Measurement of thermal neutron cross section and resonance integral for the ^{170}Er$(n, \gamma)^{171}$Er reaction by using a ^{55}Mn monitor

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The thermal neutron cross section and the resonance integral of the reaction ^{170}Er$(n, \gamma)^{171}$Er were measured by the Cd-ratio method using a ^{55}Mn monitor as single comparator. Analytical grade MnO_2 and Er_2O_3 powder samples with and without a cylindrical 1 mm Cd shield box were irradiated in an isotropic neutron field obtained from three ^{241}Am-Be neutron sources. The induced activities in the samples were measured with a 120.8% relative efficiency p-type HPGe detector. The correction factors for gamma-ray attenuation (F_g), thermal neutron self-shielding (G_{th}), and resonance neutron self-shielding (G_{epi}) effects, and the epithermal neutron spectrum shape factor (α) were taken into account. The thermal neutron cross section for the (n, γ) reaction in ^{170}Er has been determined to be 8.00 ± 0.56 b, relative to that of the ^{55}Mn monitor. However, some previously reported experimental results compared to the present result show a large discrepancy ranging from 8.3 to 86%. The present result is, in general, in good agreement with the recently measured values by 9%. According to the definition of Cd cut-off energy at 0.55 eV, the resonance integral obtained is 44.5 ± 4.0 b, which is determined relative to the reference integral value of the ^{55}Mn monitor by using cadmium ratios. The existing experimental data for the resonance integral are distributed between 18 and 43 b. The present resonance integral value agrees only with the measurement of 43 ± 5 b by Gillette [Thermal Cross Section and Resonance Integral Studies, ORNL-4155, 15 (1967)] within uncertainty limits.

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I. INTRODUCTION

The accurate knowledge of neutron cross sections is required in fundamental nuclear research and in a wide range of applications such as nuclear medicine, dosimetry, neutron activation analysis, shielding calculations, waste incineration, etc. [1,2]. The thermal cross section for the ^{170}Er$(n, \gamma)^{171}$Er reaction is of particular interest due to the versatility and safety of the neutron activation technique in the radiolabeling of intact dosage forms. The stable isotope ^{170}Er in enteric-coated pellets has recently been used in medical imaging studies to evaluate the *in vivo* behavior of radiolabeled dosage forms due to its favorable nuclear and physical properties, as well as other stable isotopes such as ^{138}Ba and ^{152}Sm [3]. In literature, the discrepancies among the experimental results for the thermal cross section, σ_0 (from 4.3 b to 15 b) and the resonance integral cross section, I_0 (from 18 to 43 b) are in the order 8–86% and 3.5–147%, respectively. It seems that there is no sufficient consistency among σ_0- or I_0-values, nor among the resonance integral to thermal neutron cross section ratios $Q_0 = (I_0/\sigma_0)$. Discrepancies have been reported for other nuclides: e.g., St-Pierre and Kennedy [4] remeasured the Q_0 and k_0 values of 14 nuclides (^{76}As, ^{88}Rb, ^{85}Sr, ^{109}Pd, ^{110}Ag^m, ^{115}Cd, ^{116}In^m, ^{128}I, ^{130}Ba, ^{134}Cs, ^{134}Cs^m, ^{170}Tm, ^{182}Ta, and ^{186}Re), as the literature values showed discrepancies greater than 5%.

The neutron cross section measurements are generally carried out by the activation method using various neutron sources with high neutron densities (obtained from reactors or accelerator-based neutron sources) and the ^{197}Au-monitor as an ultimate standard. However, accurate monitoring of highly intense neutron fields is complicated by the occurrence of burn up effects with some monitors. In particular, the burn up of the ^{197}Au and ^{170}Er isotopes having relatively high-neutron capture cross sections can give rise to the subsequent activation of the reaction products ^{198}Au ($I_0 = 1550$ b) and ^{171}Er ($\sigma_0 = 2800$ b) [5]. Hence, the specific activities of the products are not proportional to the neutron flux. To overcome this limitation, a relatively low neutron flux obtained from an isotopic neutron source ^{241}Am-Be was used in the measurement of the σ_0 and I_0 values of the reaction ^{170}Er$(n, \gamma)^{171}$Er. In addition, ^{55}Mn has been considered to be a convenient alternative monitor with good resonance parameters for the resonance integral determination in which most of the resonance captures occur at relatively high neutron energy of about 337 eV, which is quite far from the $1/v$ region. Other advantages of a ^{55}Mn monitor have been described previously [6,7]. The aim of this study is to carry out a new cross-section measurement by using the Cd-ratio method in order to clarify the existing differences in the σ_0 and I_0 values for the ^{170}Er$(n, \gamma)^{171}$Er reaction.

