Slow-Neutron Resonances in Eu^{151} and Eu^{153}†

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The total neutron cross sections of Eu^{151} and Eu^{153} have been measured between 1 and 10 ev using a high-resolution crystal spectrometer. The Breit-Wigner parameters have been obtained for the 1.055, 2.717, 3.368, and 3.710-ev resonances in Eu^{151}, and for the 1.725, 2.456, 3.294, 3.944, 6.16, and 8.87-ev resonances in Eu^{153}. The values of the radiation widths for the 1.055, 2.717, 3.368, and 3.710-ev resonance in Eu^{151} are almost identical, whereas out of the six resonances in Eu^{153} five are almost identical, and one is about 30% higher.

I. INTRODUCTION

ALTHOUGH much data has been accumulated on neutron resonances, accurate values of the radiation widths, Γ_γ, have been obtained for only a few cases.[1] Within each of the three isotopes, In^{115}, Eu^{151}, and Hf^{177}, the results indicate that the values of the radiation widths are not always constant. For each of the isotopes In^{115} and Hf^{177} only two values of Γ_γ were measured[2,3] which were found to be distinctly different. However, in Eu^{151} five values have been reported[2,4–6] which appear to fall into two groups. The grouping suggests that two values of Γ_γ correspond to the two possible spin states for slow-neutron capture. This assumption is supported by the activation of the isomeric state in Eu^{152} which was reported by Wood.[7]

The analysis of Eu data is complicated by the presence of the two isotopes Eu^{151} and Eu^{153}, both of which contain closely spaced resonances. Recently samples of enriched Eu^{151} and Eu^{153} have been made available. The measurements to be discussed were undertaken to obtain more accurate values of the radiation widths to see if the division into two groups does indeed occur, and to compare the radiation widths for the two isotopes.

II. EXPERIMENTAL DETAILS

Total neutron cross-section measurements with the BNL crystal spectrometer have been described previously.[8,9] The resolution of the spectrometer was 0.17 μsec/meter and the Be(12$\bar{3}$1) crystal planes were used. Eu samples, in the form of europium nitrate dissolved in D_2O, were prepared from enriched stable isotopes.[10] Two such samples of each isotope were prepared. The enrichment of Eu^{153} was 95.0% and of Eu^{151}, 91.9%. The $1/N$ values were 3038 barns and 16 129 barns for Eu^{153}, and 3305 and 22 080 barns for Eu^{151}. The thicknesses were known to better than 1%. A small correction to the observed transmission was made for the presence of the NO_3 radical and D_2O.

III. RESULTS AND ANALYSIS

The observed total cross sections of Eu^{151} and Eu^{153} are shown in Fig. 1. Resonance energies are listed in Tables I and II. In general, our energy values are in good agreement with other measurements. Two resonances in Eu^{153} reported by Harvey and Block[11] at 4.81 ev and 7.60 ev were not observed by us. On the other hand, the resonance reported at 5.47 ev in Eu^{151}

TABLE I. A summary of the resonance parameters in Eu^{151}. The values of σ_0 and Γ_n^0 are for the isotope.

E_0 (ev)	σ_0 (barns)	Γ (10^{-3} ev)	Γ_γ (10^{-3} ev)	$2g\Gamma_n^0$ (10^{-3} ev)
1.055±0.003	3190±30	85±3	85±3	0.214±0.005
1.80 ±0.05	...	...	...	...
2.717±0.005	1190±35	92±3	92±3	0.14 ±0.01
3.368±0.006	7640±75	94±3	92±3	1.00 ±0.05
3.710±0.006	2930±50	95±4	94±4	0.41 ±0.02
5.37 ±0.05	...	...	...	...
5.45 ±0.05	...	...	...	...
5.98 ±0.05	...	...	...	...
7.0 ±0.1	...	...	...	...
7.25 ±0.05	...	...	...	...
7.43 ±0.05	...	...	...	...
9.06 ±0.05	...	...	...	...

TABLE II. A summary of the resonance parameters in Eu^{153}. The values of σ_0 and Γ_n^0 are for the isotope.

