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ENDF-355

Comments on the ENDF/B-VI Evaluation for ^{235}U in the Neutron Energy Region from 1 to 20 eV

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/TM-12304
ENDF-355

Engineering Physics and Mathematics Division

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DATE PUBLISHED — February 1993

Prepared by the
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managed by
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for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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ABSTRACT

A discrepancy of ~6% has been reported between the measured capture resonance integral of ^{235}U and that calculated from the resonance parameters in ENDF/B-VI. This discrepancy may be due to the use of a value for the average radiation width which is too small. The possibility that small resonances whose widths are primarily capture were missed experimentally due to their proximity to resonances with large fission widths was also considered, but dismissed. Since accurate values of neutron widths, Γ_n, and total widths, Γ_T, of resonances can be determined from transmission data and are not dependent on any normalization factors, an interim solution might be to assume an average radiation width Γ_γ and calculate the fission width Γ_f for each resonance from the relation $\Gamma_T - \Gamma_n - \Gamma_\gamma$. The ratio of the partial fission widths of the two fission channels for each resonance would be kept the same as in ENDF/B-VI data files. The average value of the radiation width selected should also be consistent with differential and integral measurements.

1 Introduction

A discrepancy between the measured capture resonance integral for ^{235}U and that calculated from the resonance parameters in ENDF/B-VI was recently reported by Lubitz [1] and by Wright [2]. Lubitz reported values of 144 b·eV and 133 b·eV for the measured and calculated infinite dilute capture resonance integrals, while Wright stated that Revision 1 of ENDF/B-VI gave an underestimate for the capture integral measured using ^{10}B hardened slowing down thermal reactor spectra. Both indicated that the fission integral was slightly overestimated. Fission yield data were recorded up to several keV in recent measurements [3] carried out at the Oak Ridge Electron Linear Accelerator (ORELA) to determine the neutron energy dependence of eta for ^{235}U. Those data indicated that the fission cross-section calculated from ENDF/B-VI parameters over-estimated the fission cross-section between resonances. This led to the speculation that the discrepancy may be due to the use of too small a value for the average radiation width Γ_γ, which would then require a small reduction in the fission widths Γ_f of the resonances. It was initially thought that some small resonances whose widths are mainly capture might have been experimentally missed due to their proximity to resonances with large fission widths.

The relationship between the resonance parameters and the resonance integrals for fission I_f and for capture I_γ can be written [4] as follows

$$I_f = \frac{\pi}{2} 2.60393 \times 10^6 \left(\frac{A+1}{A}\right)^2 \sum_j \frac{\Gamma_{fj}}{E_j^2} \frac{g_j \Gamma_{nj}}{\Gamma_{Tj}} \tag{1}$$

$$I_\gamma = \frac{\pi}{2} 2.60393 \times 10^6 \left(\frac{A+1}{A}\right)^2 \sum_j \frac{\Gamma_{\gamma j}}{E_j^2} \frac{g_j \Gamma_{nj}}{\Gamma_{Tj}} \tag{2}$$

where A is the nuclear mass, $\Gamma_{Tj} = (\Gamma_{nj} + \Gamma_{fj} + \Gamma_{\gamma j})$, the total width for resonance j, Γ_{nj}, Γ_{fj} and $\Gamma_{\gamma j}$ are the neutron width, fission width, and radiation width respectively , and E_j is the resonance energy in eV. Equations 1 and 2 may not be valid when large interference terms are present in the partial cross-sections. In reactor calculations the integration is carried out using the calculated cross-section curves rather than the approximations in Equations 1 and 2.

To increase the capture resonance integral without affecting the fission integral, Equations 1 and 2 show that an increase in the radiation width is required, or that some small resonances whose widths are mainly capture have been missed in the analysis.

Table 1 gives the average radiation width for each spin from the ENDF/B-VI [5] data files over 50 eV energy intervals, together with the spread in the values assuming a Gaussian distribution. The overall mean value is 36 meV. Previous reported average values for the radiation width (see reference [6]) varied from 37.6 to 49 meV. G. de Saussure et al. [6], in a simultaneous analysis of capture-yield and fission data reported an average value for the radiation width of 43.1 meV. Leal [7],[8] analyzed the same capture-yield data and new ORELA total and fission data and obtained an average radiation width of 36 meV. However, for the analysis of thick-sample capture-yield data, corrections have to be made for self screening and the effect of neutrons initially scattered that react on subsequent collisions. There is no mention of such corrections to the capture-yield data. If these were not carried out, it may explain the lower value of the average radiation width obtained from the de Saussure capture-yield data as the corrections could be several percent in the regions of the peaks of the large resonances.

