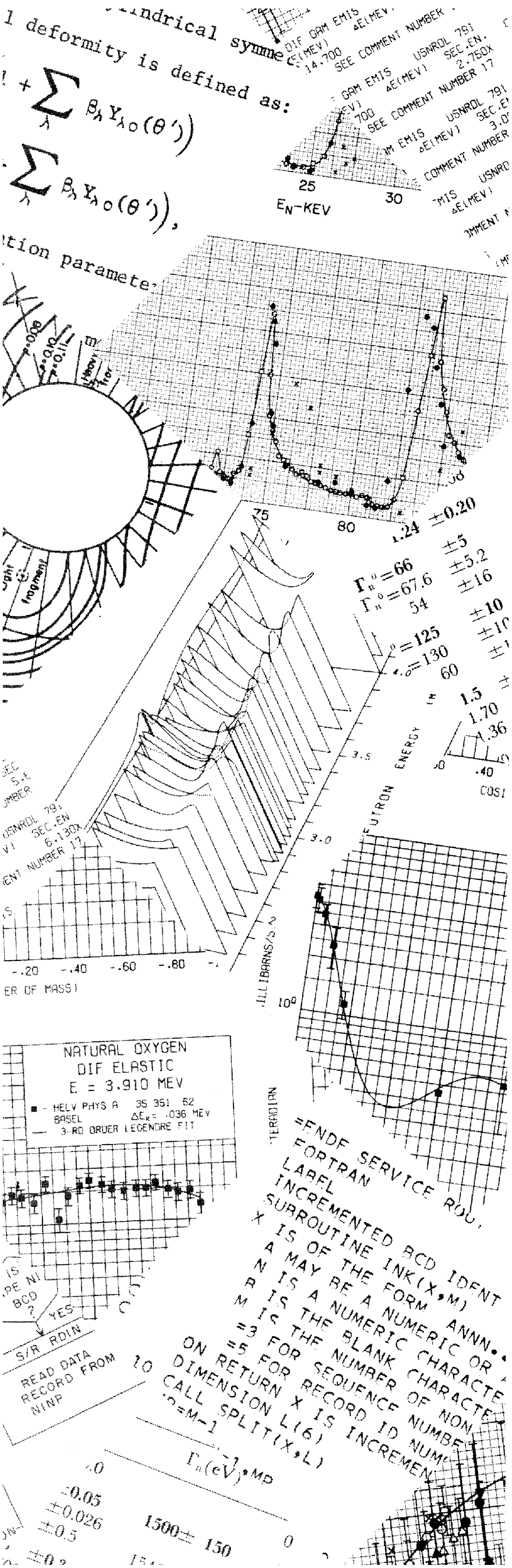

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EVALUATION OF THE NEUTRON AND GAMMA-RAY PRODUCTION CROSS SECTIONS OF ^{151}Eu AND ^{153}Eu

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Evaluation of the Neutron and Gamma-Ray Production Cross Sections of ^{151}Eu and ^{153}Eu*

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1. Introduction

This report summarizes the evaluation of neutron and gamma-ray production cross sections for europium isotopes Eu^{151} and Eu^{153}. In the ENDF/B-II files,[1] the emphasis was laid on the evaluation of the low energy neutron cross sections, and not on the evaluation of the intermediate and high energy neutron cross section data. Since the cross sections of the intermediate and high energy ranges are important for the fast reactor program, extensive studies were carried out for the cross sections, especially the radiative capture cross sections, in this energy range.

2. General Information (File 1)

2.1 General Identification

Eu 151	Eu 153
MAT = 1290 (ENDF/B-IV)	MAT = 1291 (ENDF/B-IV)
ZA = 63151.0	ZA = 63153.0
AWR = 149.623	AWR = 151.607
$R = 0.88 \times 10^{-12}$ cm	$R = 0.88 \times 10^{-12}$ cm
I = 2.5	I = 2.5

See also Table 1

2.2 Radioactive Decay[2] (MT = 453)

Eu 151

MT = 16	$Eu^{150} \rightarrow Gd^{150}$	$\lambda = 1.528 \times 10^{-5}$ sec
	$Gd^{150} \rightarrow Sm^{146}$	$= 1.221 \times 10^{-14}$ sec
MT = 17	$Eu^{149} \rightarrow Sm^{149}$	$= 8.626 \times 10^{-8}$ sec

MT = 102	$Eu^{152} \rightarrow Sm^{152}$	$\lambda = 1.691 \times 10^{-9}$ sec
MT = 103	$Sm^{151} \rightarrow Eu^{151}$	$= 2.363 \times 10^{-10}$ sec
MT = 107	$Pu^{148} \rightarrow Sm^{148}$	$= 1.494 \times 10^{-6}$ sec
Eu^{153}		
MT = 16	$Eu^{152} \rightarrow Sm^{152}$	$\lambda = 1.6909 \times 10^{-9}$ sec
MT = 102	$Eu^{154} \rightarrow Gd^{154}$	$= 2.556 \times 10^{-9}$ sec
MT = 103	$Sm^{153} \rightarrow Eu^{153}$	$= 4.140 \times 10^{-6}$ sec
MT = 107	$Pm^{150} \rightarrow Sm^{150}$	$= 7.184 \times 10^{-5}$ sec

(n,particle) Q-values are given in Table 2.

3. Resonance Parameters (File 2)

3.1 Resolved Resonance Region

A preliminary draft of [BNL-325 (1973)][3] gives resonance parameters of Eu^{151} for 105 resonances from -0.00361 to 98.61 eV and for 76 Eu^{153} resonances from 0.17280 eV to 97.1 eV. The recommended values given there were taken in ENDF/B-IV file with few exceptions. Extensive studies were carried out to obtain the resolved resonance parameters in the energy range lower than 1 eV when ENDF/B-III file was compiled. And they obtained the parameters of resonances at -0.0006 eV for Eu^{151} and -0.007 eV, 0.457 eV for Eu^{153}. These resonances are added to those given in BNL-325 (1973). For the resonances whose spin J had not been assigned, the value of spin J = 2.5 has been prescribed corresponding to g = 0.5.