E_0 (ev)	σ_0 (barns)	Γ (10^{-3} ev)	Γ_γ (10^{-3} ev)	$2g\Gamma_n^0$ (10^{-3} ev)
1.725±0.005	450±25	93±5	92±5	0.042±0.005
2.456±0.005	7548±75	94±2	92±2	0.85±0.03
3.294±0.006	3943±50	96±3	95±3	0.528±0.015
3.944±0.008	3642±40	101±3	100±3	0.56 ±0.02
6.16 ±0.02	1130±30	131±4	130±4	0.28 ±0.02
8.87 ±0.03	5324±60	105±5	101±5	1.27 ±0.09

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[6] N. Holt, Phys. Rev. 98, 1162(A) (1955).
[7] R. E. Wood, Phys. Rev. 95, 453 (1954).
[8] L. B. Borst and V. L. Sailor, Rev. Sci. Instr. 24, 141 (1953).
[9] Sailor, Foote, Landon, and Wood, Rev. Sci. Instr. 27, 26 (1956).
[10] These samples were obtained on loan from the Isotope Research and Production Division of the Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[11] J. A. Harvey and R. C. Block, Bull. Am. Phys. Soc. 1, 347 (1956).

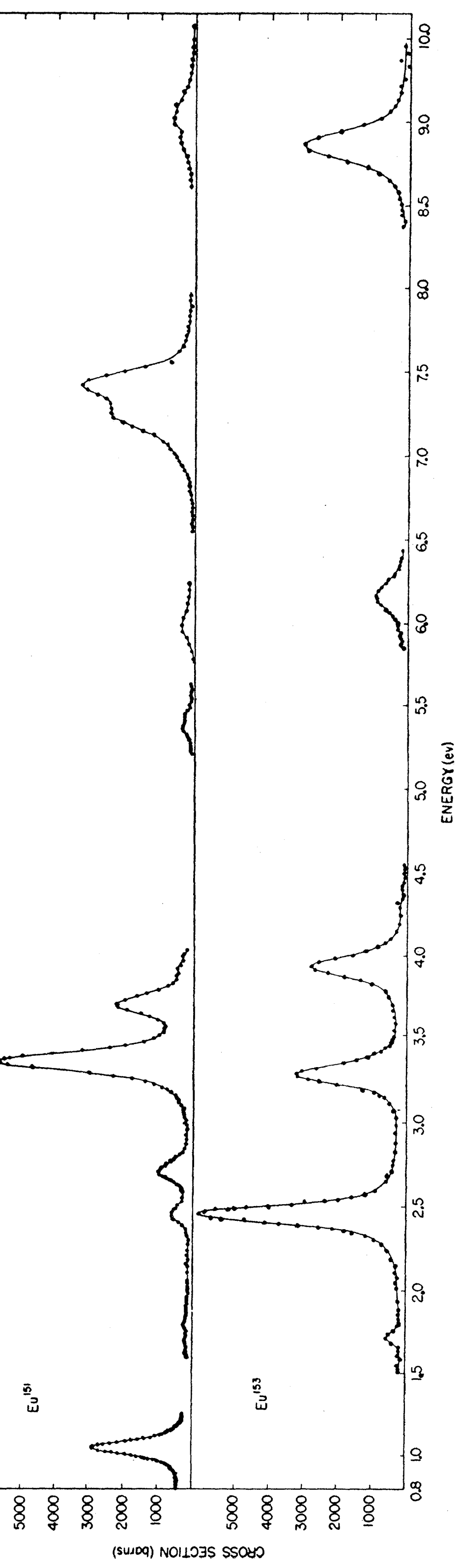

FIG. 1. Total cross section of Eu between 1 and 10 ev. The cross sections between the resonances are not given because the samples were too thin to obtain accurate values. The data shown here have not been corrected for Doppler broadening, instrument resolution, or second order contamination. The small resonance at the energy 2.45 ev in Eu^{151} is due to the contamination of Eu^{153}.

