Europium Activation Studies with Monochromatic Neutrons*

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Resonances in the europium slow neutron cross section at −0.011, +0.327, 0.461, 1.055, 2.74, 3.35, and 7.36 ev have been assigned to Eu^{151}. This was done by observing the intensity of the 9.3-hour activity of Eu^{152} produced as a function of neutron energy. The remainder of the europium resonances below 10 ev were assumed to be due to Eu^{153}; i.e., 1.76, 2.47, 3.84, 6.25, and 8.98 ev. The fraction of the compound nuclei decaying to the isomeric state of Eu^{152} was found to vary by a factor of four for different resonances in Eu^{151}. These fractions were obtained for six of the seven resonances in Eu^{151}.

I. INTRODUCTION

EUROPIUM activation studies with monochromatic neutrons were undertaken for two reasons; first, to obtain isotopic assignments of the many resonances found by Sailor, Landon, and Foote.[1] This was accomplished by irradiating Eu_2O_3 foils with monochromatic neutrons from the B.N.L. crystal spectrometer[2] and by observing the intensity of the 9.3-hour activity of Eu^{152} produced as a function of neutron energy. Previous measurements have shown resonances in Eu^{151} at −0.011 ev[3,4] and +3.3 ev,[5] and a resonance in Eu^{153} at 0.54 ev[4] (0.461 ev).

The second reason for studying europium activation was to observe variations from resonance to resonance in the decay of the compound nucleus if they exist. This was accomplished by measuring a relative population ratio of the isomeric state for each resonance. The population ratio of a given state is defined here as the fraction of the compound nuclei decaying to that state. Absolute population ratios of the isomeric state can be determined by measuring either the ratio of the isomeric activity to the ground state activity, or the ratio of the absorption cross section for the isomeric state to the total absorption cross section. It was considered impractical to measure absolute population ratios in this case; thus, relative population ratios were obtained by measuring a relative absorption cross section for the isomeric state. Preliminary population ratio variations have been observed in In^{116} by Sailor,[6] in Br^{80} and Rh^{104} by Capron and Verhoeve-Stokkink,[7] and more recently in Tl^{198} by Bergstrom, Hill, and dePasquali.[8]

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1 Sailor, Landon, and Foote, Phys. Rev. **93**, 1292 (1954).
2 L. B. Borst and V. L. Sailor, Rev. Sci. Instr. **24**, 141 (1953).
3 William J. Sturm, Phys. Rev. **71**, 757 (1947).
4 Borst, Ulrich, Osborne, and Hasbrouck, Phys. Rev. **70**, 557 (1946).
5 M. Goldhaber (unpublished); see reference 20 in William J. Sturm, Phys. Rev. **71**, 757 (1947).
6 V. L. Sailor (private communication).
7 P. C. Capron and A. J. Verhoeve-Stokkink, Phys. Rev. **81**, 336 (1951).
8 Bergstrom, Hill, and dePasquali, Phys. Rev. **92**, 918 (1953).

II. EXPERIMENTAL DETAILS

Two thin Eu_2O_3 foils, whose thicknesses were approximately 0.009 and 0.016 g/cm,[2] were used in the measurements. These foils were prepared by mixing finely powdered Eu_2O_3 with acetone and a small amount of Krylon plastic. Upon standing, the Eu_2O_3 settled out on a filter paper and the acetone evaporated. This left a reasonably uniform layer of Eu_2O_3 firmly held to the filter paper by means of the plastic binder. An average sample thickness for each filter paper was obtained by weighing. Small foils were punched from the filter papers for the activation measurements, and their thicknesses were accurately determined by transmission measurements at 0.461 ev where the cross section had been carefully measured.[1] A 12 percent variation was found in the foil thicknesses from one filter paper, but the average thicknesses obtained from the transmission measurements agreed well with those obtained by weighing. It is estimated that the error in sample thickness is less than 10 percent; however, this error would cause a negligible uncertainty in the results as the foil thickness enters only as a small correction.

The $(12\bar{3}1)$ planes of Be were used as the neutron monochromator for all irradiations excepting four points at low energy for which the (220) planes of NaCl were used. The thinner foils were irradiated at five energies in the range, 0.3 to 0.5 ev, using poor collimation. To increase intensity and to allow higher resolution by improved collimation, a single large foil was made from the thicker set of foils; this foil was used in all subsequent irradiations (0.07 to 9.0 ev). The background activity was determined in independent irradiations by rotating the crystal monochromator 1° from the Bragg angle during irradiation. To reduce the activity from environmental neutrons, the foils were shielded with 1.0 inch of B_4C at all times except while in the counter. The activity after irradiation was counted by a conventional end-window Geiger Meuller counter. A daily check of the counter sensitivity and operation was made with a cobalt source. The relative neutron flux at each energy was determined by correcting the spectrum measured with the spectrometer counter for the calculated BF_3 counter efficiency.

