Slow Neutron Scattering Cross Sections for Rare Earth Nuclides

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(Received April 23, 1953)

Coherent neutron scattering amplitudes and total scattering cross sections have been determined for a number of elements and separated isotopes of the rare earth series. One nuclide, Sm^{152}, was found to scatter with negative phase.

ALTHOUGH neutron scattering cross sections for over sixty elements and nuclides, as determined by neutron diffraction methods, have been reported by Shull and Wollan,[1] relatively few coherent scattering cross sections in the rare earth region have heretofore been measured.

As an essential part of an investigation of the magnetic scattering of neutrons by rare earth oxides,[2] as well as for their intrinsic interest, nuclear scattering properties of twelve elements or nuclides in the rare earth region have been determined, and these results are listed in Table I.

The coherent scattering data in the table have been obtained from the interpretation of the Bragg reflections from the oxides of the nuclides listed by methods which have been previously described,[1] and the total scattering cross sections were evaluated from transmission measurements at near thermal energy corrected for capture. The capture cross sections were obtained by Pomerance,[3,4] and in most cases he measured the sample on which the scattering measurements were made. The total scattering cross sections have been corrected as far as possible for magnetic scattering so that they represent only the nuclear scattering cross sections. The potential scattering cross sections have been computed from the relation $R=1.53\times10^{-13}A^{\frac{1}{3}}$.

La^{139}

The total cross section of lanthanum obtained from transmission measurements at 0.07 ev was 14.3b, from which the total scattering cross section was found to be 9.3b. This value is close to the coherent scattering cross section of 8.7b, and is in reasonable agreement with that of Harris, Muehlhause, and Thomas[5] but is somewhat lower than the total scattering cross section of 10.5b reported by Brockhouse.[6]

Ce, Ce^{140}, and Ce^{142}

The two major isotopic constituents of cerium are Ce^{140} and Ce^{142}, which together account for 99.55 percent of the normal mixture. The scattering amplitudes of Ce^{140} and Ce^{142} were obtained from neutron diffraction patterns of isotopically enriched samples of CeO_2. Both nuclides are even-even isotopes so that no spin effects are expected, and Ce^{++++} has zero magnetic moment. Transmission measurements, corrected for capture, led to total scattering cross sections equal to the coherent scattering cross sections.

TABLE I. Nuclear scattering properties of rare earth nuclides.

Nucleus	Coherent scattering amplitude (10^{-12} cm)	Coherent scattering cross section barns	Total scattering cross section[a] barns	Potential scattering cross section barns
La^{139}	0.83	8.7±0.3	9.3±0.7	7.90
Ce	0.46	2.7±0.2	2.7±0.2	...
Ce^{140}	0.47	2.8±0.1	2.8±0.1	7.94
Ce^{142}	0.45	2.6±0.2	2.6±0.2	8.00
Pr^{141}	0.44	2.4±0.2	4.0±1.0	7.96
Nd	0.72	6.5±0.4	16±3	...
Nd^{142}	0.77	7.5±0.6	7.5±0.6	8.00
Nd^{144}	0.28	1.0±0.2	1.0±0.2	8.08
Nd^{146}	0.87	9.5±0.4	9.5±0.4	8.16
Sm^{152}	−0.5	3±1	...	8.38
Sm^{154}	0.8	8±2	...	8.44
Er	0.79	7.8±0.4	15±4	...

[a] For the even-even nuclides the total bound scattering cross sections have been taken equal to the coherent scattering cross sections.

* Portions of this work were presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy at the University of Tennessee, Knoxville, Tennessee.

[1] C. G. Shull and E. O. Wollan, Phys. Rev. **81**, 527 (1951).
[2] W. C. Koehler and E. O. Wollan (to be published).
[3] H. Pomerance, Phys. Rev. **88**, 412 (1952).
[4] H. Pomerance, Phys. Rev. **83**, 641 (1951).
[5] Harris, Muehlhause, and Thomas, Phys. Rev. **79**, 11 (1950).
[6] B. N. Brockhouse (private communication).

