Cross Sections for the $B^{11}(n, \gamma)B^{12}$ Reaction*

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Cross sections for the reaction $B^{11}(n,\gamma)B^{12}$ were measured by an activation technique for neutron energies from 139 to 2325 kev and at thermal energy. Resonances in the reaction were observed at neutron energies of 430, 1030, 1280, and 1780 kev. Since the resonance at 1030 kev did not correspond to a known level in B^{12}, the total neutron cross section for boron was measured with 4-kev resolution in the neutron energy region between 950 and 1350 kev. An S-wave resonance was observed in the total cross section at 1027 ± 10 kev. This resonance corresponds to a level in B^{12} at an excitation energy of 4.31 Mev; it most probably has spin and parity of 1^-, and a width of 10 ± 4 kev. From an analysis of the capture cross section resonances, the radiation widths of the levels were found to be 0.3 ev at 430 kev, 0.3 ev at 1027 kev, 0.2 ev at 1280 kev, and 0.9 ev at 1780 kev, with estimated uncertainties of 50%. The measured value of the $B^{11}(n,\gamma)B^{12}$ cross section for thermal neutrons was 5 ± 3 mb.

INTRODUCTION

Radiative capture of neutrons by B^{11} leads to a radioactive isotope, B^{12}, which beta decays with an end-point energy of 13.4 Mev and a half-life of about 20 msec. Resonances in the capture cross section might be expected at neutron energies of 430, 1280, 1780, 2450, and 2580 kev, corresponding to know levels in B^{12} which have been observed in total neutron cross-section measurements and in charged particle reactions.[1] From the magnitude of the cross section of the $B^{11}(n,\gamma)B^{12}$ reaction at these resonances, the radiation widths of the corresponding levels in B^{12} may be obtained.

Previous measurements of the capture of thermal neutrons by B^{11} have given an upper limit of 50 mb for the cross section.[2] No attempts to observe the capture of fast neutrons have been reported.

EXPERIMENTAL PROCEDURE

A. $B^{11}(n,\gamma)B^{12}$ Reaction

The $B^{11}(n,\gamma)B^{12}$ reaction was studied by an activation technique similar to that described previously.[3] Samples consisting of a powdered mixture of natural boron and iodine were bombarded with monoenergetic neutrons and the resulting B^{12} beta-ray activity was observed. The neutron source was turned on for 100 msec, after which the beta particles from B^{12} decays were observed by a scintillation telescope for a period of 100 msec. Pulses from the telescope were fed through a time-to pulse-height converter whose output pulse height was proportional to the time interval between the end of the neutron bombardment and the detection of the B^{12} decay. These output pulses were then stored in a 100-channel pulse-height analyzer. Enough bombarding and counting cycles were used at each energy to give a good measure of counting rate as a function of time after the end of the bombardment. The observed decrease in counting rate with time indicated that the activity had a lifetime of about 20 msec and served to identify it as B^{12} produced by the $B^{11}(n,\gamma)B^{12}$ reaction.

Neutrons for this experiment were produced using a 3-Mev Van de Graaff generator and the $Li^7(p,n)Be^7$ and $H^3(p,n)He^3$ reactions. The former reaction was used to produce neutrons of energies between 140 and 1470 kev, while the $H^3(p,n)He^3$ reaction was used as the source of neutrons between 1560 and 2325 kev. The Li target was an evaporated layer of Li metal about 40 kev thick. However, in order to obtain adequate counting rates, the distance between target and sample was such that neutrons emitted over a large angular interval were able to interact with the boron. This angular spread introduced an additional neutron energy spread so that the over-all energy resolution for the Li target was 50–70 kev. For the $H^3(p,n)He^3$ reaction, tritium gas at a pressure of slightly less than one atmosphere was contained in a thin-walled stainless steel cylinder 3 cm long, separated from the accelerating tube vacuum system by a nickel window 0.003 mm thick. The tritium target thickness, together with the energy spread caused by the large angle subtended by the sample, resulted in an over-all neutron energy spread of 100–200 kev.

When the primary neutron group has an energy greater than 656 kev, the $Li^7(p,n)Be^7$ reaction produces a second group of lower energy neutrons. Corrections for the presence of this second group were made using the known intensity of the low-energy group and the magnitude of the B^{11} capture cross section obtained in this experiment.

Measurements at thermal energies were accomplished by placing the boron sample and the beta-ray counter in the center of a paraffin cube whose edges were 25 cm long. The paraffin block was bombarded with neutrons produced by the $Li^7(p,n)Be^7$ reaction, and

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[1] C. K. Bockelman, Phys. Rev. **80**, 1011 (1950); C. K. Bockelman, D. W. Miller, R. K. Adair, and H. H. Barschall, *ibid.* **84**, 69 (1951); F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1–340 (1959).

[2] K. Way, L. Fano, M. R. Scott, and K. Thew, *Nuclear Data*, National Bureau of Standards Circular No. 499 (U. S. Government Printing Office, Washington, D. C., 1950).

[3] W. L. Imhof, R. G. Johnson, F. J. Vaughn, and M. Walt, Phys. Rev. **114**, 1037 (1959).

the reaction rate due to thermal neutrons was obtained from the observed difference in the counting rates from the boron sample with and without a cadmium cover. For this measurement a boron sample enriched to 98.5% in B^{11} was used.

