Neutron Resonances in the Rare Earth Elements*

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The neutron cross sections of the fifteen rare earth elements (excepting $_{61}$Pm) have been measured in the energy range from 0.07 to ~20 ev with a crystal spectrometer. The resonances found are summarized in a table giving the resonant energies, E_0, and a qualitative value of the strength, $\sigma_0\Gamma^2$. For some cases, the isotope responsible for the resonance has been identified and is also listed.

INTRODUCTION

THE slow-neutron cross sections of most of the rare earth elements are characterized by complicated resonance structure. Previous measurements[1–4] with adequate resolution of rare earth cross sections have been limited primarily to energies below 1 ev. Several of the elements in this group have never been studied, mainly because of the difficulty in obtaining suitable samples. During the past two years, the authors have made systematic measurements of the rare earth cross sections over the range of neutron energies from 0.07 to ~20 ev. The objectives of this study were: (1) to locate any resonances that might exist and to assign each of these to the proper element; (2) to assign each resonance to the proper isotope; and, (3) to obtain the Breit-Wigner parameters for each resonance. At the present time, the first objective has been largely completed; however, the second and third objectives have been only partially accomplished and cannot be completed in the foreseeable future. Since a knowledge of the location and approximate "strength" of resonances is of value to many applications, we are presenting a summary of the results in their present status. Some of the measurements presented here have appeared previously,[5–7] but are included in this summary for completeness. Typical experimental cross-section curves appear in references 6 and 7.

TABLE I. Key to qualitative description of strengths of resonances listed in Table II.

$\sigma_0\Gamma^2$ (barn ev^2)	Qualitative description	Abbreviation
>100	very strong	v.s.
50–100	strong	s.
10– 50	moderate	m.
1– 10	weak	w.
<1	very weak	v.w.

EXPERIMENTAL DETAILS

Total Cross-Section Measurements

The total cross section as a function of neutron energy was measured with the BNL crystal spectrometer. Procedures have been described in detail previously.[8] The spectrometer resolution function was approximately triangular, having a full width at half-maximum of 0.85 microsecond per meter.[9]

Samples

The quality of the specimens has been of primary importance to these measurements. Because of the large number of resonances in these elements, the presence of impurities, consisting of the other rare earths, can lead to considerable confusion as to the element responsible for an observed "line." The extreme variations of the strength of resonances within any one isotope make more difficult the assignment to the proper element. Thus, an observed "weak" resonance might truly be a weak resonance in the element under study or might possibly be a "strong" resonance in a trace impurity. An effort was made to work only with highly pure materials and wherever possible to verify the observed structure by using samples from two or more independent sources.

Specimens were obtained from three primary sources: (1) samples of Sm, Gd, Dy, Ho, Er, Tm, Yb, and Lu of unusually high purity were obtained on loan from Dr. F. H. Spedding, of the Ames Laboratory; (2) La, Ce, Pr, Nd, Sm, Eu, and Yb were purchased from the Research Chemicals, Inc., Burbank, California; and, (3) Eu, Gd, Tb, Dy, Er, Yb, and Lu were purchased from Jarrell-Ash Company, Boston, Massachusetts (Johnson, Matthey and Company, Ltd.). The neutron measurements constitute a very sensitive "spectroscopic" analysis of these specimens. It was found that samples from these three sources were quite reliable, being within the purity indicated by the supplier as far as the sensitivity of our measurements could determine. Enriched isotopes of samarium were obtained from the Isotope Research and Production Division of the Oak Ridge National Laboratory.

The preparation of samples has been discussed in other papers.[6,7]

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[1] Borst, Ulrich, Osborne, and Hasbrouck, Phys. Rev. **70**, 557 (1946).
[2] W. J. Sturm and G. P. Arnold, Phys. Rev. **71**, 556 (1947).
[3] W. J. Sturm, Phys. Rev. **71**, 757 (1947).
[4] Bernstein, Borst, Stanford, Stephenson, and Dial, Phys. Rev. **87**, 487 (1952).
[5] Sailor, Foote, and Landon, Phys. Rev. **89**, 904 (1953).
[6] Foote, Landon, and Sailor, Phys. Rev. **92**, 656 (1953).
[7] Sailor, Landon, and Foote, Phys. Rev. **93**, 1292 (1954).
[8] L. B Borst and V. L. Sailor, Rev. Sci. Instr. **24**, 141 (1953).
[9] Seidl, Hughes, Palevsky, Levin, Kato, and Sjöstrand, Phys. Rev. **95**, 476 (1954).