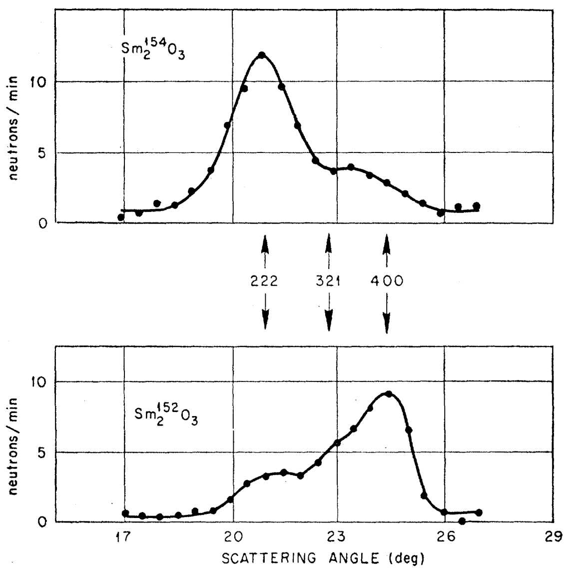

FIG. 1. Neutron diffraction patterns of isotopically enriched samarium oxides.

Both isotopes have cross sections low compared to potential scattering and so also does normal cerium. These results indicate the existence of positive energy resonances in both the major isotopes of cerium. Hibden and Muehlhause,[7] however, using Co and Mn detected neutrons were unable to find resonance effects at these energies.

A sample of normal CeO_2 was prepared from reagent grade cerium nitrate, and the analysis of the neutron pattern for the sample suggested a coherent scattering cross section of 2.2 barns. From the isotopic amplitudes the calculated value for the normal element is 2.7b. This discrepancy is well outside of experimental error and may be due to impurities in the normal cerium oxide which were indicated by the anomalously high total cross section of the sample. The better value is undoubtedly the calculated one and this value appears in the table.

A measurement of the scattering amplitude of cerium from transmission through CeO_2 was reported by Verdaguer, del Rio, Keller, and Kind.[8] These authors give as the scattering amplitude $f_{Ce}=+0.22\pm0.02\times10^{-12}$ cm, and this amplitude corresponds to a cross section of 0.61b, which is nearly a factor of four smaller than the result quoted here.

Nd, Nd^{142}, Nd^{144}, Nd^{146}

Two samples of normal Nd_2O_3 were studied. Pomerance measured the thermal absorption cross sections of the two samples and found 100b for one sample and 42b for the other. The transmission cross section was measured for the high-capture sample at 0.07 ev and also at 1.44 ev,[9] and these values were found to be about 10 percent higher than those of Sturm and Arnold.[10] Both sets of data suggest a total scattering cross section of about 16b. The low-capture sample, after correction for capture on a $1/v$ law indicated a total scattering cross section of 20b. The application of a $1/v$ correction law is probably somewhat questionable. A more reliable estimate of 16 ± 3b has been obtained from the analysis of the diffuse scattering in the diffraction pattern of Nd_2O_3.

The cross sections listed for the separated isotopes of neodymium are strictly correct only for the sample studied and must be corrected for isotopic analysis. However, these cross sections are approximately correct for the individual nuclides because the isotopic enrichment was in each case approximately 95 percent. The three cases studied are all examples of zero spin nuclei so that no spin effects are to be expected. The low-scattering cross section of Nd^{144} indicates the effects of a resonance at positive energies.

The three isotopes, Nd^{142}, Nd^{144}, Nd^{146}, together make up 65 percent of the normal element, the remainder being Nd^{143} (13.0 percent), Nd^{145} (9.2 percent), Nd^{148} (6.8 percent) and Nd^{150} (5.95 percent). The contribution of the three even-even isotopes to the coherent scattering amplitude of normal neodymium is $+0.32\times10^{-12}$ cm as compared to $+0.72\times10^{-12}$ cm. The effective weighted scattered amplitude of the remaining isotopes must therefore be positive and equal to 0.40×10^{-12} cm. The contribution of these three isotopes to the total scattering cross section is only 3.8b. The effective weighted total cross section of the remaining isotopes must hence be of the order of 12b. It is therefore indicated that one or more of the remaining isotopes has a large coherent scattering amplitude and probably exhibits pronounced spin-dependent scattering.

Pr^{141}

The relative magnitude of the coherent and total scattering cross sections of praseodymium indicate a strong spin dependence of scattering. Harris, Muehlhause, and Thomas[5] suggest a scattering resonance in praseodymium at 10 ev. The total scattering cross section of praseodymium has been measured by Brockhouse[6] at Chalk River to be 4.0 barns in exact agreement with our value.

Sm^{152}, Sm^{154}

An attempt was made to evaluate the scattering properties of Sm^{152} and Sm^{154} from samples of isotopically enriched samarium oxide. Both samples contained approximately 3 percent of Sm^{149} which is responsible for the large capture cross section of samarium, and Sm^{152} has a thermal capture cross section of 200b in its

[7] C. T. Hibden and Muehlhause, Phys. Rev. **76**, 100 (1949).
[8] Verdaguer, del Rio, Keller, and Kind, Helv. Phys. Acta **25**, 80 (1952).
[9] We are indebted to Mr. L. A. Rayburn for this measurement.
[10] W. J. Sturm and G. Arnold, Phys. Rev. **71**, 556 (1947).

own right.[11] The measured total cross section at 1.163A was 880b/molecule for the Sm^{152} sample and 396b/molecule for the Sm^{154} sample.