II. EXPERIMENTAL

The irradiations were performed in one of the four positions (position 2 seen in Fig. 1) of the neutron irradiator unit consisting of three ^{241}Am-Be neutron sources, inserted in a paraffin moderator and shielded by a Cd-sheet and lead bricks. This irradiator has been previously described in detail [8].

The thermal neutron flux (ϕ_{th}) and epithermal neutron flux (ϕ_{epi}) at the sample irradiation position of the neutron irradiator have been measured to be $(1.5 \pm 0.2) \times 10^4$ and

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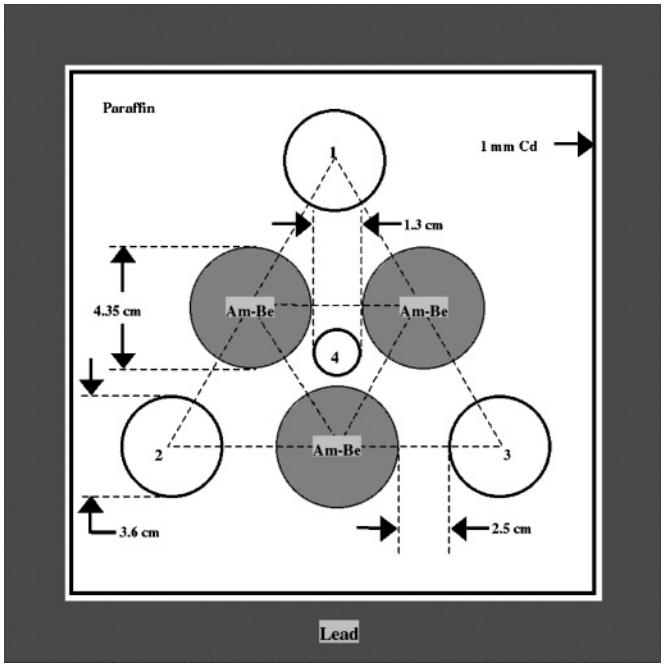

FIG. 1. Top view of the triple ^{241}Am–Be neutron source configuration (not to scale). Paraffin: 70 cm, lead: 10 cm thickness. The activity of each source is a 592 GBq and the sample irradiation positions are numbered by circles 1 to 4.

$(1.4 \pm 0.1) \times 10^3$ cm^{-2} s^{-1}, respectively. The measured Cd-ratio of the ^{197}Au monitor was used to determine the ratio of thermal to epithermal neutron fluxes, $f = \phi_{th}/\phi_{epi}$. The equation, $f = Q_0(\alpha) \cdot (R_{\mathrm{Cd}} \cdot F_{\mathrm{Cd,Au}} - 1)$ resulted in $f = 10.42 \pm 0.31$, using the following values of $Q_0 = 15.7$, effective resonance energy $\bar{E}_r = 5.65$ eV, cadmium transmission factor for epithermal neutrons, $F_{\mathrm{Cd,Au}} = 0.991$, $E_\gamma = 411.8$ keV for the ^{197}Au$(n, \gamma)^{198}$Au reaction [9], and the epithermal spectrum shape factor $\alpha = 0.083 \pm 0.016$. The α shape factor at the fixed sample irradiation position was determined using the "Cd-ratio for dual monitor" method with ^{98}Mo and ^{197}Au monitors [8].

A. Samples

The Cd filter was a cylinder box with 1 mm thickness, 10 mm diameter, and 20 mm height. The analytical grade finely grained samples (obtained from Aldrich Inc.) were filled in polystyrene tubes with 1 mm wall thickness and 6.5 mm internal diameter. The MnO_2 and Er_2O_3 powders were diluted by thoroughly mixing Al_2O_3 powder so as to minimize errors due to neutron self-shielding effect. The percentages of dilution for the samples were experimentally determined in order to obtain optimum counting statistics in the measurements. A total of ten diluted Er_2O_3 samples were individually prepared. Five of them were used for Cd-covered irradiation and the remaining five samples were used for obtaining bare irradiation data. The same sample preparation procedures were employed for a total of ten samples of MnO_2. In addition, two samples for each type sample (Er_2O_3 and MnO_2) were prepared for use in neutron self-shielding calculations.