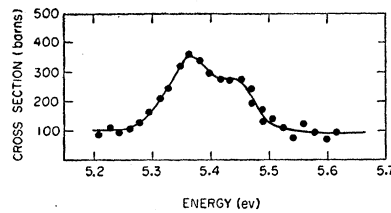

FIG. 2. Total neutron cross section of Eu^{151} in the region of the 5.37- and 5.45-ev resonances.

by Harvey and Block was found to be a double resonance. The energy of these resonances shown in Fig. 2 are 5.37 and 5.45 ev. There seems to be an unresolved resonance at approximately 7.0 ev which makes the curve asymmetric.

The methods used in analyzing the total cross-section data for resonance parameters have been described previously.[2,12] In the case of Eu^{153} all the observed resonances were analyzed. Each resonance was corrected for second order contamination,[13] resolution, background due to adjacent resonances, and contamination due to the other isotopes. The Doppler correction is included in the method of shape analysis.

The correction for instrument resolution has to be made for each resonance analyzed. However, since this correction for the first four resonances is very small, it was neglected except at the peaks. At the other resonance the correction was calculated at several points and the values for other points were obtained by interpolation. An example of such a correction curve is shown in Fig. 3 for the 8.87-ev resonance.

The Breit-Wigner shapes for each resonance were generated using the computed parameters in order to see how good the experimental points fit these theoretical curves. Typical fits are shown in Fig. 4 for the 6.16-ev resonance, and in Fig. 5 for the 8.87-ev resonance. Curve A is the true Breit-Wigner shape of the resonance, curve B represents the Doppler-broadened Breit-Wigner shape, and curve C is the resolution

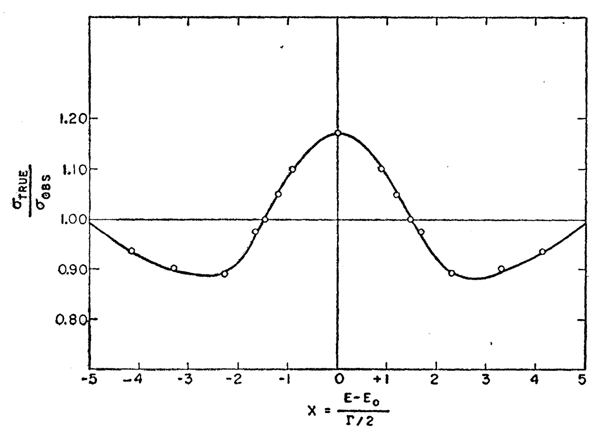

FIG. 3. The resolution correction curve for the 8.87-ev resonance in Eu^{153}.

[12] V. L. Sailor, Phys. Rev. **91**, 53 (1953).
[13] R. Haas and F. J. Shore, Rev. Sci. Instr. (to be published).

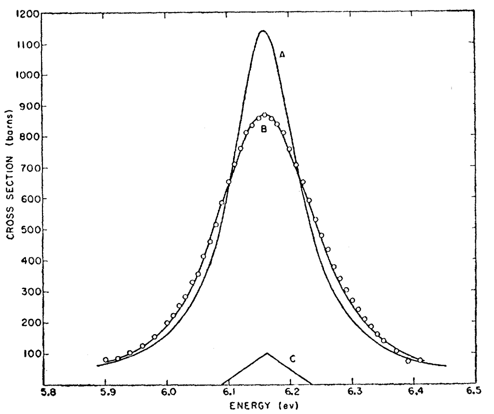

FIG. 4. Total neutron cross section of Eu^{153} in the region of the 6.16-ev resonance. Curve A is the true Breit-Wigner shape of the resonance, curve B represents the Doppler-broadened Breit-Wigner, and Curve C is the resolution triangle.

triangle. Similar curves were obtained for each of the resonances analyzed but are not shown.

In Eu^{151} only four resonances (1.055, 2.717, 3.368, and 3.710 ev) could be analyzed to the precision required for this study. Although the 1.80-ev resonance appears to be a single resonance, it could not be analyzed because it is very weak. The observed peak cross section of about 200 barns would require a much larger sample thickness to get data of the desired accuracy. The remaining resonances have not been analyzed for various reasons, i.e., their cross sections may be too small, they may be too close together, or the resolution correction becomes excessively large.