Energy Min· (eV)	Energy Max· (eV)	Spin	Average Value (meV)	Spread (meV)	No· Resonances
0·0000E+00	0·5000E+02	3	0·3668E+02	0·6443E+01	35
		4	0·3634E+02	0·1773E+01	55
0·5000E+02	0·1000E+03	3	0·3618E+02	0·2056E+01	37
		4	0·3600E+02	0·1265E+01	53
0·1000E+03	0·1500E+03	3	0·3630E+02	0·3090E+01	37
		4	0·3605E+02	0·2926E+01	55
0·1500E+03	0·2000E+03	3	0·3573E+02	0·2266E+01	36
		4	0·3585E+02	0·2559E+01	55
0·2000E+03	0·2500E+03	3	0·3601E+02	0·2606E+01	35
		4	0·3543E+02	0·2529E+01	55
0·2500E+03	0·3000E+03	3	0·3601E+02	0·2864E+01	35
		4	0·3578E+02	0·2341E+01	57
0·3000E+03	0·3500E+03	3	0·3507E+02	0·4659E+01	36
		4	0·3642E+02	0·7480E+01	55
0·3500E+03	0·4000E+03	3	0·3727E+02	0·3619E+01	36
		4	0·3554E+02	0·2631E+01	54
0·4000E+03	0·4500E+03	3	0·3431E+02	0·2939E+01	36
		4	0·3511E+02	0·4702E+01	56
0·4500E+03	0·5000E+03	3	0·3539E+02	0·2234E+01	34
		4	0·3588E+02	0·4322E+01	54

Table 1: The average radiation widths for ENDF/B-VI in 50 eV intervals.

2 Comments on the analysis of neutron time of flight data

Even sophisticated shape analysis programs to determine resonance parameters from neutron time of flight data can often only yield some of the required parameters. In the analysis of transmission data only the neutron width Γ_n and total width Γ_T can be determined, provided that the that the spin weighting factor g is known. The relationship between the parameters and the area of the resonance dip is given below and is almost independent of the resolution function and the Doppler effect. Melkonian et al. [9] have shown that

$$A_{tr,t} \propto g\Gamma_n^i\Gamma_T^j \tag{3}$$

where $A_{tr,t}$ is the area of a resonance transmission dip for a sample of thickness t and where i and j are exponents which lie between 1/2 and 1, and between 0 and 1/2 respectively. When the product of the thickness t and the peak cross-section σ_0 approaches zero, i approaches unity and j zero, and when $t\sigma_0$ approaches infinity, i and j approach one half. For a very thin sample the area is proportional to the product $g\Gamma_n$, and for a very thick sample the square of the area is proportional to $g\Gamma_n\Gamma_T$. The area of a transmission resonance dip does not depend on the normalization of the data, but changes in the background will change the measured area.

The shape of the resonance will give information about the total width Γ_T and the ratio $g\Gamma_n/\Gamma_T$, provided that the Doppler and resolution widths are less than the total width of the resonance, or that accurate values of the transmission extend out into the regions where these functions have a smaller effect.

From transmission data, the reaction width Γ_R is determined as the difference between the measured total width and the neutron width. For non-fissile nuclides, the reaction width is in general equal to the radiation width Γ_γ. For resonances where the neutron width dominates the total width, capture yield data are needed to determine accurate values of Γ_γ. For fissile nuclides, the reaction width is the sum of the capture and fission widths and further information is required to determine values for these widths.

The area of a resonance in a yield measurement of reaction X is related to the partial widths as follows:

$$A_{X,t} \propto g\Gamma_n^i \Gamma_X^k \Gamma_T^j \tag{4}$$

where $A_{X,t}$ is the area of a resonance for reaction X for sample thickness t and i, j and k are exponents. As most measurements of reaction yields are carried out with thin samples, i.e., $n\sigma_0$ approaches zero, $i = k = 1$ and $j = -1$. Thus, the area of a resonance in capture is $\propto g\Gamma_n\Gamma_\gamma\Gamma_T^{-1}$ and the area in fission is $\propto g\Gamma_n\Gamma_f\Gamma_T^{-1}$. For partial cross sections, the area of a resonance is proportional to the normalization of the data and it is important to get the correct normalization of yield data to obtain accurate values of the partial widths. Uncertainties in the background can be reduced by fitting the data in the regions between the resonances.

As in the case of transmission data, the shape of a resonance in the yield data gives information about the total width Γ_T and the product $g\Gamma_n\Gamma_x/\Gamma_T^2$, provided the Doppler and resolution widths are less than the total width of the resonance or that accurate values of the yield extend out into the regions where these functions have a smaller effect and the effect of neutrons that are initially scattered but react on subsequent collisions is also small.