3.2 Unresolved Resonance Region

Unresolved resonance parameters of Eu^{151} and Eu^{153} were given from 99.1 eV to 10 keV and 97.22 eV to 10 keV respectively. The parameters listed in Table 3 were mostly obtained from the preliminary draft of BNL-325 (1973). A discussion of these will be presented in the section on the neutron capture cross section.

4. Neutron Cross Sections (File 3)

4.1 Total Cross Section (MT = 1)

Several measurements of the total cross section in the low energy range were evaluated and represented as resolved resonance parameters. In the intermediate energy range between 0.8 keV - 24 keV, the total cross section of natural europium was measured by Egelstaff.[4] Compared to the recent measurements by Rahn[5] for Eu^{151} (energy range of 0.2 keV to 3 keV) and for Eu^{153} (energy range 0.06 keV to 3 keV) Egelstaff's data is about 30% too small. The smooth total cross section calculated using the unresolved resonance parameters (Table 3) agrees with Rahn's data within 10% for both Eu^{151} and Eu^{153}. Although Rahn's total cross section data show that the resonance shape and the average values over several resonances fluctuate, the data were represented as unresolved resonance parameters, so that self shielding and the doppler effect could be calculated. Because of no data between 30 keV to 2.3 MeV, the total cross section was calculated by the optical model using mostly Becchetti and Greenlees' optical parameters.[6] The details of the optical model calculations will be described in a later section.

Between 2.3 MeV to 15 MeV, the data obtained by Foster et al.[7] for natural europium were taken for both Eu^{151} and Eu^{153} isotopes. Above this energy range, the total cross section was evaluated from a comparison between the optical model calculation and Foster's data.

4.2 Elastic Scattering Cross Section (MT = 2)

The elastic scattering cross sections in the energy range higher than the unresolved resonance energy were obtained by subtracting the non-elastic cross section from the evaluated total cross section.

4.3 Nonelastic Scattering Cross Section (MT = 3)

The nonelastic scattering cross section was calculated by summing up all cross sections except the elastic scattering cross section.

4.4 Inelastic Scattering Cross Section (MT = 4, 51, 52 ..., 91)

The inelastic scattering cross sections were given as total (MT = 4), and discrete level excitation cross sections (MT = 51 ...) of the first 9 levels for Eu^{151} and 11 levels for Eu^{153} and continuum level excitation cross section (MT = 91). The level scheme for these discrete levels is tabulated in Table 4 and References 8-13.

Since no experimental data are available for the individual level excitation cross sections, they were calculated using the code COMNUC-3[15,16] for the neutron energies up to 3 MeV. (The optical model parameters used in these calculations will be discussed in the section on the optical model.) Above 3 MeV, inelastic scattering is mostly the excitation of the continuum of levels, so that the inelastic scattering cross section for discrete level excitation above this energy was neglected and the inelastic scattering cross section for continuum level excitation was calculated by the cascade calculation of GROGI-3.[17,18] The level density parameters for the continuum of levels were taken from the Cook data [19] for deformed nuclei using the Gilbert-Cameron formula.[20]

In this study, the inealstic scattering cross section of the discrete levels were calculated assuming them to be a compound nuclear process, but europium isotopes are highly deformed nuclei and some excitation levels are due to the rotational motion. The inelastic scattering which excite this level by direct process is not negligibly small. This deficiency will be improved by the future calculation using JUPITOR code.[21]

4.5 (n,p) and (n,n',p) Cross Sections (MT = 103, 28)

The statistical model calculation based on the compound nuclear process for the (n,p) cross section produces a very small cross section compared to the experimental values obtained by Kenna[22] for Eu^{151} at 14.0 MeV, and by Coleman et al.[23] for Eu^{153} at 14.5 MeV. And there are no other experimental data for other neutron energies. The cross section curve of (n,p) reactions calculated by the semi-empirical statistical model code THRESH[24,25] was adopted after it was normalized to the experimental values mentioned above.

No cross section measurement for (n,n'p) reaction is available, so that this cross section was calculated by using the GROGI-3 code.

4.6 (n,α) and (n,n'α) Cross Sections (MT = 107, 22)

These cross sections were calculated in the same way as the (n,p) and (n,n'p) cross sections. The cross sections for the (n,α) reaction calculated using GROGI-3 code are very small compared with the experimental values by Rama Prasad et al.[26] for Eu^{151} and by Khurana[27] for Eu^{153}.* So that the cross section curves were calculated by the THRESH code, and the values normalized to the above experimental values. Furthermore, the (n,α) cross section at thermal neutron energy[29] which is not negligibly small (9.0 $\pm$ 2.0 mb) for Eu^{151}, was added over the whole energy range 10^{-5} eV to 20 MeV as a background.

No experimental data are available for (n,n'α) reaction cross section, and the cross section was calculated using GROGI-3 code.

*Recently, Pruys[28] reported the preliminary results for (n,p), (n,α), and (n,2n) reaction cross sections at 14 MeV. These data are not included as they are preliminary.

4.7 (n,2n), (n,3n) Cross Sections (MT = 16)(MT = 17)

Eu^{151}

The several (n,2n) cross sections in which the residual nucleus goes to the meta stable state with 12.6 h for half life have been measured at 14.8 MeV.[30-32] These data agree within 20% with each other. However, these values (about 0.5 barn) are small compared to the value (about 2 barn) calculated using the statistical model. Neighbouring nuclei show that the (n,2n) cross section, in which the residual nucleus goes to the other metastable state and the ground state are of similar magnitude so that the values calculated by GROGI-3 code were adopted as the evaluated data.

Eu^{153}

For Eu^{153}, the (n,2n) cross section which goes to metastable state Eu^{151m_1} with 9.3 h half life and Eu^{151m_2} with 96 min half life have been measured.[26,28,31,32] These data are shown in Table 5. Since these cross sections are partial cross sections, we adopted the calculated cross section by GROGI-3 code as the evaluated data. For (n,3n) reaction, no experimental results are available for both Eu^{151} and Eu^{153} isotopes, so that the values calculated by GROGI-3 were adopted.

4.8 (n,d), (n,t) and (n,He^3) Reaction Cross Section (MT = 104, 105, 107)

No experimental data are available, so that the values calculated by THRESH were adopted as the evaluated data.