B. Irradiation and counting

The samples were exposed to the isotropic neutron field in a fixed position in the irradiation hole, having a very large volume compared to the sample volume. Accordingly, the effect of thermal flux depression at the irradiation position could be neglected. The sample irradiations were performed with and without Cd box at the same fixed position. The mean of the five measured specific activities from the chosen gamma-rays are taken. The irradiation times for the (n, γ) reactions of ^{55}Mn and ^{170}Er were chosen for a period of three to five half-lives, yielding enough activity to be measured in a γ-ray spectrometry system. The suitable waiting times were employed to minimize dead time losses and eliminate the possible contributions of the 843.8 keV γ-ray from ^{27}Mg (9.45 m) to the 846.7 keV peak of ^{56}Mn.

The irradiated samples were measured by a γ-ray spectrometry system equipped with a coaxial p-type HPGe detector (Canberra GC11021) with a measured relative efficiency of 120.8%, an energy resolution of 1.95 keV and a peak-to-Compton ratio of 85.7:1 at 1332.5 keV of ^{60}Co. The detector was interfaced to a Digital Spectrum Analyzer (Canberra DSA-1000) based on digital signal processing. The net peak areas under the full energy peaks were evaluated both manually and by the interactive peak fitting module of Genie-2000 software. Each spectrum was collected in 4096 channels memory with a gain of 0.52 keV/channel, and in the live-time mode. The samples were counted at a distance of 10 cm from the detector in order to keep possible true coincidence effects at a reasonably low level. The chosen counting times varied between 15 h and 45 h for ^{171}Er and between 2.5 and 10 h for ^{56}Mn, and they were long enough to ensure good statistical quality of data. Background measurements were subtracted from the sample spectra.

The gamma-ray detection efficiency as a function of energy was determined with an uncertainty between 2.5% and 3.5%, using calibrated powder standard containing a mixture of ^{241}Am, ^{109}Cd, ^{57}Co, ^{123}Te^m, ^{51}Cr, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{60}Co, and ^{88}Y radionuclides, obtained from Isotope Products Laboratories, Inc., traceable to NIST.

III. EXPERIMENTAL ANALYSIS

For the determination of thermal neutron and resonance integral cross sections, the reaction rates have been used in the analysis of the measured spectral data from the induced activities. The data analysis is briefly described below.

A. Thermal neutron cross section

The thermal neutron cross section for the reaction ^{170}Er$(n, \gamma)^{171}$Er has been determined relative to that of the ^{55}Mn$(n, \gamma)^{56}$Mn reaction, taking into account the thermal neutron self-shielding effect, G_{th} as follows:

$$\sigma_{0,\mathrm{Er}} = \left[\frac{(r - r_{\mathrm{Cd}}/F_{\mathrm{Cd}})_{\mathrm{Er}}}{(r - r_{\mathrm{Cd}}/F_{\mathrm{Cd}})_{\mathrm{Mn}}}\right] \cdot \left[\frac{G_{th,\mathrm{Mn}}}{G_{th,\mathrm{Er}}}\right] \cdot \sigma_{0,\mathrm{Mn}}, \quad (1)$$

TABLE I. The calculated γ-ray attenuation factors and some nuclear data used in the analyses.

Nuclear reaction	Cadmium transmission factor, F_{Cd} [12]	Effective resonance energy[a], E_r (eV) [13,14]	Half-life (h) [5]	The measured gamma-ray		
				Energy (keV) [5]	Emission probability, γ (%) [5]	Self attenuation factor, F_g [11]
^{55}Mn$(n,\gamma)^{56}$Mn	1.00	468 ± 51	2.5789(1)	846.754(20)	98.9(3)	1.010
^{170}Er$(n,\gamma)^{171}$Er	1	129 ± 2.97	7.516(2)	308.291(18)	64(3)	1.036

[a]For $E_{Cd} = 0.55$ eV.