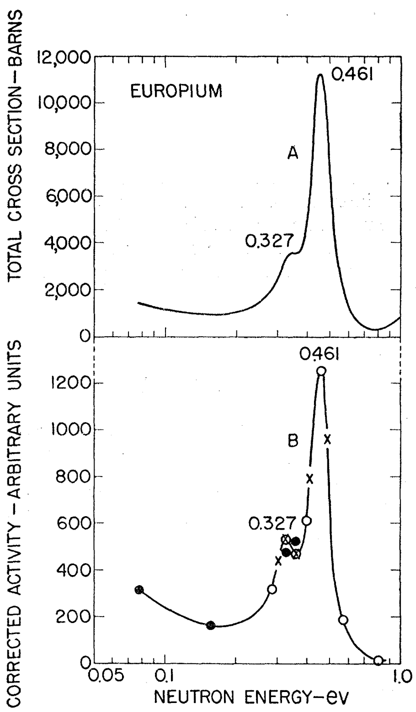

FIG. 1. Comparison of the total cross section below 1.0 ev, curve A, and the observed activities after all corrections have been applied, curve B. The crosses represent the thin-sample data and the open circles the thick-sample data using the Be crystal. The solid circles are for the thick sample using the NaCl crystal. The uncertainties due to counting statistics are smaller than the plotted points.

III. ANALYSIS

The objective of the analysis was to obtain a corrected activity which would be proportional to the absorption cross section for the isomeric state. The decay of the induced activity was followed as a function of time and the activity at the end of the irradiation was calculated on the assumption that only a 9.3-hour activity was present. The saturated activity (i.e., the activity which would be produced for an infinite irradiation time) was determined from the relation

$$A_\infty = C(A_0 - A_r)/(1-e^{-\lambda t}),$$

in which A_0 represents the activity of the foil at the end of the irradiation, t the total time of the irradiation, A_r the activity remaining in the foil from the previous irradiation, and C a normalization constant for the spectrometer beam monitor. The saturated background activity was then subtracted to give the activity produced by Bragg reflected neutrons.

Assuming that at any neutron energy the total cross section is equal to the sum of contributions from several resonances (i.e., $\sigma_t = \sigma_1 + \sigma_2 + \cdots$), the saturated 9.3-hour activity produced by Bragg reflected neutrons can be represented by the following:

$$A_\infty = K\Phi[1-\exp(-N\sigma_t)] \times [\sigma_1 R_1/\sigma_t + \sigma_2 R_2/\sigma_t + \cdots]. \quad (1)$$

The term $[1-\exp(-N\sigma_t)]$ is the fraction of the incident monochromatic neutron flux, Φ, absorbed in a foil of thickness, N, atoms/cm^2. The contribution to the activity from one resonance is $\sigma_1 R_1/\sigma_t$, where R_1 is the absolute population ratio of the isomeric state (9.3-hour activity) for that resonance, and so on with R_2, etc. The proportionality constant K includes the absolute value of the flux, area of foil irradiated, efficiency of the beta detector, absorption of beta particles in foil, and back scattering of beta particles from the aluminum foil mounting. It was thus possible to determine relative population ratios (KNR_1, $KNR_2 \cdots$) for closely spaced resonances by using the appropriate number of terms from the following equation:

$$KN[\sigma_1 R_1 + \sigma_2 R_2 + \cdots] = \frac{A_\infty}{\Phi} \frac{N\sigma_t}{[1-\exp(-N\sigma_t)]}. \quad (2)$$

All cross sections used in this paper were taken from the analysis of Sailor *et al.*[1] The total cross section was used as the absorption cross section since the resonance scattering was negligible for the resonances under study.

IV. RESULTS AND DISCUSSION

All of the results agreed quite well with the assumed 9.3-hour half-life. There was the possibility that the buildup of long-lived Eu activities should not be neglected in the calculations since the same foil was used repeatedly. It was found that this built-up activity was less than 1.5 counts per minute after all of the irradiations were completed. This was less than 3 percent of the total background, which confirmed the assumption that it could safely be ignored.

