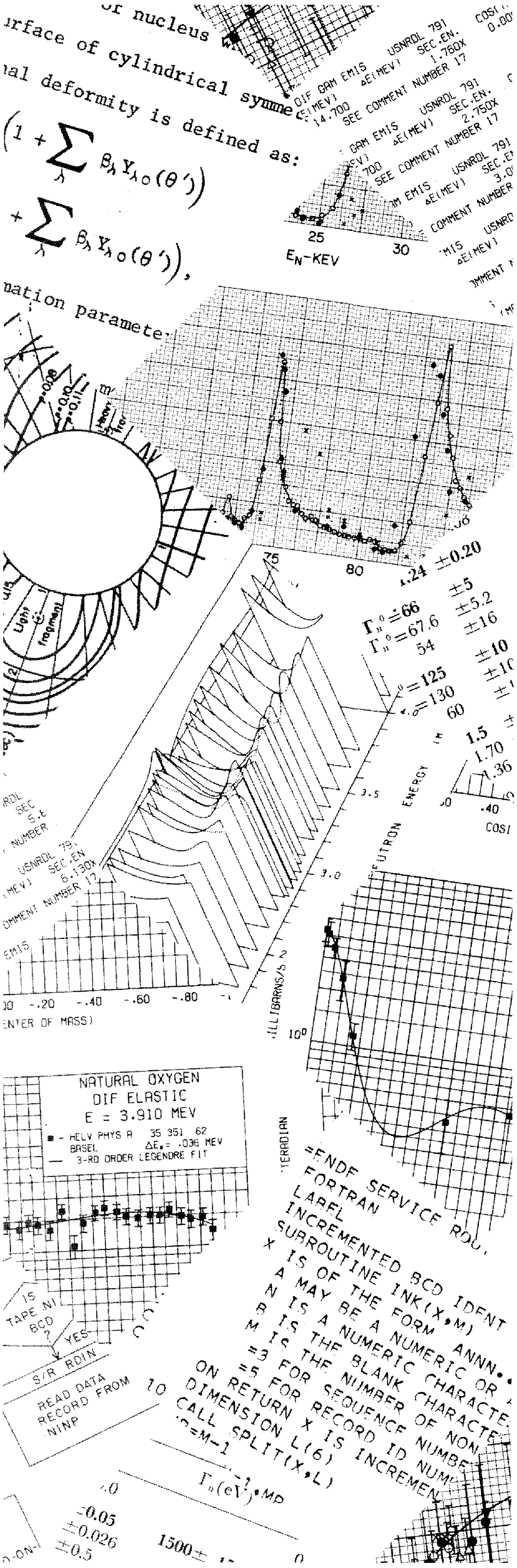

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EVALUATION OF THE NEUTRON CROSS SECTION FOR ^{152}Eu AND ^{154}Eu

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INFORMAL REPORT

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National
Neutron
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Evaluation of the Neutron Cross Section for ^{152}Eu and ^{154}Eu*

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1. Introduction

This report summarizes the evaluated results for the neutron cross sections for europium isotopes Eu^{152} and Eu^{154}. No experimental data are available for these isotopes except for a few reactions, so that the evaluations were mostly carried out by nuclear model calculations. These data have been compiled in the format of ENDF/B-IV.

2. General Information (File 1)

2.1 General Identification

Eu^{152}	Eu^{154}
MAT = 1292 (ENDF/B-IV)	MAT = 1293 (ENDF/B-IV)
ZA = 63152.0	ZA = 63154.0
AWR = 150.620	AWR = 152.600
$R = 0.88 \times 10^{-12}$cm	$R = 0.88 \times 10^{-12}$cm
I = 3	I = 3

3. Resonance Parameters (File 2)

3.1 Resolved Resonances

The resolved resonance parameters were generated by taking into account their statistical properties for level spacing and Γ_n^o fluctuation. The method used in this calculation was similar to the procedure used by Cook,[1] however, instead of using the Monte Carlo calculation, the level spacing and the Γ_n^o fluctuation of Eu^{152} and Eu^{154} isotopes are respectively determined by using the statistical properties of Eu^{151} and Eu^{153} isotopes.

The values of average level spacing and the reduced neutron width are determined by the procedure of Barr et al.[2] That is, the ratios of the average values for odd even nuclei to those for odd-odd nuclei were estimated from their neighboring nuclei. These ratios were multiplied to the values of Eu^{151} and Eu^{153} to obtain the ones for Eu^{152} and Eu^{154}. The gamma ray width Γ_γ were taken as constant values for all resonances. The number of resolved resonances in Eu^{152} and Eu^{154} are 108 and 77 respectively.