4.9 The Radiative Capture Cross Section (MT = 102)

The radiative capture cross section at low energy range was calculated from the resonance parameters discussed in the section of File 2 and the cross section presented as smooth cross section in the energy ranges from 10^{-5} eV to 0.84 eV for Eu^{151} and from 10^{-5} eV to 0.77 eV for Eu^{153}.

For natural europium, several measurements[33,34,35,36,37,38] have been carried out in the energy range from 100 eV to 200 keV. Block's[34]* data of 1 keV to 10 keV are about 30% higher than Konks' data[33] and Macklin's data[37] between 3 keV and 40 keV almost agree with Konks' data. Lepine's data[35] are about 30% higher than the Macklin data.[37] Recent data by Chou is about 5% and 30% higher than Konks' data in the energy region of between 2 keV and 10 keV and of between 100 eV to 1 keV respectively.

<u>Eu^{151}</u>

The experiment for Eu^{151} isotope in the intermediate energy range was carried out by Konks[33] (0.76 eV to 42 keV) and by Czirr[40] (0.2 keV to 12.5 keV). The data by Czirr is about 25% higher than Konks' data. In this energy range, Barr[41] made the extensive study to get resonance parameters and estimated the radiative capture cross section to an accuracy of ±25%. Konks and the other data in this intermediate energy range between 10^2eV to 10^4eV show some structure. But the cross section of this region was given in the form of unresolved resonance parameter (File 2) rather than the smooth curved cross section (File 3), so that the self shielding effect and the doppler effect of this cross section could be calculated.

The resonance parameters determined were based on Konks' data and Rahn's total cross section data. The smooth cross section obtained from these parameters is about 20 to 30% higher than the one obtained by ENDF/B-III resonance parameters.

Between 10 keV to 42 keV, we took Konks data as the evaluated data in the

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*Recently Block[39] made another measurement of radiative capture cross section for the separated isotopes. However, their analysis of the experimental data was not finished, so that we could not include their data for our evaluation.

form of smooth cross section. Johnsrud[42] measured the activation cross section of Eu^{152} 9.3 h metastable state between 160 keV and 2.5 MeV. This cross section was taken as capture cross section in ENDF/B-II file. However, the recent integral experiment by Harker[43] shows that the capture cross section corresponding to transitions to the Eu^{152} ground state is about 1.5 times that which goes to the 9.3 h Eu^{152m_1} state.

Since there are no other experimental data for this high energy range, we calculated the cross section by nuclear model calculation using COMNUC-3. The values are similar to the theoretical calculations carried out by Benzi[13] and Schenter.[45] As pointed out by Gruppelaar,[46] the capture cross section in the energy range between 0.1 to 1 MeV is sensitive to the excitation level of target nucleus, so that the excitation level was carefully evaluated.

Since there is no way to find out Moldauer's Q value, because no experimental data are available for the inelastic cross section, we assumed that the value of Q is zero. But the correlation factor due to the degree of the freedom associated with open chanel was taken into account in the calculation. The value of gamma strength function used in the COMNUC-3 calculation was slightly increased to get the same capture cross section as Konks' data in the range of 10 keV to 40 keV. This effect can be understood from the radiative strength function shown by Bartholomew.[47] The COMNUC-3 calculation was performed to the energy range up to 3 MeV. Beyond this energy to 20 MeV,* the capture cross section was obtained by GROGI-3 for compound process code and Cvelbar's formula[48]

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*COMNUC-3 can calculate the capture cross section due to direct and semidirect reactions. But in the high energy range where these reactions are predominant in the capture process, many channels such as proton and α particle channel are widely opened and this requires a large calculation time to compute the capture cross section.

based on Lane-Lynn[49] and Brown's[50] formula was used to calculate the capture cross section due to direct and semi-direct reaction. This is shown in Fig. 1.

As mentioned above, recently Harker made the integral measurement for Eu^{151} capture cross section using the hard spectrum of CFRMF facility[43]. The integral cpature cross section which is calculated using this evaluated cross section and the flux obtained by his transport calculation, agrees with his experimental value within his error assignment.

$\underline{Eu^{153}}$

The capture cross section of Eu^{153} was evaluated in the same manner as for Eu^{151}.

No experimental data are available for the microscopic capture cross section of Eu^{153}. But Konks made a measurement for the natural europium so that the cross section for Eu^{153} was obtained by subtracting Eu^{151} cross section from that of the element. Compared to Konks' data, the ENDF/B-II data is about 40% smaller and Barr's[41] estimation and Benzi's calculation are about 20% larger over the neutron energy range of 1 keV to 10 keV. Similar to the Eu^{151} isotope, the radiative capture cross sections of Eu^{153} between 100 eV to 10 keV were given as the unresolved resonance parameters. These parameters were determined based on Konks' data and Rahn's total cross section data.

The cross section between the energy range 10 keV to 40 keV was taken from Konks data as smoothed cross section. Beyond this energy, the capture cross section was calculated by nuclear model calculations in the same way as for the Eu^{151} isotope.

The shape of the calculated cross section is similar to Benzi's calculated cross section except near 1 MeV. The difference is due to the difference of the excited states used. The (n,γ) cross-section is shown in Fig. 2.

Harker's integral experimental value for Eu^{153} was compared with the value calculated in the same way as in the Eu^{151} case. The calculated value agree with the experimental value within his error limits.

After this evaluation was done, the preliminary capture data between 4.0 - 65.0 keV were reported by Hockenbury et al.[61] These data are about 10 - 18% higher than the evaluated values, but we took the Konks data in ENDF/B-IV evaluation from the consideration of Harker's integral experimental data and the COMNUC-III calculations. The recent measurements of Chou et al.[62] for natural element are close to Konks' data.

5. Angular Distribution of Secondary Neutrons (File 4)

5.1 Elastic Scattering (MT = 2)

No experimental data were available, so the values calculated by ABACUS-2[51] (NABAK PDP-version) using the optical model was adopted as the evaluated data. The Legendre coefficients, calculated by CHAD[52] (NUCHAD in the PDP version) were given in File 4. Since the elastic scattering due to the compound process is small in the energy range above 3 MeV, the angular distribution of elastically scattered neutrons was calculated by taking only the shape elastic scattering into account above 3 MeV.