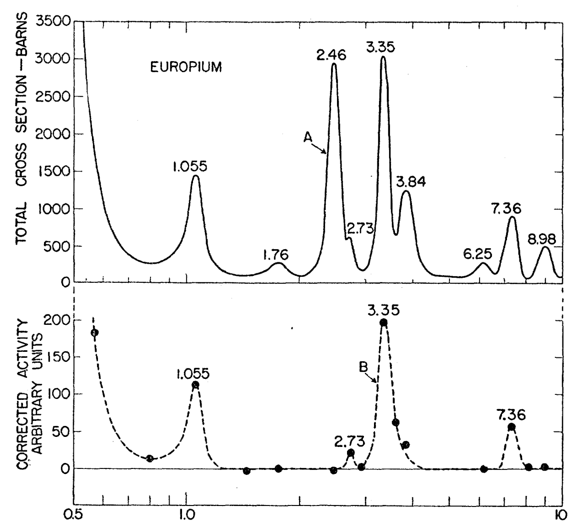

FIG. 2. Comparison of the total cross section between 1.0 and 10 ev, curve A, and the observed activities after all corrections have been applied, curve B. Activations were made at a sufficient number of points to determine the resonance structure for Eu^{151} as indicated by the dashed line. The uncertainties due to counting statistics are smaller than the plotted points.

The corrected activities, which were proportional to the absorption cross section for the isomeric state of Eu^{152}, are shown in Figs. 1 and 2; the proposed resonance structure for Eu^{151} is also indicated. The resonances at −0.011, +0.327, 0.461, 1.055, 2.73, 3.35, and 7.36 ev have been assigned to Eu^{151}; the remaining resonances below 10 ev have been assigned to Eu^{153}; i.e., 1.76, 2.47, 3.84, 6.25, and 8.98 ev. All of the assignments are statistically definite with the possible exception of the resonance at 6.25 ev. The previous assignments at −0.011 ev[3,4] and +3.3 ev[5] have been corroborated, but the assignment of the 0.54 (0.461) ev[4] resonance to Eu^{153} has been found to be in error.

It was necessary to apply an arbitrary normalization constant to two of the three sets of data shown in Fig. 1, because of differences in resolution and foil size. The thin-sample data were normalized to the point at 0.360 ev, and the data with the NaCl crystal were normalized to the average of the points at 0.327 and 0.360 ev. The average normalization of two points was used for the NaCl data because the resolution was too poor to measure the true shape of the curve as measured with the Be crystal.

The differences in the shape of the activity curve compared to the total cross section curve in Fig. 1 clearly demonstrate differences in the population ratios for the three resonances below 1.0 ev. To calculate the population ratios for the two resonances at 0.327 and 0.461 ev, it was assumed that only these two resonances contribute to the activity in the range 0.28 to 0.60 ev. Calculating the cross sections from the parameters obtained by Sailor *et al.*[1] leads to an equation in two unknowns for each of the eleven activations with the Be crystal. These eleven equations were solved by the method of least squares, giving the results shown in Table I for the 0.327- and 0.461-ev resonances. The standard deviation from the least squares solutions was less than the estimated error indicated in Table I. The activity and cross section due to the resonances at 0.327 and 0.461 ev were then subtracted from the measured activity and cross section at 0.077 and 0.155 ev using the known parameters and population ratios. Assuming the remaining activity and cross section to be due to the resonance at −0.011 ev, the population ratio given in Table I was obtained for this resonance. The estimated error on this ratio was much larger than that indicated by the average of the two points used. The remaining population ratios were obtained by using the measured total cross section directly. No attempt was made to make resolution corrections on either the total cross section or the activations. This correction becomes important at 1.0 ev and becomes increasingly more important the higher the energy.

TABLE I. Relative population ratios of the isomeric state of Eu^{152} for different resonances in Eu^{151}. The quoted errors are based upon the statistics of the points, the number of points used in the calculations, and an estimate of effects not considered in the analysis. No errors are listed for the highest energy resonances because the effects of resolution are very important, and the resolution for the activation studies was not well known.

Resonance energy[a] (ev)	Relative population ratio
−0.011	0.24±0.03
+0.327	0.19±0.02
0.461	0.11±0.01
1.055	0.08±0.03
2.73	...
3.35	~0.06
7.36	~0.06

[a] The negative energy resonance value is taken from reference 3, the other values from reference 1.

An absolute population ratio of 0.19±0.03 for the isomeric state of Eu^{152} was obtained by Hayden, Reynolds, and Inghram[9] for a Eu sample subjected to slow neutron irradiation in a graphite moderated pile. Using the results obtained in this study with their absolute population ratio, it is possible to obtain absolute population ratios for all of the resonances. These results have not been listed because of the unknown flux distribution in the irradiation of their sample.

It might be expected that the population ratios would fall into two groups depending on the spin of the compound nucleus. The results of this study are consistent with this hypothesis within the limits of error quoted, but it is interesting to note that the population ratios appear to decrease with increasing resonance energy. It would be very interesting to perform this same experiment on other elements and see if similar results were obtained.

V. ACKNOWLEDGMENTS

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[9] Hayden, Reynolds, and Inghram, Phys. Rev. **75**, 1500 (1949).