The thermal neutron cross-sections for these isotopes have been measured by Hayden et al.[3] and compiled by Walker.[4] The preliminary draft of new BNL-325 recommends these values to be 2300 ± 1000 barn for Eu^{152} (ground) and 1500 ± 400 barn for Eu^{154} (8 yr h). The parameters of the lowest resonances were adjusted so that the calculated thermal neutron capture cross sections agreed with the values recommended in the new BNL-325.[5]

3.2 Unresolved Resonances

Unresolved resonance parameters of Eu^{152} and Eu^{154} were given in the energy regions from 61.5 eV to 10 keV and 60.0 eV to 10 keV, respectively. As mentioned above, Barr and Devaney[2] evaluated the unresolved resonance parameters by studying the changes of these parameters from odd-odd nuclei to odd-even nuclei of Lu^{175}, Lu^{176}, and Ta^{180}, Ta^{181}. The unresolved resonance parameters were estimated by using the new BNL-325 values. These values are tabulated in Table 1.

4. Neutron Cross Section (File 3)

4.1 Total Cross Section (MT = 1)

Between 10^4 eV to 2.5 MeV neutron energy, the total cross sections were calculated using the ABACUS-2 code[6] of the optical model. The optical model parameters used in the calculation will be discussed in a later section. Above 2.5 MeV, the total cross sections for Eu^{152} and Eu^{154} were assumed to be the same as those of Eu^{151} and Eu^{153} respectively.[7] The values of the later isotopes between 2.5 MeV and 15 MeV are the experimental values of natural europium measured by Foster.[8]

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 non-elastic 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), discrete level excitation cross sections (MT = 51 ...) for the first 5 levels for both Eu^{152} and Eu^{153} and continuum level excitation cross section (MT = 91). The level scheme for these discrete level is tabulated in Table 2.[9,10,11,12]

Since no experimental data are available for the individual level excitation cross sections, they were calculated using the COMNUC-3 code[14,15] for energies up to 3 MeV. Above 3 MeV, neutron energy, 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 code.[16] The level density parameters for the continuum of levels were taken from Cook's data[18] for the deformed nuclei using the Gilbert-Cameron formula.[19]

In this study, the inelastic scattering cross sections of the discrete levels were calculated assuming them to be due to 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 excites these levels by a direct process is not negligibly small. This deficiency will be improved by the future calculations using the JUPITOR Code.[20]

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

No experimental values were available, so that we calculated these by nuclear model codes. For (n,p) reaction, the semi-empirical statistical model code THRESH[21] was used, but the evaluation[7] of Eu^{151} and Eu^{153} indicated that the cross sections around 14 MeV calculated by this code were small compared to the experimental values. Thus, the calculated cross sections for Eu^{152} and Eu^{154} were normalized by the factors obtained for Eu^{151} and Eu^{153} respectively.

The (n,n'p) cross sections were calculated by using GROGI-3.

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

These cross sections were obtained in the similar manner as the cases of (n,p) and (n,n'p) reactions.

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

These cross sections were calculated by using the GROGI-3 code. The optical model parameters described in the later section were used. The Q-values used in this calculation are shown in Table 3.

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

The cross sections calculated by THRESH were adopted as the evaluated cross sections.

4.9 The Radiative Capture Cross Section (MT = 102)

The radiative capture cross sections at low energy range were calculated from the resonance parameters discussed in the section of File 2 and are presented as smooth cross sections. The cross sections between 100 eV to 10 keV are presented as the unresolved resonance parameters.

For energy higher than 10 keV, the cross sections were evaluated by the COMNUC-3 calculation. The calculation was done similarly to the ones for Eu^{151} and Eu^{153}. That is, we assumed Moldauer's Q value to be zero, and the correlation correction factor due to the degree of freedom associated with open channel was taken into account in the calculation. From 3 MeV to 20 MeV, the capture cross section was obtained by GROGI-3 for compound process, the Cvelbar's formula[23] based on Lane-Lynn[24] and Brown's[25] formula was used to calculate the capture cross section due to direct and semi-direct reaction.

5. Angular Distribution of Secondary Neutrons (File 4)

5.1 Elastic Scattering (MT = 2)

These were calculated by ABACUS-2 (NABAK PDP-10 Version)[6] and the Legendre coefficients calculated by CHAD (NUCHAD in PDP-10 Version)[26] were given in the File 4. Since the elastic scattering due to the nuclear compound process is small in the energy range above 3 MeV, the angular distribution of elastic scattering neutron was calculated by taking only the shape elastic scattering into account above 3 MeV.