5.2 Inelastically Scattered Neutrons (n,2n), (n,3n), (n,n'p), and (n,n'α) Reaction (MT = 51,..., 91, MT = 16, 17, 22, 23)

Neutrons from these reactions were assumed to be isotropic in the center of mass system.

6. Energy Distribution of Secondary Neutrons (File 5)

6.1 (n,2n), (n,3n) and (n,n') reactions (MT = 16, 17, and 91)

The energy distribution of neutrons from the (n,2n), (n,3n) and the inelastic scattering cross section of the continuum part were assumed as Maxwellian. The effective temperature of these Maxwellians were obtained by the Weisskopf formula.[53]

7. Multiplicities and Transition Probability Array of Gamma Rays (File 12)

7.1 Radiative Capture Gamma-Ray Multiplicity

The gamma-ray spectra due to thermal neutron capture in Eu^{151} isotope and natural europium element were measured by Groshev et al.(11,54) and Rasmussen et al.,(55) respectively. The high energy gamma ray parts were also measured by Shera(56) for each isotope of Eu^{151} and Eu^{153}, (11) the gamma ray which is less than 1 MeV were measured by Michaelis.(57) Groshev's and Shera's data have been used as evaluated data for radiative capture reaction (MT = 102) between 10^{-5} eV to 1 MeV neutron energy.

The multiplicities increase as a function of incident neutron energy to preserve the total energy release. There are no experimental data for neutron energies larger than 1 MeV. So the gamma ray production cross sections for all reactions were calculated by the GROGI-3 code. The multiplicities are tabulated in this file.

7.2 Transition Probability Array for Gamma Ray due to Inelastic Neutron Scattering

The electro magnetic transition probabilities from the excited levels of Eu^{151} and Eu^{153} isotopes were measured by several authors(8,10,12,58) using the coulomb excitation and the other excitation reactions. The evaluated transition probabilities were calculated from these data. Most data were taken from the Nuclear Data Sheet compiled by ORNL.(12)

8. Angular Distribution of Gamma Rays (File 14)

All gamma ray produced by neutron capture (MT = 102) inelastic neutron scattering (MT = 51 - 60) and non elastic scattering are assumed to be isotropic.

9. Energy Distribution of Secondary Gamma Rays (File 15)

The energy distribution of the secondary gamma ray due to thermal neutron capture was expressed by histogram type spectrum with 0.25 MeV bin energy width. The ones due to the non-elastic scattering for the neutron energy more than 1 MeV are tabulated as histogram type spectrum with 0.5 MeV bin energy width.

10. Nuclear Model Calculation

10.1 Optical Model Parameter

In this evaluation work, optical model calculation has been used to obtain the neutron, proton and α particles penetrabilities. A spherical optical potential in the following form was used.

$$U(r) = V_c - Vf(x) + \left(\frac{h}{M_\pi C}\right)^2 V_{so}(\sigma \cdot \ell)\frac{1}{r}\frac{d}{dr} f(x_{so})$$

$$- i\left[Wf(x_W) - 4W_D \frac{d}{dx_D} f(x_D)\right]$$

where

$$V_c = ZZ'e^2/r \qquad r \geq R_c$$

$$= (ZZ'e^2/2R_c)(3 - r^2/R_c^2) \quad r \leq R_c$$

$$R_c = r_c A^{1/3}$$

$$f(x) = (1 + e^x)^{-1} \quad \text{where } x = (r - r_o A^{1/3})/a$$

$$\left(\frac{h}{M_\pi C}\right)^2 = 2.0 \text{ (fermi)}^2$$

The neutron parameters at a neutron energy E_n(MeV) are mostly taken from Becchetti and Greenlees[6] data, which are shown as follows:

$V = 56.3 - 0.32E - 24(N-Z)/A$

$r_o = 1.17 \qquad a = 0.75$

$W = 0.22E - 1.56$ or zero whichever is greater

$W_D = 13 - 0.25E - 12(N - Z)/A$, or zero whichever is greater

$r_W = r_D = 1.26 \qquad a_W = a_D = 0.58$

$V_{so} = 6.2$

$r_{so} = 1.1 \quad a_{so} = 0.75$

where the unit of length is in Fermis.

For protons, the following parameters are used:

$V = 54. - 0.32E + 24(N-Z)/A + 0.4(Z)/A^{1/3}$

$r_o = 1.17 \quad a = 0.75$

$W = 0.22E - 2.7$, or zero, whichever is greater.

$W_D = 11.8 - 0.25E + 12(N-Z)/A$, or zero, whichever is greater.

$r_W = r_D = 1.32, \quad a_W = a_D = 0.51 + 0.7(N-Z)/A$

$V_{so} = 6.2$

$r_{so} = 1.01, \quad a_{so} = 0.75$

The alpha parameters are taken from the data obtained by C. R. Bingham et al.[59]

V	=	200	W	=	102.9
r_o	=	1.254	r_W	=	1.254
a	=	0.669	a_W	=	0.669
V_{so}	=	0.0	W_D	=	0
R_c	=	1.5			

10.2 Statistical Model Calculation

Hauser-Feshbach calculation for inelastic scattering cross section and capture cross section was done with the revised version of COMNUC-III.[16] In this calculation, we assumed the fluctuation correlation $Q = 0$, but the correlation correction factor $S^{J\pi}_{cc'}$[17] was taken into account. The level density parameters for deformed nuclei of Gilbert and Cameron[20] and Cook et al.[19] which were built in the code were used.

For the (n,2n), (n,3n), (n,n'p), (n,n'α) and the γ ray production cross sections, the GROGI-3 code which calculates the cascade process was used. (The data of Q-value used in the calculation is shown in Table 2.)

The transmission coefficients of neutron, proton, and α particle used in this code were obtained by the ABACUS-2 code.

The angular distribution of elastic scattering cross section was calculated by the ABACUS-2 code and the Legendre coefficient of this angular distribution was calculated by the CHAD code.