The simultaneous analysis of transmission measurements and yield measurements will give more accurate values of the partial widths than from transmission measurements alone. For fissile isotopes, the simultaneous analysis of transmission and fission yield data gives values for Γ_n and Γ_f, and the radiation width is then determined from the difference between the total width and the sum of the neutron and fission widths. The greater the contribution of the neutron and fission widths to the total width, the larger the uncertainty in the radiation width.

3 Measurements

The experimental details of the eta measurements are fully described in the report by Moxon et al. [3], and will only be described briefly in this report. The measurements used to determine the neutron energy dependence of eta ($\eta = \nu\sigma_f/(\sigma_f + \sigma_\gamma)$) for ^{235}U in the neutron energy range below 300 meV also covered the energy range up to a few keV. A 9.6-meter flight path on the ORNL pulsed neutron source ORELA was used. The measurements were carried out using a NE213 liquid scintillator in conjunction with a pulse shape discriminator to separate fast neutron events from γ-ray events in the detector. The output from the detector consisted of three channels (i) fast neutrons from fission events, (ii) γ-rays from fission and capture events in the ^{235}U sample, and (iii) rejected events. The detector was also used to measure the γ-rays emitted from the $(n, \alpha\gamma)$ reaction in a sample of ^{10}B to calculate the incident neutron spectrum. The ratio of the fast neutron counts from the ^{235}U sample to the incident neutron spectrum calculated from the γ-ray counts from the ^{10}B sample gives an accurate energy dependence of the fast neutron yield, i.e., the

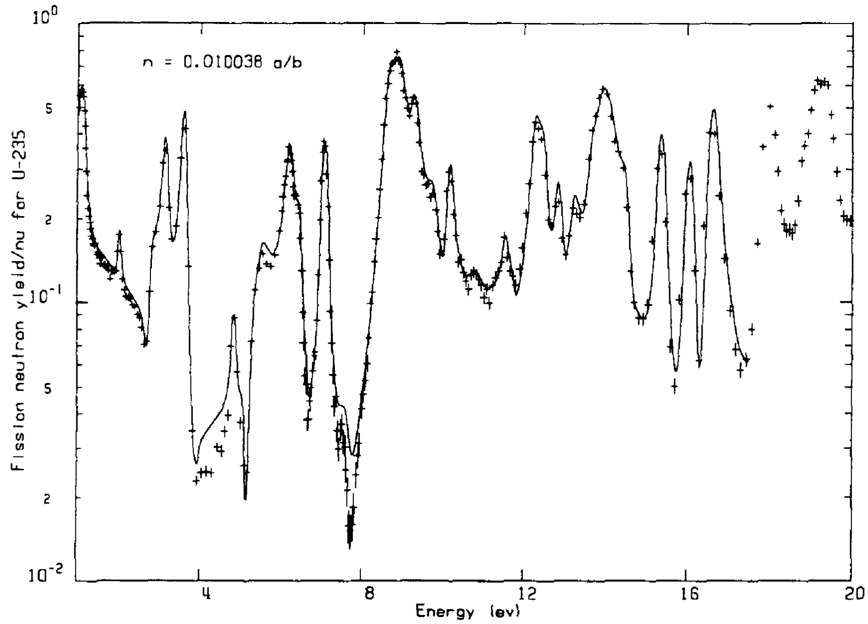

Figure 1: Fission neutron yield for sample n=0.010038a/b from 1 to 20 eV.

number of fast neutrons emitted per incident neutron. The experimental fission yield, i.e., the number of fission events taking place in the sample per incident neutron, is obtained by normalizing the fast neutron yield to the value of the fission yield at thermal. The calculated yield was obtained from a modified version of the program REFIT [10], using cross-sections calculated by NJOY from the resonance parameters given in ENDF/B-VI.

Figure 1 shows the measured fission yield covering the energy range from 1 to 20 eV for a sample of thickness n = 0.010038a/b, normalized to the calculated value in the energy range 0.02 to 0.03 eV. The solid line is the value calculated from the ENDF/B-VI resonance parameters. This illustrates that there is satisfactory agreement between the calculated and measured values in the regions of the resonances with large neutron and fission widths. However, in the region between the resonances, the measured data are much lower than those calculated from the ENDF/B-VI parameters. The figures in reference [7] comparing the measured fission cross-section to the calculated values, also show this trend.