5.2 Inelastically Scattered Neutron, (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, 16, and 91)

The energy distribution of neutron from the (n,2n), (n,3n) and the inelastic scattering cross section of continuum part were assumed to be Maxwellian. The effective temperature of these distributions were obtained by the Weisskopf formula.[27]

7. Nuclear Model Calculations

7.1 Optical Model Parameter

In this evaluation work, optical model calculations have been used to obtain the neutron, proton and α particle 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

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

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

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

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

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

The neutron parameters at a neutron energy E_n(MeV) are mostly taken from Becchetti and Greenlees[28] data, which is shown as follows:

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

$$r_o = 1.17 \quad a = 0.75$$

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

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

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

$$V_{so} = 6.2$$

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

where the unit of length is in Fermi.

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.[29]

$V =$	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		

7.2 Statistical Model Calculation

Hauser-Feshbach calculation for inelastic scattering cross section and capture cross section was done with the revised version of COMNUC-III.[14] In this calculation, we assumed the factor Q = 0, but the width fluctuation correction factor $S^{J\pi}_{cc'}$[15] was taken into account. The level density parameters for deformed nuclei of Gilbert and Cameron[19] and Cook et al.[18] 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 3.)

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

The angular distributions of elastic scattering cross section were calculated by the ABACUS-2 code and the Legendre coefficients of these angular distributions were calculated by the CHAD code.

8. Uncertainty Estimates

Estimates of the cross section uncertainties for Eu-152 and Eu-154 were made for File 3 data. The uncertainties given in Tables 4 and 5 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.

9. Evaluated Cross-Sections

The curves showing the general trend and behaviour of the evaluated cross-sections of ^{152}Eu and ^{154}Eu are shown in Figs. 1 and 2.

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Table 1

Unresolved Resonance Parameters

Isotope	Eu^{152}	Eu^{154}
Γ_γ(eV)	9.2×10^{-2}	9.6×10^{-2}
Dobs (eV)	0.444	0.8034
$S_o(eV^{\frac{1}{2}})$	4.035×10^{-4}	2.726×10^{-4}
$S_1(eV^{\frac{1}{2}})$	1.0905×10^{-4}	0.6542×10^{-4}

Table 2

Nuclear Level Structure of Eu^{152} and Eu^{154}

Eu^{152}		Eu^{154}	
E_{ex} (keV)	J^π	E_{ex} (keV)	J^π
0.0	3^-	0.0	3^-
50.0	0^-	68.0	0^-
89.5	4^+	82.8	4^+
108.1	5^+	122.1	5^+
130.0	7^-	172.2	7^-
147.8	8^-	180.0	8^-
Continuum			
> 166 keV		> 231.9 keV	

Table 3

Nuclear Reactions and Their Q Values

Isotope	(n,γ)	(n,2n)	(n,3n)	(n,p)	(n,d)	(n,t)	(n,He_3^3)	(n,α)
Eu^{152}	8.5510	6.305	14.276	2.6584	3.3744	2.7135	6.1948	-8.8255
Eu^{154}	8.667	6.438	14.990	1.5124	4.2404	3.8495	7.3319	-7.3015

	(n,n'α)	(n,n'p)
Eu^{152}	-1.65	5.599
Eu^{154}	+0.607	6.465

These data are obtained from Mass Table of Wapstra and Gove.[30]

Table 4

Estimated Uncertainties in the Evaluated Cross Section of Eu-152*

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	20	50	40	25	25	15	15	15	15	15
Elastic	3	2	20	50	40	25	25	15	15	15	15	15
Non-elastic	3	3	20	50	50	50	50	35	35	20	20	20
Total (n,n')	3	4	-	-	-	50	30	30	30	30	30	30
Discrete (n,n')	3	51-55	-	-	-	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
(n,n'p)	3	28	-	-	-	-	-	-	-	-	400	400
(n,γ)	3	102	20	-	30	30	30	30	35	30	50	50
(n,p)	3	103	300	300	300	300	300	40	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	300	300	300	300	300	300	50	30	30	30