11. Uncertainty Estimates

Estimates of the cross section uncertainties for Eu-151 and Eu-153 were made for File 3 and File 12 data. The uncertainties given in Tables 6 and 7 represent rough estimates of the standard deviations of rather broad energy groups. Uncertainties are given for the thermal neutron energy point, and the ones for the other energies are given for energy groups whose upper energy bound is shown.

12. Evaluated Cross-Sections

As mentioned earlier, the evaluated capture cross-sections of ^{151}Eu and ^{153}Eu are shown in Figs. 1 and 2 compared against the experimental data. The other cross-sections from the data files are shown plotted in Figs. 3 and 4.

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Table 1

Properties of the Stable Europium Isotopes

Isotope	Fractional Abundance	Isotopic Mass
Eu^{151}	0.478	150.91988
Eu^{152}	0.	151.92168
Eu^{153}	0.522	152.92126
Eu^{154}	0.	153.92298

Table 2

Nuclear Reactions and their Q Values

Isotope	(n,γ)	(n,2n)	(n,3n)	(n,p)	(n,d)	(n,t)	(n,He^3)	(n,α)
Eu^{151}	6.351	7.9705	14.417	0.70644	2.6654	4.3935	5.4468	-7.8655
Eu^{153}	6.444	8.551	14.857	0.02656	3.6684	5.6685	6.8379	-5.8315

	(n,n'α)	(n,n'p)
Eu^{151}	-1.964	+4.890
Eu^{153}	-0.2741	+5.893

These data are obtained from mass table of Wapstra and Gove.[62]

Table 3

Unresolved Resonance Parameters

Isotope	Eu^{151}	Eu^{153}	
Energy (eV)	99.1 - 10^4	97.22 - 10^3	10^3 - 10^4
Γ_γ(eV)	9.2×10^{-2}	9.477×10^{-2}	0.1137
Dobs (eV)	0.655	1.3	1.3
S_0($eV^{\frac{1}{2}}$)	4.07×10^{-4}	2.5×10^{-4}	2.5×10^{-4}

Table 4

Nuclear Level Structure of Eu^{151} and Eu^{153}

Eu^{151} E_{ex} (keV)	J^π	Eu^{153} E_{ex} (keV)	J^π
0.0	$5/2^+$	0.0	$5/2^+$
22.0	$7/2^+$	83.37	$7/2^+$
194.0	$1/2^+$	97.43	$5/2^-$
196.0	$11/2^-$	103.179	$3/2^+$
243.0	$7/2^-$	151.61	$7/2^-$
308.0	$7/2^+$	172.854	$5/2^+$
350.0	$9/2^-$	191.40	$9/2^+$
505.0	$7/2^+$	634.6	$1/2^+$
510.0	$9/2^-$	635.0	$3/2^+$
620.0	$11/2^-$	682.0	$5/2^+$
		694.0	$3/2^+$
		707.0	$5/2^-$
Continuum			
> 700 keV		> 720 keV	

Table 5

(n,2n) Reaction Cross Sections

Eu^{151}

En (MeV)	Cross Section (mb)	Lifetime of Residual State	Reference
14.8 ± 0.2	480 ± 20%	16.6 h	(30)
14.8 ± 0.8	500 ± 200	15 ± 1 h	(32)
14.8 ± 0.5	640 ± 64	13.4 h	(31)

Eu^{153}

En (MeV)	Cross Section (mb)	Lifetime of Residual State	Reference
14.8 ± 0.8	750 ± 200	9.3 ± 0.5 h	(32)
14.8 ± 0.5	164 ± 15%	9.3 h	(31)
14.5	91 ± 12	96 min (M2)	(26)
	625 ± 90	9.3 h (M1)	(26)
14.5	140 ± 40	9.3 h	(28)

Table 6

Estimated Uncertainties in the Evaluated Cross Section of Eu-151*

Cross Section	ENDF/B Designation MF	MT	Neutron Energy (eV) Thermal	1	10^4	10^5	$3x10^5$	10^6	$3x10^6$	10^7	$1.4x10^7$	$2.0x10^7$
Total	3	1	6	10	5	5	5	5	5	5	5	5
Elastic	3	2	6	15	10	10	10	10	10	10	10	10
Non-elastic	3	3	3	5	10	10	10	10	20	20	20	20
Total (n,n')	3	4	-	-	-	50	30	30	30	30	30	30
Discrete (n,n')	3	51-59	-	-	-	50	50	50	50	-	-	-
Continum (n,n')	3	91	-	-	-	-	-	-	30	30	30	30
(n,2n)	3	16	-	-	-	-	-	-	-	20	20	20
(n,3n)	3	17	-	-	-	-	-	-	-	-	30	30
$(n,n'\alpha)$	3	22	-	-	-	-	-	-	-	400	400	400
(n,n'p)	3	28	-	-	-	-	-	-	-	400	400	400
(n,γ)	3	102	3	5	10	10	10	20	25	30	50	50
(n,p)	3	103	100	100	100	100	100	100	20	20	20	20
(n,d)	3	104	-	-	-	-	-	-	-	200	200	200
(n,t)	3	105	-	-	-	-	-	-	-	200	200	200
(n,He^3)	3	106	-	-	-	-	-	-	-	-	-	200
(n,α)	3	107	100	100	100	100	50	50	50	30	30	30
$Total_{(n,x\gamma)}$	12	3+102	10	20	20	20	20	30	30	30	30	30