where r and r_{Cd} are reaction rates per target atom for bare and Cd-covered isotope irradiation, respectively. σ_0 is thermal neutron cross section and F_{Cd} is the cadmium transmission correction factor for epithermal neutrons, which accounts for the fact that in some cases, the specific epithermal reaction rate of a cadmium covered isotope significantly differs from the specific epithermal reaction rate of the bare isotope. However, each of the isotopes considered has a good $1/v$ behavior, since the Westcott correction factors, g (20°C), for ^{55}Mn and ^{170}Er are close to unity. Thus the Westcott formalism does not have to be introduced into Eq. (1), which is written in the Hϕgdahl formalism modified for a $1/E^{1+\alpha}$ epithermal neutron flux shape [10]. Then, the reaction rates r and r_{Cd} are determined by

$$r = \frac{A_{sp}^{-} \cdot F_g \cdot M}{\theta \cdot N_A \cdot \gamma \cdot \varepsilon_p} \quad \text{and} \quad r_{Cd} = \frac{A_{sp}^{+} \cdot F_g \cdot M}{\theta \cdot N_A \cdot \gamma \cdot \varepsilon_p} \tag{2}$$

with

$$A_{sp}^{-} = \frac{N_p/t_m}{w \cdot S \cdot D \cdot C} \quad \text{and} \quad A_{sp}^{+} = \left(\frac{N_p/t_m}{w \cdot S \cdot D \cdot C}\right)_{Cd}, \tag{3}$$

where A_{sp}^{-} and A_{sp}^{+} are the specific activities obtained after bare and Cd-covered irradiation; N_p is the net number of counts under the full-energy peak collected during measuring (live) time, t_m; w is the mass of the irradiated element; $S = 1 - e^{-\lambda t_{irr}}$ is the saturation factor with decay constant, λ and irradiation time, t_{irr}; $D = e^{-\lambda t_d}$ is the decay factor with decay time, t_d; $C = (1 - e^{-\lambda t_r})/\lambda t_r$ is the measurement factor correcting for decay during the measuring true time, t_r; M is atomic weight; θ is isotopic abundance; N_A is Avogadro's number; γ is absolute γ-ray emission probability; ε_p is full-energy peak efficiency; F_g is correction factor for γ-ray attenuation. The F_g correction factors have been calculated for 308.3 keV from ^{171}Er and for 846.7 keV γ-rays from ^{56}Mn at fixed sample geometry for the case of a cylinder coaxially positioned with the detector, using the simple relation, $F_g = \mu x/(1 - e^{-\mu x})$, where x is the sample thickness (in cm) and μ is the linear attenuation coefficient (in cm^{-1}). The latter is determined from the total mass attenuation coefficients, μ/ρ (cm^2 g^{-1}), for the mixtures, which are taken from the XCOM database [11]. The calculated F_g correction factors for the radioactivity measurements and other nuclear data used in the analyses are given in Table I.

1. Resonance integral

The resonance integral was measured at a particular irradiation position, $I_0(\alpha)$ for a real epithermal neutron flux distribution (represented by a $1/E^{1+\alpha}$-shape), which is characterized by the epithermal spectrum shape factor, α as follows [15,16]:

$$I_0(\alpha) = (1\text{ eV})^{\alpha}\left[\frac{I_0 - 0.429 g\sigma_0}{(\bar{E}_r)^{\alpha}} + \frac{0.429\sigma_0}{(2\alpha+1)(E_{Cd})^{\alpha}}\right]. \tag{4}$$

In general, the epithermal spectrum shape factor (α) is assumed to be energy independent [17]. In Eq. (4), the knowledge of the effective resonance energy, $\bar{E}_r$ (eV), as defined by Ryves [18], is required. The cadmium cut-off energy, E_{Cd} is also set at 0.55 eV for a small sample in a 1 mm thick Cd box (height/diameter $\cong$ 2) according to the definition of EANDC [19]. The literature values of $\bar{E}_r$ for ^{55}Mn and ^{170}Er are given in Table I. The term (I_0–$0.429 g\sigma_0$) given in Eq. (4) denotes the reduced resonance integral, i.e., with the $1/v$ tail subtracted by a factor of $0.429 \cong 2 \cdot \sqrt{E_{th}/E_{Cd}}$, where E_{th} is the mean thermal neutron energy (0.0253 eV). The $(1\text{eV})^{\alpha}$, reference energy term, which originates from the definition of the epithermal neutron flux in a nonideal $1/E^{1+\alpha}$ distribution [10,20], is numerically unity. Thus, it is clearly observed that Eq. (4) is only valid for $E_{Cd} = 0.55$ eV. Then, the $I_0(\alpha)$ experimental value for the ^{170}Er$(n,\gamma)^{171}$Er reaction is determined relative to that for the ^{55}Mn$(n,\gamma)^{56}$Mn reaction, using reference values of the cross sections ($\sigma_{0,Er}$; $\sigma_{0,Mn}$ and $I_{0,Mn}$) and the measured cadmium ratios R_{Cd}, as follows:

$$I_0(\alpha)_{Er} = \left[\frac{(R_{Cd}-1)_{Mn}}{(R_{Cd}-1)_{Er}}\right] \cdot \left[\frac{\sigma_{0,Er}}{\sigma_{0,Mn}}\right] \cdot \left[\frac{G_{epi,Mn}}{G_{epi,Er}}\right] \cdot \left[\frac{G_{th,Er}}{G_{th,Mn}}\right] \times I_0(\alpha)_{Mn}. \tag{5}$$

The cadmium ratio R_{Cd} can be easily determined from the measured specific activities for both ^{56}Mn and ^{171}Er isotopes, defined as $R_{Cd} = A_{sp}^{-}/(A_{sp}^{+}/F_{Cd})$. In Eq. (5), the thermal neutron self-shielding factor, G_{th} and epithermal self-shielding

TABLE II. The calculated neutron self-shielding factors for diluted Er_2O_3 and MnO_2 samples.

	Neutron self-shielding factors	
	Thermal, G_{th}	Epithermal, G_{epi}
96.6%Al_2O_3 + 3.4% MnO_2	0.997	0.903
95.0%Al_2O_3 + 5.0% Er_2O_3	0.983	0.822

TABLE III. Typical experimental uncertainties for the thermal neutron cross section measurements.

Uncertainties due to	Uncertainties (%)	
	^{170}Er	^{55}Mn
Statistical uncertainty[a]	0.83	0.39
Detection efficiency	2.5	2.8
Mass of sample	0.01	0.01
Half-life	0.03	0.004
Isotopic abundance	0.24	–
Gamma-ray emission probability	4.7	3.0
Thermal neutron self-shielding factor	0.5	0.1
Cadmium transmission factor	0.1	–
Monitor thermal neutron cross section	–	0.75
Total uncertainty	5.4	4.2

[a]Uncertainties are based on counting statistics of $\pm 1.65\sigma$.

factor, G_{epi} are estimated from a simplified procedure [6,7]. The necessary nuclear data, such as resonance parameters, absorption, scattering, total microscopic cross sections were taken from JENDL-3.3 and ENDF/B-VI online data libraries. The calculated G_{th} and G_{epi} factors for the case of an isotropic neutron field and small right cylinder geometry are given in Table II. Finally, a relationship similar to Eq. (4) is essentially required for the conversion of $I_0(\alpha)$ value measured at an irradiation position to the I_0 value tabulated in literature.

IV. RESULTS AND DISCUSSION

The experimental thermal neutron cross section and resonance integral cross section for the ^{170}Er$(n,\gamma)^{171}$Er reaction were determined relative to that for the ^{55}Mn$(n,\gamma)^{56}$Mn reaction. The reference values, $\sigma_{0,\mathrm{Mn}} = 13.3 \pm 0.1$ b and $I_{0,\mathrm{Mn}} = 14.0 \pm 0.3$ b for the ^{55}Mn monitor were used in Eqs. (1) and (5).

The typical uncertainties estimated for σ_0 and $I_0(\alpha)$ values of ^{170}Er and ^{55}Mn are given in Tables III and IV, respectively.

TABLE V. Experimental ^{170}Er$(n,\gamma)^{171}$Er cross sections.

Number of experiments	Thermal neutron cross section, σ_0(b)	Resonance integral, I_0(b)
1	8.00 ± 0.56	44.43 ± 3.97
2	8.07 ± 0.57	43.44 ± 3.90
3	8.02 ± 0.56	43.67 ± 3.92
4	7.89 ± 0.56	45.35 ± 4.08
5	7.98 ± 0.56	45.55 ± 4.11
Average	8.00 ± 0.56	44.5 ± 4.0

The main sources of uncertainty are photon emission probabilities (4.7% for the 308.3 keV γ-ray from ^{171}Er), the reference resonance integral cross section of ^{55}Mn (2.2% for I_0), and detection efficiencies (2.5% for ^{170}Er and 2.8% for ^{55}Mn) at the chosen γ-rays.