*Percentage errors

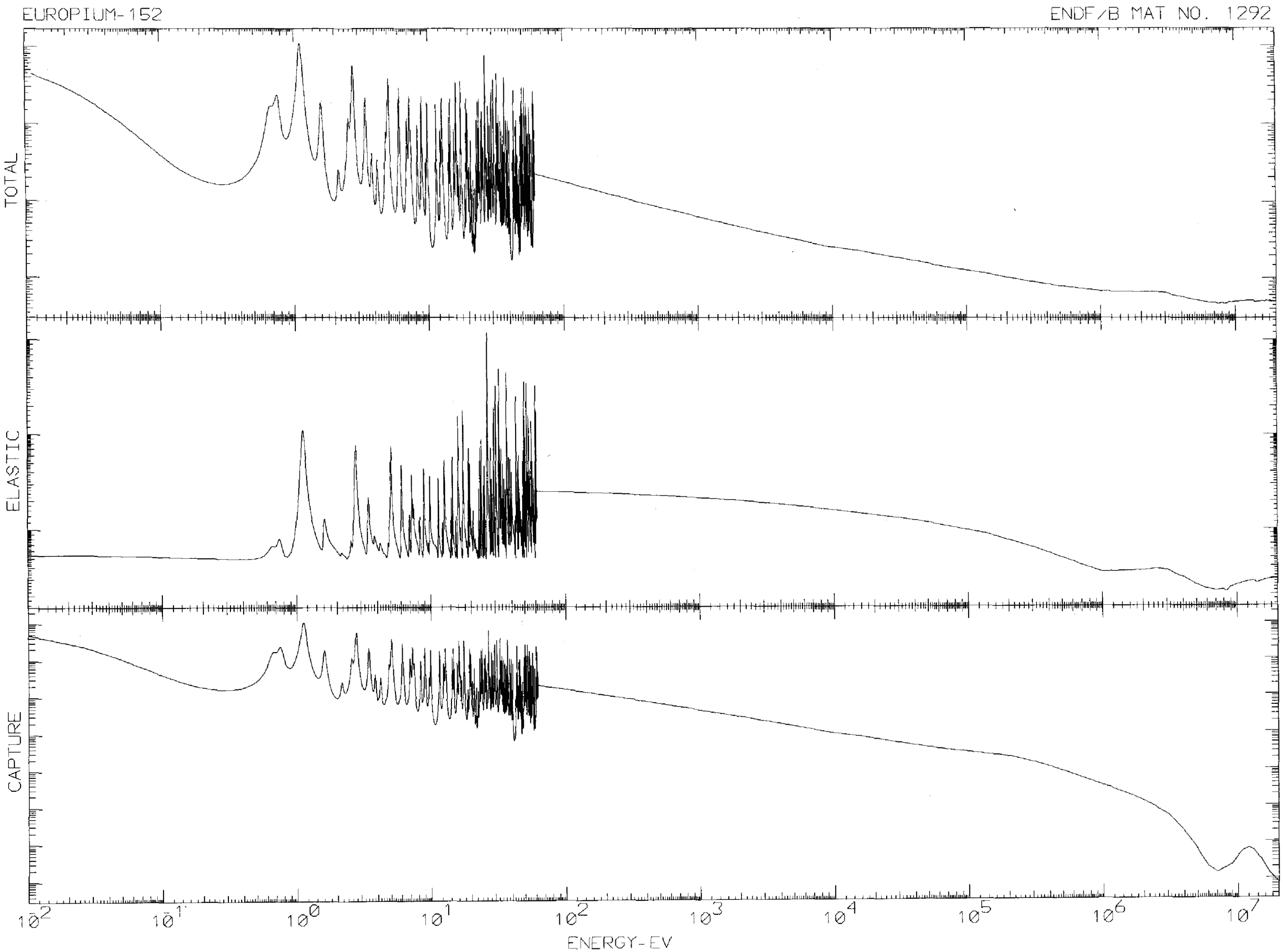
Table 5

Estimated Uncertainties in the Evaluated Cross Section of Eu-154*

Cross Section	ENDF/B Designation MF	ENDF/B Designation MT	Thermal	1	10^4	10^5	$3x10^5$	10^6	$3x10^6$	10^7	$1.4x10^7$	$2.0x10^7$
Total	3	1	20	50	40	25	25	15	15	15	15	15
Elastic	3	2	20	50	40	25	25	15	15	15	15	15
Non-elastic	3	3	20	50	50	50	50	35	35	20	20	20
Total (n,n')	3	4	-	-	-	50	30	30	30	30	30	30
Discrete (n,n')	3	51-55	-	-	-	50	50	50	50	-	-	-
Continum (n,n')	3	91	-	-	-	-	30	30	30	30	30	30
(n,2n)	3	16	-	-	-	-	-	-	0	20	20	20
(n,3n)	3	17	-	-	-	-	-	-	0	-	30	30
(n,n'α)	3	22	-	-	-	-	-	-	0	-	400	400
(n,n'p)	3	28	-	-	-	-	-	-	0	-	400	400
(n,γ)	3	102	20	-	30	30	30	30	35	30	50	50
(n,p)	3	103	-	-	-	-	-	40	20	20	20	20
(n,d)	3	104	-	-	-	-	-	-	0	200	200	200
(n,t)	3	105	-	-	-	-	-	-	0	200	200	200
(n,He^3)	3	106	-	-	-	-	-	-	0	-	-	200
(n,α)	3	107	300	300	300	300	300	50	50	30	30	30