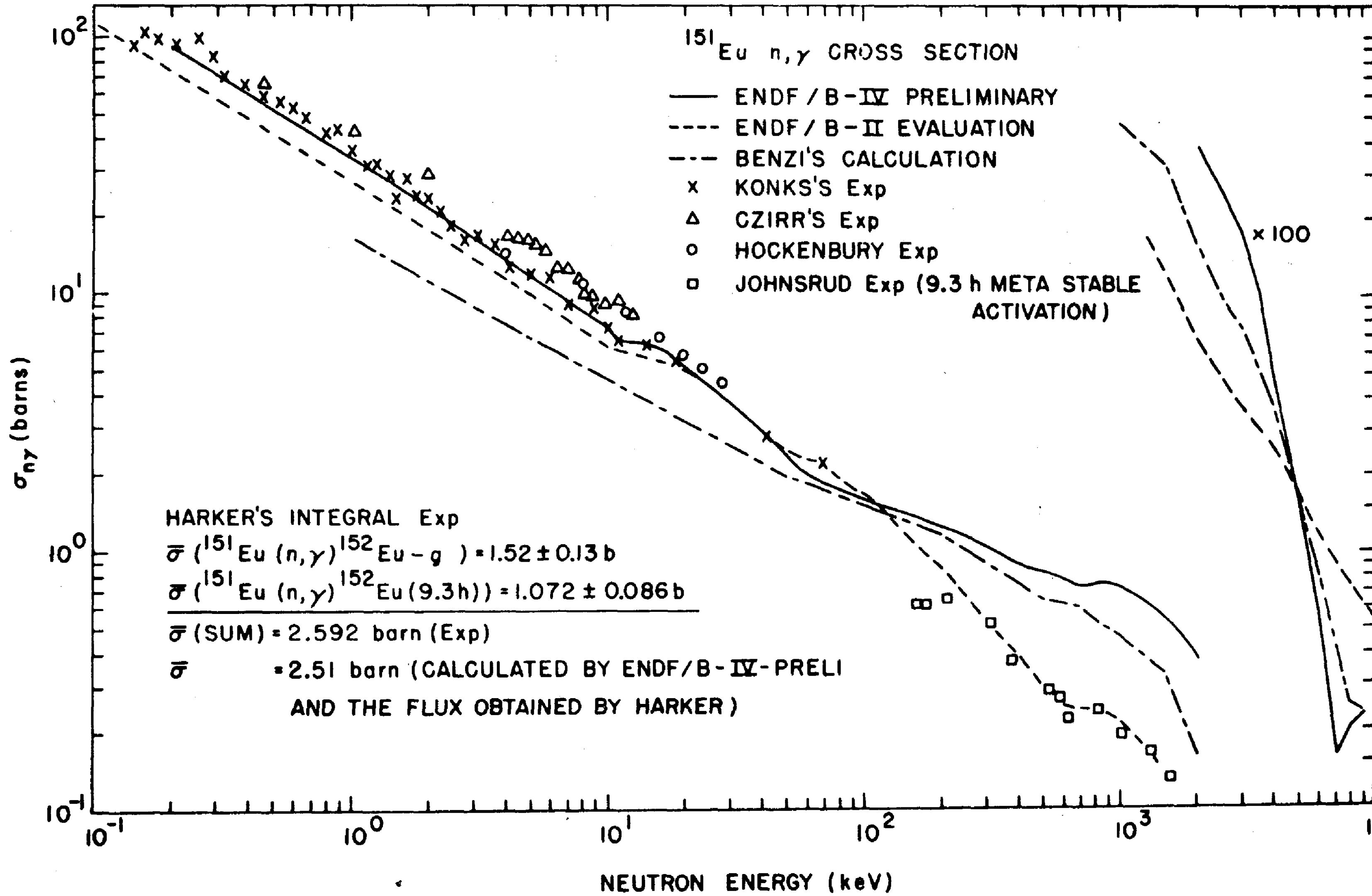
*Percentage errors.

Table 7

Estimated Uncertainties in the Evaluated Cross Section of Eu-153*

Cross Section	ENDF/B Designation MF	ENDF/B Designation MT	Neutron Energy (eV) Thermal	1	10^4	10^5	$3x10^5$	10^6	$3x10^6$	10^7	$1.4x10^7$	$2.0x10^7$
Total	3	1	6	10	5	5	5	5	5	5	5	5
Elastic	3	2	6	15	10	10	10	10	10	10	10	10
Non-elastic	3	3	3	5	10	10	10	10	20	20	20	20
Total (n,n')	3	4	-	-	-	50	30	30	30	30	30	30
Discrete (n,n')	3	51-61	-	-	-	50	50	50	50	-	-	-
Continum (n,n')	3	91	-	-	-	-	-	-	30	30	30	30
(n,2n)	3	16	-	-	-	-	-	-	-	20	20	20
(n,3n)	3	17	-	-	-	-	-	-	-	-	30	30
(n,n'α)	3	22	-	-	-	-	-	-	-	400	400	400
(n,n'p)	3	28	-	-	-	-	-	-	-	400	400	400
(n,γ)	3	102	3	5	10	10	10	20	25	30	50	50
(n,p)	3	103	-	-	-	-	-	-	20	20	20	20
(n,d)	3	104	-	-	-	-	-	-	-	200	200	200
(n,t)	3	105	-	-	-	-	-	-	-	200	200	200
(n,He^3)	3	106	-	-	-	-	-	-	-	-	-	200
(n,α)	3	107	100	100	100	100	50	50	50	30	30	30
$Total_{(n,x\gamma)}$	12	3+102	10	20	20	20	20	30	30	30	30	30

*Percentage errors.



^{151}Eu n,γ CROSS SECTION
ENDF/B-IV PRELIMINARY
ENDF/B-II EVALUATION
BENZI'S CALCULATION
KONKS'S Exp
CZIRR'S Exp
HOCKENBURY Exp
JOHNSRUD Exp (9.3 h META STABLE ACTIVATION)
×100
HARKER'S INTEGRAL Exp
$\bar{\sigma}$ (^{151}Eu (n,γ)^{152}Eu − g) = 1.52 ± 0.13 b
$\bar{\sigma}$ (^{151}Eu (n,γ)^{152}Eu(9.3h)) = 1.072 ± 0.086 b
$\bar{\sigma}$ (SUM) = 2.592 barn (Exp)
$\bar{\sigma}$ = 2.51 barn (CALCULATED BY ENDF/B-IV-PRELI AND THE FLUX OBTAINED BY HARKER)
$\sigma_{n\gamma}$ (barns)
NEUTRON ENERGY (keV)
10^{-1}
10^0
10^1
10^2
10^3
10^4