The data obtained with different irradiation and counting times of the samples were relatively close to each other. The results obtained from five independent measurements are given in Table V, and a consistency among the measured data is found. Averaging over five measurements yields the σ_0 value of 8.00 ± 0.56 b and the I_0 value of 44.5 ± 4.0 b for the ^{170}Er$(n,\gamma)^{171}$Er reaction.

The results for σ_0 and I_0 values of the ^{170}Er$(n,\gamma)^{171}$Er reaction together with earlier experimental and evaluated literature values are given in Table VI. The percentage differences between the present σ_0 value and the earlier experimental σ_0 values ranged from 8.3 to 86%. On the other hand, the resonance integral values in the literature show a large scatter, having discrepancies between 1.3% and 147% compared to the present measured value.

A comparison of the experimental σ_0 values for the ^{170}Er$(n,\gamma)^{171}$Er reaction shows that the present σ_0 value of 8.00 ± 0.56 b is within 8.3–9.7% with the values obtained by De Corte [21], De Corte and Simonits [22], and Barnes [23], but disagrees with the measurements of Heft [24], Glomset and Pappas [25], Gilette [26], and Mangal and

TABLE IV. Typical experimental uncertainties for the resonance integral cross section measurements.

Uncertainties due to (x_j)	Relative uncertainty, s_j (%)	Error propagation factor, Z(x_j)	Relative uncertainty on the resonance integral value, $s_j \times$ Z(x_j) (%)
α-shape parameter	19	0.06	1.2
Cadmium cut-off energy	15	0.03	0.45
Cadmium ratio of ^{56}Mn	1.6	1.10	1.8
Cadmium ratio of ^{171}Er	2.3	1.25	2.9
Thermal neutron self-shielding factor for Mn sample	0.1	1.00	0.10
Thermal neutron self-shielding factor for Er sample	0.5	1.00	0.50
Epithermal neutron self-shielding factor for Mn sample	0.2	1.00	0.20
Epithermal neutron self-shielding factor for Er sample	2.3	1.00	2.30
Reference resonance integral cross section of ^{55}Mn	2.2	1.51	3.3
Reference thermal neutron cross section of ^{55}Mn	0.75	1.51	1.2
Reference thermal neutron cross section of ^{170}Er	6.9	1.00	6.9
Effective resonance energy of ^{55}Mn	11	0.04	0.44
Effective resonance energy of ^{170}Er	2.3	0.07	0.16
Total uncertainty, S_T (%)			8.8

TABLE VI. Thermal neutron cross section and resonance integral cross section for ^{170}Er$(n,\gamma)^{171}$Er reaction.

Year	Ref.	Thermal neutron cross section, σ_0 (b)	%Diff.[a] in σ_0	Resonance integral Cross section, I_0 (b)	%Diff.[a] in I_0	Cadmium cut-off energy, E_{Cd} (eV)	Monitor(s) used
			Experimental results				
	This work	8.00 ± 0.56	–	44.5 ± 4.0	–	0.55	Mn
2003	De Corte [21]	8.86 ± 0.35	−9.7	–	–	0.55	Au
1997	Knopf and Waschkowski [29]	15 ± 1	−46.7	–	–	–	Absolute method
1989	De Corte and Simonits [22]	8.85 ± 0.27	−9.6	39.1 ± 1.76	13.8	0.55	Au
1978	Heft [24]	6.0 ± 1	33.3	38 ± 7	17.1	0.50	Sc, Co, Au, U
1975	Steinnes [39]	–		24 ± 4	85.4	0.50	Au
1974	Van Der Linden *et al.* [38]	–		24 ± 2.8	85.4	0.55	Au
1972	Glomset and Pappas [25]	5.8 ± 0.3	37.9	18 ± 2	147.2	–	Au
1969	Hoyodom [37]	–		32.2	38.2	0.50	Au
1968	Vertebnyj *et al.* [28]	12 ± 5	−33.3	–	–	–	Absolute method
1967	OAEP [36]	–		32.2	38.2	–	Au
1967	Gilette [26]	5.70 ± 0.15	40.4	43 ± 5	3.5	0.54	Co, Au
1963	Mangal and Gill [27]	4.3 ± 0.65	86.0	–	–	–	Au
1954	Barnes [23]	8.72 ± 1.78	−8.3	–	–	–	Au
			Evaluated data				
2007	NuDat [5]	5.8 ± 0.3		45 ± 3		–	–
2006	ENDFB-VII [30]	8.85		41.9		–	–
2005	JEFF 3.1 [40]	5.776		45.211		–	–
2003	Kolotov and De Corte [13]	8.86 ± 0.35		39.2 ± 2		0.55	–
2002	JENDL 3.3 [35]	5.776		45.211		–	–
1999	Holden [34]	6 ± 1		26 ± 4		0.50	–
1976	BROND 2.2 [32]	5.8 ± 0.12		–		–	–
1984	Mughabghab [33]	5.8 ± 0.3		45 ± 3		0.50	–
1976	Fedorova *et al.* [41]	–		44 ± 7		0.50	–
1973	BNL [31]	5.7 ± 0.2		20 ± 2		0.50	–
1972	Rahn *et al.* [42]	–		44 ± 7		0.50	–