*Percentage errors

Figure 1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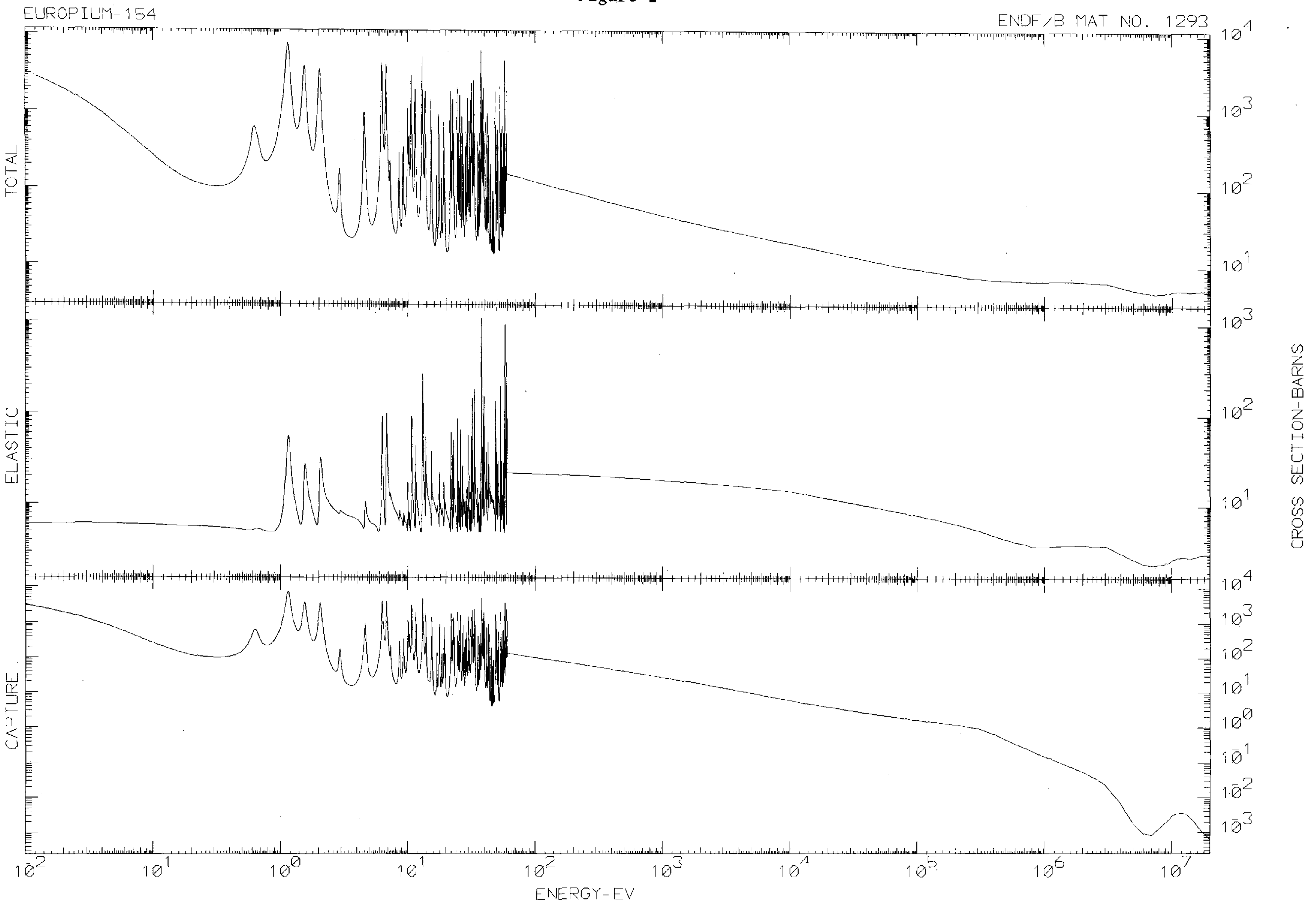
ENDF/B MAT NO. 1292
TOTAL
ELASTIC
CAPTURE
CROSS SECTION-BARNS
ENERGY-EV

Figure 2



EUROPIUM-154
ENDF/B MAT NO. 1293
TOTAL
ELASTIC
CAPTURE
CROSS SECTION-BARNS
ENERGY-EV