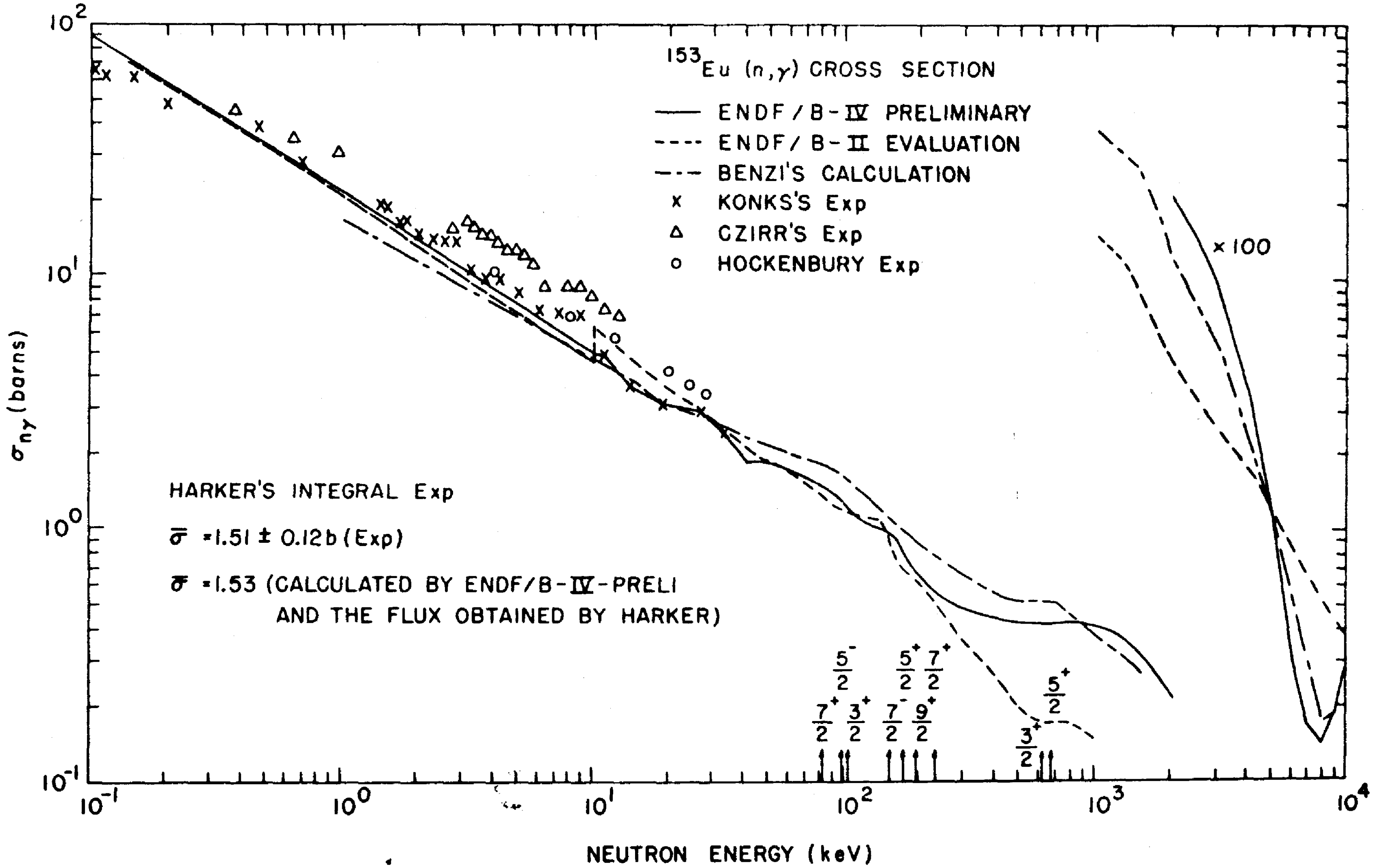
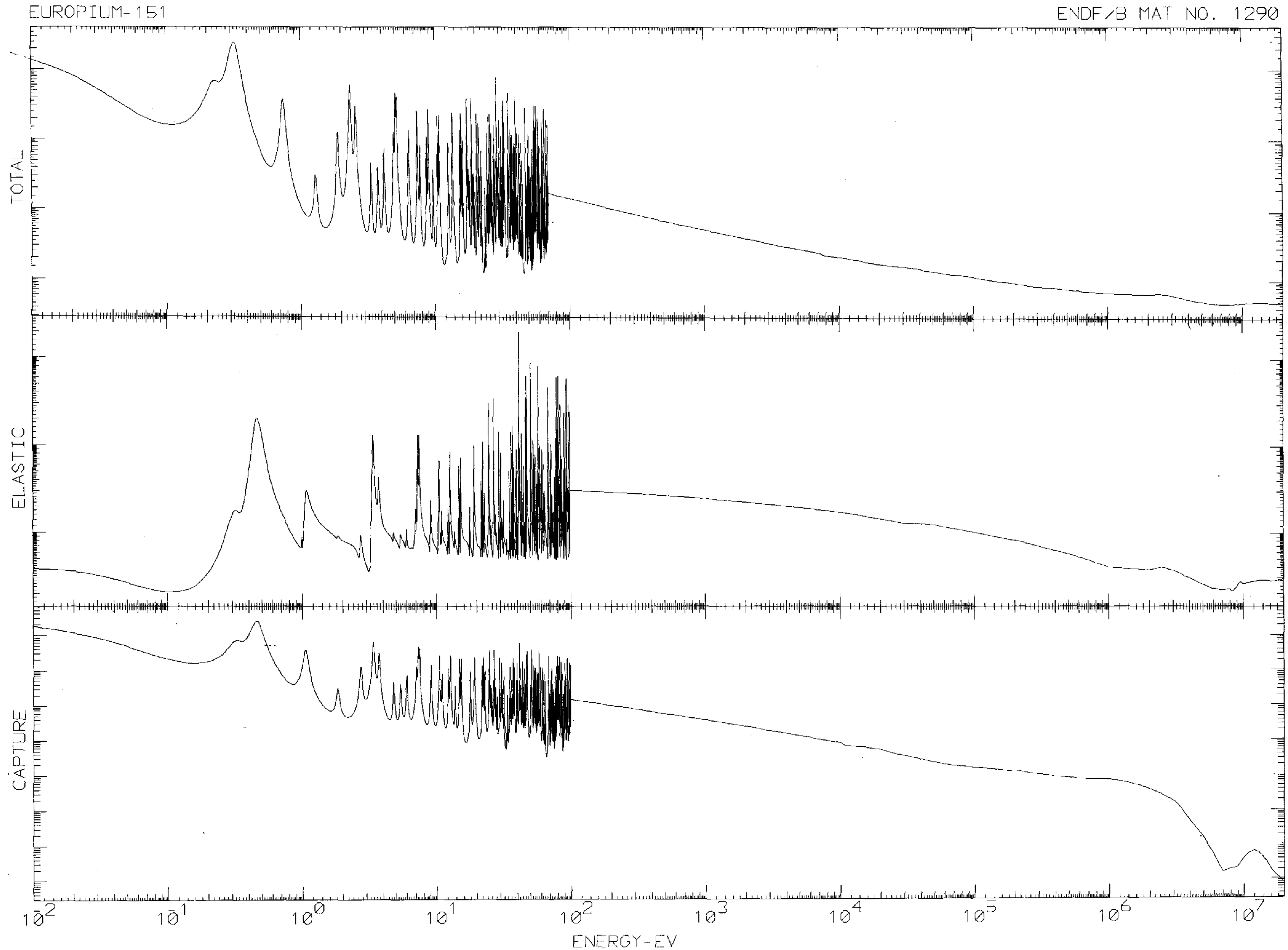
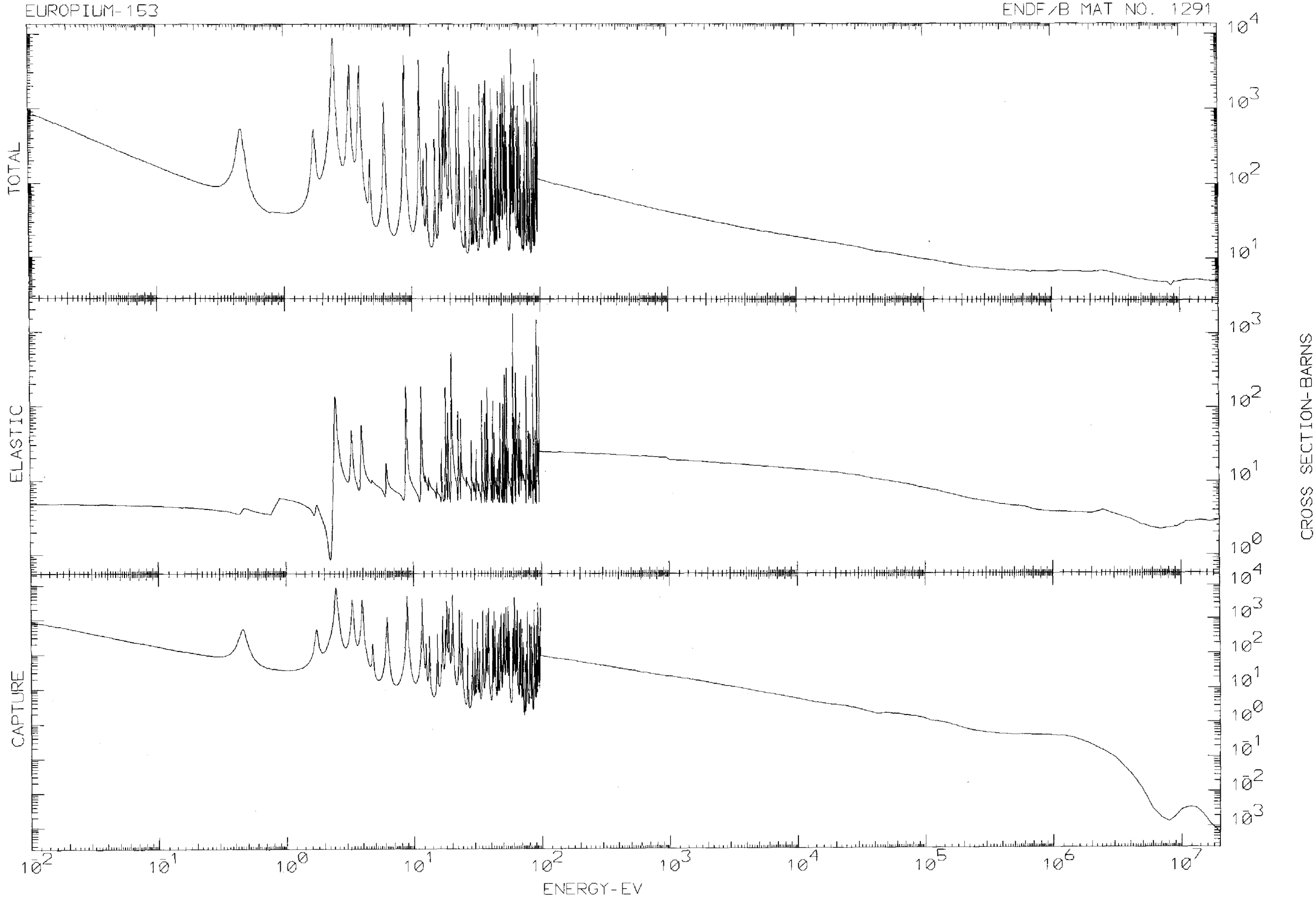

153Eu (n,γ) CROSS SECTION
ENDF/B-IV PRELIMINARY
ENDF/B-II EVALUATION
BENZI'S CALCULATION
KONKS'S Exp
CZIRR'S Exp
HOCKENBURY Exp
×100
HARKER'S INTEGRAL Exp
σ̄ =1.51 ± 0.12b (Exp)
σ̄ =1.53 (CALCULATED BY ENDF/B-IV-PRELI AND THE FLUX OBTAINED BY HARKER)
σnγ (barns)
NEUTRON ENERGY (keV)

Figure 3



EUROPIUM-151
ENDF/B MAT NO. 1290
TOTAL
ELASTIC
CAPTURE
CROSS SECTION-BARNS
ENERGY-EV

Figure 4



EUROPIUM-153
ENDF/B MAT NO. 1291
TOTAL
ELASTIC
CAPTURE
CROSS SECTION-BARNS
ENERGY-EV