The diffraction peaks in both these samples were extremely weak due to the strong absorption, but rough values for the coherent cross sections were obtained. In Fig. 1 portions of the patterns obtained are illustrated. From a consideration of the relative intensities of the reflections shown, it can be deduced that Sm^{152} has a negative scattering amplitude, and from the absolute intensities approximate cross sections were evaluated. No effort has been made to extract total scattering cross sections from the transmission data.

Er

Erbium has six stable isotopes all of which except Er^{167} (22.9 percent) are even-even nuclei. Bernstein *et al.*[12] have measured the total cross section of Er in Er_2O_3 over the near thermal energy range and they find capture resonances at 0.45 ev and 0.58 ev. The total cross section which was obtained at $\lambda = 1.163$A (0.06 ev) for Er was 138b and this compares favorably with 135b taken from the curve of Bernstein and coworkers. Pomerance found the thermal absorption cross section to be 166 ± 17b. The contribution of the magnetic scattering of Er at 0.06 ev to the total scattering cross section is 5b based on the experimentally determined form factor. From the diffuse scattering in the diffraction pattern a value of 15 ± 4b was obtained which is not inconsistent with the less precise value of 26 ± 11b from the transmission data.

The cooperation of Dr. F. H. Spedding of the Ames Laboratory, and of Dr. G. E. Boyd of the Chemistry Division of the Oak Ridge National Laboratory in making these samples available to us is gratefully acknowledged. For the loan of the isotopically enriched samples we are indebted to the Stable Isotopes Division of the Laboratory, and for x-ray analyses of all the samples to Mr. B. S. Borie and Mr. R. M. Steele.

[11] Lapp, Van Horn, and Dempster, Phys. Rev. **71**, 745 (1947).
[12] Bernstein, Borst, Stanford, Stephenson, and Dial, Phys. Rev. **87**, 487 (1952).

PHYSICAL REVIEW VOLUME 91, NUMBER 3 AUGUST 1, 1953

The Gamma Radiation from B^{11} Bombarded by Protons*

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(Received April 20, 1953)

The spectrum of gamma radiation emitted when B^{11} is bombarded by protons has been investigated with a NaI scintillation counter. Capture gamma rays have been found which occur in a direct transition to the ground state of C^{12} and a cascade transition through a level in C^{12} at 4.45 Mev. Yield curves for these gamma rays have been obtained for proton energies up to 2.8 Mev, and the cross sections for emission of the various gamma rays are given. In addition to the well-known resonance at 0.163 Mev, new resonances have been found at 0.675 Mev with $\Gamma = 0.33$ Mev and 1.388 Mev with $\Gamma = 1.27$ Mev. Spin and parity assignments for these states which are deduced from the results of this and the $B^{11}(p, \alpha)Be^8$ reactions are 2^- (or 3^+) and 1^-, respectively. A 2.13-Mev gamma ray has also been observed, which is produced in an inelastic scattering reaction involving the first excited state of B^{11}. This reaction exhibits a resonance at 2.664 Mev with a width of 48 kev. The cross section at resonance is 3.1×10^{-26} cm^2.

I. INTRODUCTION

In the bombardment of boron by protons a number of gamma rays have been found by various investigators, but the variation of their yield with energy is known only in a rough way or over a limited energy region. The purpose of this investigation was to determine the energies of the gamma rays from proton reactions with B^{11} and their yields for proton bombarding energies up to about 3 Mev.

Previous work on gamma rays from B^{11} reactions has been confined to the reaction

$$B^{11}+H^1 \rightarrow (C^{12}) \rightarrow C^{12}+\gamma_0$$
$$\searrow C^{12*}+\gamma_1 \rightarrow C^{12}+\gamma_1+\gamma_2.$$

The yield curve for this capture radiation in the region up to 500-kev bombarding energy was investigated by Tangen,[1] who found the position of the well-known low-energy resonance to be 162 kev, with a width of 5.3 kev. From measurements of the absorption of secondary electrons he concluded that the radiation is harder off resonance than at 162 kev. Excitation curves at higher energies have been made by Herb, Kerst,

* This work was assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
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[1] R. Tangen, Kgl. Norske Videnskab. Selskabs, Skrifter No. 1 (1946).