Table 2 shows preliminary values of the fission and radiation widths obtained from the latest ORELA fast neutron fission yield measurements for the 'isolated' resonances that have small fission widths in the energy region up to 20 eV. The fission widths were obtained simply by comparing the measured areas of the resonances for fission to those calculated from the parameters. Difficulties in determining the shape of the underlying fission yield due to the effect of large nearby resonances increased the uncertainty on the observed areas for some of the smaller resonances. The radiation width was determined as follows:

$$\Gamma_\gamma = \Gamma_T - \Gamma_n - \Gamma_f \tag{5}$$

where the neutron and total widths are taken from the ENDF/B-VI data files and the fission widths determined from the latest ORELA data. The weighted mean value for Γ_γ is 38.20 ± 1.24 meV assuming an uncertainty of 5% on the total width, as no uncertainty is

E_R (eV)	$\Gamma_f + \Gamma_\gamma$ (meV)	Γ_f (meV)	Γ_γ (meV)	ENDF/B-VI Γ_f (meV)	ENDF/B-VI Γ_γ (meV)
2·0342	48·22	7·42	40·80	11·15	37·08
3·6137	89·10	50·14	38·96	52·71	36·39
4·8518	40·30	3·00	37·30	4·29	36·01
7·0790	70·07	33·17	36·90	32·71	37·36
10·165	104·7	61·2	43·5	67·74	37·00
11·667	44·28	3·28	41·0	6·50	37·78
12·397	63·84	27·84	36·0	24·81	39·02
15·409	95·16	56·09	39·07	55·72	39·44
16·087	57·82	21·15	36·67	22·44	35·38
16·642	146·0	109·52	36·48	113·23	32·80

Table 2: The preliminary fission and radiation widths determined from the latest ORELA fission yield data.

given in the ENDF/B-VI data files.

The ratio of the γ-ray counts to the fast neutron counts from a ^{235}U sample is almost proportional to a constant plus α, the ratio of the capture cross-section σ_γ to the fission cross-section σ_f. The accuracy of the alpha measurement is poor due to the fact that the efficiency of the detector for detecting fission events via the γ-rays is about twice that for detecting capture events. The initial comparison with the values in ENDF/B-VI suggested that some small capture resonances had been missed in the analysis. However, this is now thought not to be true and the explanation is that the fission cross-section between resonances is much lower than given in ENDF/B-VI and the capture cross-section higher than calculated from ENDF/B-VI parameters.

4 Conclusions

The purpose of the present study was to suggest a solution to the discrepancy between the measured infinitely dilute capture resonance integral and that calculated from the ENDF/B-VI parameters.

As shown above, the values of Γ_n and Γ_T are determined from transmission data and are not dependent on any normalization factors. Therefore, an interim solution might be to assume an average radiation width and then calculate fission widths as follows:

$$\Gamma_f = \Gamma_T - \Gamma_n - \Gamma_\gamma \tag{6}$$

The ratio of the partial fission widths of the two fission channels is kept the same as in the ENDF/B-VI data files. Table 3 shows calculated resonance integrals for values of Γ_γ from 35 to 40 meV [11]. A value for Γ_γ of between 38 and 39 meV would give the desired values for the fission and capture resonance integrals. This is in agreement with the provisional value of 38.2 meV obtained from the latest ORELA measurements up to a few keV which were made primarily to determine η below 300 meV.

A detailed shape analysis correcting for effects of sample attenuation and multiple scattering effects needs to be done for capture data used in resonance analysis for ENDF/B-VI,

Γ_γ (meV)	I_f (b)	I_γ (b)	α
35	282·17	130·13	0·461
36	279·17	133·17	0·477
37	276·18	136·20	0·493
38	273·20	139·24	0·510
39	270·37	142·15	0·526
40	267·82	145·03	0·542

Table 3: The fission integral, capture integral, and integral alpha calculated using different values of Γ_γ.

as well as for recent ORELA fission yield data (Fig. 1). Such an analysis was not able to be done at this time.

5 Acknowledgements

The author would like to express his appreciation to those who contributed in the discussions about this work, Dr. C. R. Lubitz from Knolls Atomic Power Laboratory (KAPL) for his many long discussions over the telephone and carrying out the integral calculations, Dr. J. A. Harvey for supplying his data and for the discussions about the results of the preliminary analysis, and Dr. L. C. Leal for the discussions about the evaluation used in ENDF/B-VI. The author would also like to thank Dr. D. C. Larson, Dr. L. W. Weston, Dr. R. Gwin and Dr. R. W. Peelle for their help and support in carrying out this work. This work was financed by a contract with KAPL under contract No. F.A. 92-14.

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