The resonance parameters obtained for Eu^{151} are given in Table I. It was found that the radiation widths for these resonances are almost constant. The fit for the 3.710-ev resonance and for the neighboring large resonance at 3.368 ev are shown in Fig. 6 and Fig. 7. The experimental data are in good agreement with the theoretical curve B. The radiation width for the resonance at $E_0=3.710$ ev, previously reported by Landon[4] as $(69\pm7)\times10^{-3}$ ev, was found to be $(94\pm4)\times10^{-3}$ ev. This resonance was difficult to analyze with the natural europium samples which Landon used because of the neighboring large resonance, and the Eu^{153} resonance at 3.944 ev.

The resonance parameters obtained for Eu^{153} are given in Table II. Out of the six resonances measured, five of them have radiation widths which are almost identical, with an average of 98×10^{-3} ev. The resonance at 6.16 ev has a radiation width whose value of 130×10^{-3} ev is 30% higher than the average value. It is highly unlikely that this is a double resonance

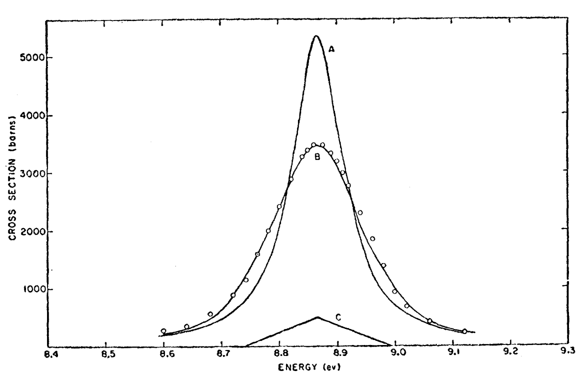

FIG. 5. Total neutron cross section of Eu^{153} in the region of the 8.87-ev resonance. Curve A is the true Breit-Wigner shape of the resonance, curve B represents the Doppler-broadened Breit-Wigner, and curve C is the resolution triangle.

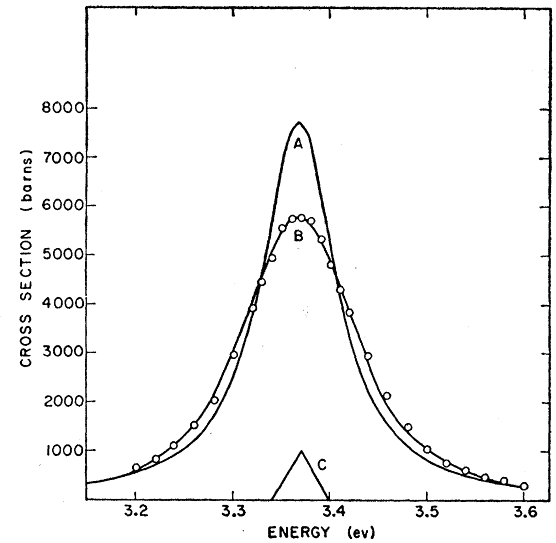

FIG. 6. Total neutron cross section of Eu^{151} in the region of the 3.68-ev resonance.

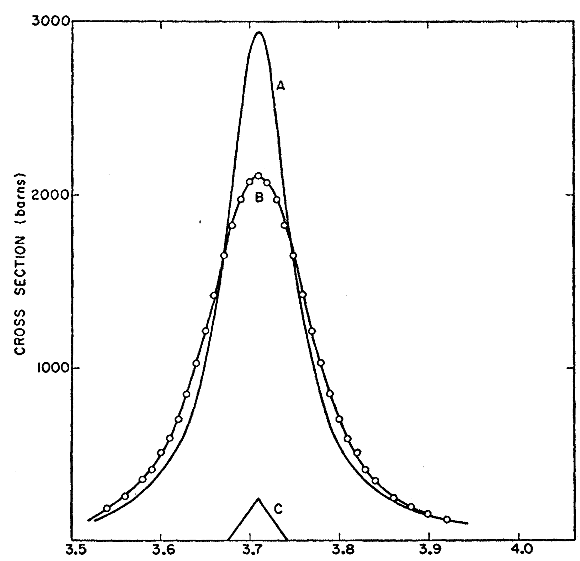

FIG. 7. Total neutron cross section of Eu^{151} in the region of the 3.71-ev resonance.

since the Doppler-broadened curve and the experimental curve agree so well, and since the shape is so symmetrical (see Fig. 4).