DESCRIPTION OF THE TABLES

The resonances which were found are listed for each element in Tables I and II.

Energy Scale

The resonant energy, E_0, is based on the energy scale of the BNL crystal spectrometer which is believed to have a precision of approximately $\delta E=\pm 0.003$ ev at 1 ev and $\delta E=\pm 0.10$ ev at 10 ev. On this energy scale, the prominent resonance in indium[10] occurs at 1.458 ev and in gold[11] at 4.91 ev. In spectra containing many closely spaced resonances it was frequently impossible to obtain E_0 to the usual precision due to the distortion introduced by adjacent resonances.

Resonances Above 20 Ev

In a few cases, unusually prominent resonances were found above 20 ev and occasionally extra time was spent obtaining good counting statistics at these higher energies. A few such resonances have been listed in Table II, but, of course, results above 20 ev are generally incomplete, and many resonances undoubtedly were not observed.

Strength of a Resonance

The "strength" of a resonance may be defined[12] as the product $\sigma_0\Gamma^2$ (barn ev^2). Numerical values of $\sigma_0\Gamma^2$ have been entered in the tables for the few cases which have been carefully analyzed by methods of "shape analysis."[13] For all other resonances, the strength is indicated qualitatively as shown in Table I. The qualitative entries are based on values of $\sigma_0\Gamma^2$ obtained by "area analysis."[12]

Column two of the tables lists the elemental "strength" of each resonance; i.e., the strength in a sample containing the element in its natural isotopic ratios. In cases for which isotopic assignment has been possible, the isotopic strength, $\sigma_0\Gamma^2/F$ is listed in column four, where F is the abundance of the isotope in the natural element.

Isotopic Assignments

The isotopic assignments of the resonances in samarium were made with enriched stable isotopes.[14] It should be noted that it was not possible to make definite assignments to a few of the resonances. The europium resonances were assigned[15] by observing the nine-hour Eu^{152} activity produced in the reaction, $Eu^{151}(n,\gamma)Eu^{152}$. Resonances not producing this activity were assumed to belong to Eu^{153}. In the case of a few individual resonances, assignment was made by comparing the measured thermal activation cross sections[16] to that expected by extrapolating the resonance to thermal energy. A few assignments have been tentatively made on the basis of the strengths of the resonances. Where the assignment is subject to question, the entries appear in italics.

Special Entries and References

A few resonances at thermal energies are listed for completeness. The values were obtained from the literature and appear in parentheses. Also references are made to independent results obtained with other instruments, but such results have not been incorporated in the tables.

DISCUSSION

General Features

The general features of the observed resonant structures are in good agreement with previous conclusions based on other types of data. The importance of the stability of the target nucleus in determining level densities, as was pointed out by Hurwitz and Bethe,[17] is well illustrated by these data. No resonances were found in the closed shell isotopes La^{139}, Ce^{140}, and Pr^{141} within the range of the measurements. Few resonances have been positively identified in even-even target nuclei, and such resonances invariably have been unusually strong, in agreement with previous conclusions by Goldhaber.[18] On the basis of the few isotopic assignments which can be made for resonances in even Z elements, it appears that most of the resonances are in the even-odd isotopes. The spacings of levels in the even-odd and odd-even isotopes appear to be quite similar.

It is interesting to note that in any one isotope the reduced strengths of resonances vary over a large range; extreme values differing by as much as a factor of 100. These variations in strength represent corresponding variations in the neutron width, Γ_n, because there is much evidence that the radiation width, Γ_γ, is not subject to large variations.

Failure to Observe Resonances

Examination of the tables will show immediately that more resonances have been found in the range from 0 to 10 ev than were found from 10 to 20 ev.