[a]% Diff. means that the percentage difference = 100 × (1 − present value/literature value).

Gill [27] by 33–86%. On the other hand, the time-of-flight measurements obtained by Vertebnyj *et al.* [28] and Knopf and Waschkowski [29] differ significantly (about 33–47%) from the recent activation results, primarily as a result of insufficient corrections for scattered neutrons.

In addition, two of the recent evaluated σ_0 data, 8.85 b of ENDFB-VII [30] and 8.86 b of Kolotov and De Corte [13], are higher than all other evaluated literature values, that is, 5.7 ± 0.2 b of BNL [31], 5.8 ± 0.12 b of BROND 2.2 [32], 5.8 ± 0.3 b of Mughabghab [33], 6 ± 1 b of Holden [34], 5.776 b of JENDL 3.3 [35], and 5.8 ± 0.3 b of NUDAT [5].

The present resonance integral value $I_0 = 44.5 \pm 4.0$ b at the cadmium cut-off energy of 0.55 eV for the ^{170}Er$(n,\gamma)^{171}$Er reaction given in Table VI agrees only with the result of Gilette [26]. It is close to the experimental values obtained by De Corte and Simonits [22] and Heft [24] by 14–17%, but disagrees with the values of OAEP [36], Hoyodom [37], Glomset and Pappas [25], Van Der Linden *et al.* [38] and Steinnes [39] by 38–147%.

For the ^{170}Er$(n,\gamma)^{171}$Er reaction, the older evaluated data of BNL ($I_0 = 20 \pm 2$ b) [31] and of Holden (26 ± 4 b) [34] are lower by about a factor of 2 with respect to 45 ± 3 b of NUDAT [5], 41.9 b of ENDFB-VII [30], 45.211 b of JEFF 3.1 [40], 39.2 ± 2 b of Kolotov and De Corte [13], 45.211 b of JENDL 3.3 [35], and the values of 44 ± 7 b calculated by Fedorova *et al.* [41] and Rahn *et al.* [42].

It may be concluded that the recently evaluated and experimental resonance integral cross sections for the ^{170}Er$(n,\gamma)^{171}$Er reaction are in the 40–45 b range, and the present measured value of 44.5 b with an uncertainty of 9% falls within that range.

V. SUMMARY

The wide variation in previously reported σ_0 and I_0 values for the ^{170}Er$(n,\gamma)^{171}$Er reaction, given in Table VI indicates that there is still a consistency problem among those measured and evaluated ones. Therefore, the ^{55}Mn monitor has been chosen for the resonance integral determination in this study because of its well seperated resonance energy at about 337 eV, which is quite far from the 1/v region. Consequently,

the present resonance integral value for the ^{170}Er$(n,\gamma)^{171}$Er reaction obtained by the activation method agrees within uncertainty limits only with the result of 43 ± 5 b obtained by Gillette [26], who also used the activation method with ^{197}Au and ^{59}Co monitors. This result implies that the ^{55}Mn monitor ($\bar{E}_r = 468$ eV) can be considered as an alternative comparator to the ultimate standard ^{197}Au-monitor ($\bar{E}_r = 5.65$ eV) for more accurate resonance integral determination when using $1/E^{1+\alpha}$ epithermal neutron distributions.

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