The results reported here do not provide conclusive evidence for the existence of two distinct groupings of radiation widths. It is generally assumed that the Porter-Thomas distribution[14] for radiation widths would be quite narrow due to the large number of degrees of freedom, i.e., the large number of exit channels for the process. The value of Γ_γ for the Eu^{153} resonance at 6.16 ev is anomalously large, and would not fit such a distribution. The possibility cannot be excluded that this one resonance belongs to one spin state while the five remaining resonances belong to the opposite spin state.

[14] R. G. Thomas and C. E. Porter, Phys. Rev. **104**, 483 (1956).

In Eu^{151}, the two resonances at -6×10^{-4} ev and 0.327 ev, previously reported as having smaller Γ_γ, were not remeasured. Since none of the four resonances reported here fall into this group, it would be worthwhile to remeasure these and check the earlier results. The correlation between the activation[7] of the isomeric state of Eu^{152} and the smaller values of Γ_γ tends to support the earlier results. It would be interesting to extend Wood's activation measurements to higher energies using the enriched samples to see if the correlation is really significant.

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$Li^6(n,t)He^4$ Reaction at Intermediate Energies*

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The $Li^6(n,t)He^4$ reaction cross section has been measured in a neutron energy interval extending from 9 kev to 340 kev. The cross section descends from 1.77 barns at 9 kev to a minimum of 0.74 b at 100 kev before rising to a peak resonance value of 2.75 barns at 258 kev. The cross section from 9 kev to 90 kev is not proportional to $E^{-\frac{1}{2}}$, but can be represented by $\sigma=3.96E^{-0.367}$ with σ in barns and the neutron energy E in kev. Angular distributions of the tritons are presented for neutron energies of 150, 200, 258, 300, 350, and 565 kev. These distributions, measured in a relative manner, are placed on an absolute scale by normalizing to the cross section data of this experiment, extended to 565 kev by use of previously measured cross sections.

INTRODUCTION

When Li^6 is bombarded by neutrons with energies between thermal and 1 Mev, three nuclear reactions are energetically possible—elastic scattering, radiative capture, and the $Li^6(n,t)He^4$ reaction. The (n,t) reaction cross section is 945 barns at thermal energies[1] and is expected to decrease with increasing neutron energy, obeying the $1/v$ law up to rather appreciable energies. At higher energies, between 140 and 650 kev, Blair and Holland[2] have observed a strong resonance centered at 250 kev. This resonance also appears in the total neutron cross section[1,3] of Li^6 and has been attributed to the presence of an excited state in Li^7 at 7.46 Mev with $J=5/2^-$.[3,4]

Of particular interest is the behavior of the cross section at lower energies where the $1/v$ dependence of the cross section might be modified by the 250-kev resonance. Gorlov *et al.*[5] report cross-section measurements in the energy interval 9 to 700 kev. They observe the resonance due to the 7.46-Mev state of Li^7, but at a somewhat higher energy. The cross sections at the lowest energies of 9, 20, and 50 kev are about 15, 32, and 47% higher than a $1/v$ extrapolation of the cross section from the thermal value. Since it might be expected that the cross sections at these energies should be smaller, corresponding more nearly to the $1/v$ extrapolation, the present experiment was undertaken. The measurements of this experiment are in essential agreement with Gorlov *et al.* However, the position of the resonance

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] *Neutron Cross Sections*, compiled by D. J. Hughes and J. A. Harvey, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955), and D. J. Hughes and R. Schwartz, Supplement No. 1, 1957.

[2] J. M. Blair and R. E. Holland (unpublished). These results, corrected for more recent measurements of the U^{235} fission cross section, are given in Supplement No. 1 of reference 1.

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