[10] V. L. Sailor and L. B. Borst, Phys. Rev. **87**, 161 (1952).
[11] H. H. Landon and V. L. Sailor, Phys. Rev. **93**, 1030 (1954).
[12] Melkonian, Havens, and Rainwater, Phys. Rev. **92**, 702 (1953).
[13] Sailor, Landon, and Foote, Phys. Rev. **93**, 1292 (1954), see p. 1293.
[14] These samples of enriched samarium isotopes were obtained on loan from the Isotope Research and Production Division of the Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[15] R. E. Wood, Phys. Rev. **95**, 453 (1954).
[16] Isotopic thermal activation cross sections have been compiled in "Nuclear Data," Natl. Bur. Standards Circ. No. 499 (U. S. Government Printing Office, Washington, D. C., 1950).
[17] H. Hurwitz, Jr., and H. A. Bethe, Phys. Rev. **81**, 898 (1951).
[18] M. Goldhaber, Brookhaven National Laboratory Report BNL-C-9, 96, 1949 (unpublished).

TABLE II. A summary of resonances in the slow-neutron cross sections of the rare earth elements. A key to the abbreviations appears in Table I. Entries in italics indicate regions in which only the most prominent resonances could be observed.

Element	E_0 (ev)	Strength ($\sigma_0\Gamma^2$)	Isotope	Isotopic strength $\sigma_0\Gamma^2/F$	Other measurements
$_{57}$La	(no resonances observed below 20 ev)				a
$_{58}$Ce	(no resonances observed below 20 ev)				
$_{59}$Pr	(no resonances observed below 20 ev)				b
$_{60}$Nd	4.38 ±0.04	w.			c
$_{61}$Pm	(no stable isotopes)				
$_{62}$Sm[d]	0.0976±0.0005	68±1	149	490±10	e, f, g
	0.871 ±0.005	m.	149	v.s.	
	3.43 ±0.02	w.	147	m.	
	4.98 ±0.05	w.	149	m.	
	6.45 ±0.10	w.	149(?)	m.	
	8.2 ±0.1	v.s.	152	v.s.	h
	9.1 ±0.2	w.	149(?)	m.	
	12.0 ±0.5	w.			
	15.2 ±0.5	w.	149(?)	m.	
	17.2 ±0.5	w.	149(?)	m.	
	19.1 ±0.5	s.	147	v.s.	
	21.1 ±0.5	s.	150	v.s.	
$_{63}$Eu	(−0.011)[f,j]	m.	151[k]	s.	e
	0.327 ±0.001	14.5±0.7	151	30.0± 1.5	f
	0.461 ±0.001	102 ±5	151	213 ±10	f, e
	1.056 ±0.005	14.5±1.0	151	30.4± 2.0	
	1.76 ±0.02	w.	153	w.	
	2.46 ±0.01	45.2±0.5	153	86 ±10	
	2.73 ±0.05	w.	151(?)	w.	
	3.35 ±0.01	s.	151	v.s.	l
	3.84 ±0.02	m.	153	s.	
	6.25 ±0.04	w.	153	m.	
	7.36 ±0.03	s.	151	v.s.	
	8.98 ±0.05	m.	153	s.	
	10.6 ±0.2				
	11.8 ±0.1				
	12.8 ±0.3				
	15.1 ±0.2				
	19.5 ±0.4				
$_{64}$Gd	(0.031)[f] or (0.044)[e]	s.[e]	155 and 157[m]	v.s.[e]	n
	2.01 ±0.01	w.			o
	2.57 ±0.02	m.			o
	2.81 ±0.03	w.			o
	6.33 ±0.06	m.			o
	7.8 ±0.1	w.			o
	11.9 ±0.2				o
	16.9 ±0.4				o
	21.1 ±0.5				o, h
	22.5 ±0.6				o, h
	30.5 ±0.8				o, h
	34.0 ±1.0				o, h
$_{65}$Tb	3.37 ±0.03	m.	159	m.	
	5.4 ±0.2	w.	159	w.	
	10.6 ±0.3	m.	159	m.	
	11.4 ±0.2	s.	159	s.	
	(no data above 13 ev)				

Undoubtedly, many resonances were present which were not observed, particularly at higher energies. The probability of observing a resonance decreases as the resonant energy is increased.

There are several reasons for failing to observe certain resonances. At higher energies, the resolution of the instrument becomes insufficient to separate adjacent resonances, and under such conditions only the stronger resonances can be observed. In elements where the average spacing between resonances is small this situation is aggravated. At high energies, where resolution is poor, even an isolated weak resonance is apt to be unobservable because the poorer resolution tends to flatten and broaden the resonance until it cannot be observed above the background. In most cases, an additional handicap to detecting weak resonances was the lack of enough material to prepare sufficiently thick samples.

Resonances in isotopes having low natural abundance appear very weak superimposed on a background composed of potential scattering and the resonance contributions from the other isotopes. Such resonances can be observed only if the neighboring resonant structure is of favorable shape and the instrument resolution very good. It was possible, for example, to observe several resonances in Lu^{176} (2.6 percent abundance) in

TABLE II.—*Continued.*

Element	E_0 (ev)	Strength ($\sigma_0\Gamma^2$)	Isotope	Isotopic strength $\sigma_0\Gamma^2/F$	Other measurements
$_{66}$Dy	(−1.01)[f]	v.s.[f]			
	1.72 ±0.01	m.			*p*
	2.73 ±0.02	w.			
	3.70 ±0.03	w.			
	4.36 ±0.05	w.			
	5.49 ±0.04	v.s.			*p*
	7.8 ±0.2				
	9.9 ±0.5	v.w.			
	10.6 ±0.15	m.			
	13.5 ±0.5				
	16.8 ±0.3				
	19.5 ±0.5				
	74 ±5	s.			
$_{67}$Ho[q]	3.96 ±0.03	77±10	165	77±10	
	12.8 ±0.2	v.s.	165	v.s.	*r*
	19.0 ±0.3		165		*r*
	22.0 ±0.4		165		*r*
	39 ±1		165		*r*
$_{68}$Er[s]	0.47 ±0.01	m.			*t*
	0.58 ±0.01	m.			*t*
	6.10 ±0.06	s.			
	9.62 ±0.09	m.			
	16.2 ±0.2	m.			
	21.2 ±0.3				
	27.5 ±0.4				
$_{69}$Tm[q]	3.92 ±0.03	380±40	169	380±40	*r*
	14.8 ±0.2	s.	169	s.	*r*
	17.6 ±0.3	m.	169	m.	*r*
$_{70}$Yb[d]	0.597 ±0.001	1.28±0.10	168	995±90	
	4.55 ±0.03	v.w.			
	8.09 ±0.08	w.			
	13.3 ±0.14	w.			
	18.2 ±0.2	w.			
$_{71}$Lu[q]	0.142 ±0.001	1.4±0.3	176	54±12	
	1.57 ±0.01	v.w.	176	m.	
	2.62 ±0.02	w.	176	v.s.	*r*
	4.80 ±0.04	w.	176(?)	v.s.	*r*
	5.30 ±0.05	m.	175	m.	*r*
	11.4 ±0.2	m.	175	m.	*r*
	14.4 ±0.3		175		*r*
	20.6 ±0.5		175(?)		*r*

[a] J. Rainwater and W. W. Havens, Jr. [unpublished, see R. H. Adair, Revs. Modern Phys. **22**, 249 (1950)].
[b] R. S. Carter and J. A. Harvey, Phys. Rev. **95**, 645 (1954).
[c] Reference 2 (no resonances observed).
[d] Reference 5.
[e] Reference 1.
[f] Reference 3.
[g] A. W. McReynolds and E. Andersen, Phys. Rev. **93**, 195 (1954).
[h] Albert, Yeater, and Gaerttner, Phys. Rev. **95**, 644 (1954).
[i] Reference 7.
[j] Norman Holt, JENER, Kjeller, Norway (unpublished).
[k] Isotopic assignments made by R. E. Wood (see reference 15).
[l] M. Goldhaber [unpublished, see reference 20 in W. J. Sturm, Phys. Rev. **71**, 757 (1947)].
[m] Lapp, Van Horn, and Dempster, Phys. Rev. **71**, 745 (1947).
[n] B. N. Brockhouse and D. G. Hurst, Phys. Rev. **83**, 841 (1951).
[o] R. R. Palmer and L. M. Bollinger, Phys. Rev. **91**, 450 (1953).
[p] Reference 2.
[q] Reference 6.
[r] Pilcher, Carter, and Stolovy, Phys. Rev. **95**, 645 (1954).
[s] Foote, Sailor, and Landon, Phys. Rev. **90**, 362 (1953).
[t] Reference 4.

the region below 4 ev, but at higher energies they could not be observed because of poorer resolution. Isotopes such as La^{138} (0.089 percent abundance) were of too low natural abundance to give observable resonances.

Future improvements in instrument resolution and the use of enriched isotopes will unquestionably reveal many new resonances in this group of elements.

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