The activation samples were hollow Plexiglass cylinders containing powdered boron mixed with 20% powdered iodine by weight. These cylinders had a wall thickness of 0.08 cm and were 2.54 cm in diameter and 0.5 cm in length.

The beta particles emitted by the B^{12} nuclei were detected by two 2.54-cm diameter plastic scintillators operated in coincidence, and placed with their axes collinear with the axis of the activation sample and with the incident neutron beam. The front scintillator, which was in contact with the boron sample, was 1.27 cm thick while the back scintillator had a thickness of 2.54 cm. The electronic biases were set so only pulses corresponding to electrons of energy greater than 3.5 Mev were accepted.

The cross sections were calculated from the observed B^{12} activities, the amount of B^{11} in the samples, and the effective neutron flux striking the B^{11} activation samples. The effective neutron flux was determined by measuring the $I^{127}(n,\gamma)I^{128}$ reaction rate produced in the iodine of the samples during the bombardments. The number of $I^{127}(n,\gamma)I^{128}$ events was deduced from measurements of the 25-min half-life I^{128} activity induced in the sample. The $I^{127}(n,\gamma)I^{128}$ cross sections used to determine the neutron flux were those of Bame and Cubitt[4] and of Johnsrud *et al.*[5] A smooth curve was drawn through the data of Bame and Cubitt for neutron energies between 139 and 1000 kev, and this curve was extended to fit the data of Johnsrud *et al.* for energies above 1000 kev. At thermal energies the value of the capture cross section of I^{127} was taken to be 5.6 barns.[6]

To estimate the number of $B^{11}(n,\gamma)B^{12}$ reactions induced by room-scattered background neutrons, the B^{12} activity was measured as a function of the distance between the sample and the neutron source. The flux of background neutrons should be rather constant in the vicinity of the neutron source, while the intensity of source neutrons should decrease inversely with the square of the distance from the source. For distances less than 25 cm from the source, the B^{12} activity was found to vary inversely with the square of the source-to-sample distance, indicating that the effect of room-scattered background neutrons was negligible in the experiment.

B. Total Cross Section of Boron

The total cross section of boron was obtained by measuring the transmission of a boron sample in the energy region near 1 Mev with an energy resolution of about 4 kev. The neutrons were produced in a 3-kev thick lithium target by the $Li^7(p,n)Be^7$ reaction. The effect of the second group of lower energy neutrons was eliminated by using neutron time-of-flight discrimination. Since the time-of-flight served only to separate the main neutron group from the second group, from the gamma rays, and from any room-scattered neutrons, it did not influence the energy resolution, which was determined by the lithium target thickness and the energy spread of the incident protons.

The total cross section sample consisted of boron powder packed in a 2.54-cm diameter tantalum cylinder with a wall thickness of 0.014 cm. During the transmission measurement the sample was placed at a distance of 12 cm from the lithium target and at the center of the entrance to an iron shielding collimator having an inside diameter of 5.08 cm. The neutrons were detected by a plastic scintillator having a diameter of 5.08 cm and a length of 2.54 cm which was placed in the collimator at a distance of 92 cm from the boron sample. An identical tantalum cylinder containing no boron was used to determine the "sample-out" counts. In-scattering corrections amounting to about 0.5% of the cross section were applied to the data.

RESULTS

In Fig. 1 are shown the $B^{11}(n,\gamma)B^{12}$ cross sections obtained from this experiment. The errors shown are those due to counting statistics only, and indicate the relative accuracy of the data points. Uncertainties in the absolute values of the cross sections are due to the uncertainties in the iodine cross sections which were used and to uncertainties in the detection efficiencies of the B^{12} and I^{128} decays. The probable errors of the

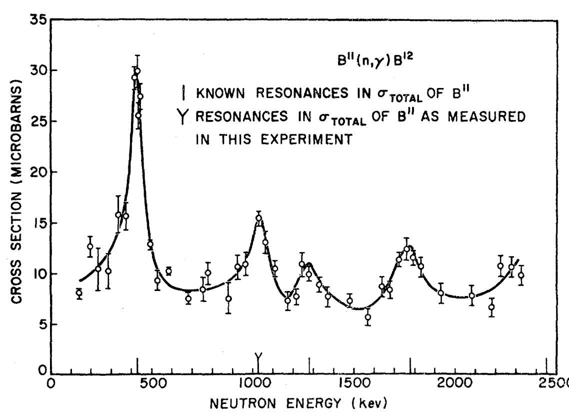

FIG. 1. Cross sections for the $B^{11}(n,\gamma)B^{12}$ reaction. Indicated on the energy scale are previously known resonances in the total cross section of B^{11}. Also shown is a resonance in the total cross section of B^{11} as measured in this experiment.

[4] S. J. Bame, Jr., and R. L. Cubitt, Phys. Rev. **113**, 256 (1959).
[5] A. E. Johnsrud, M. G. Silbert, and H. H. Barschall, Phys. Rev. **116**, 927 (1959).
[6] *Neutron Cross Sections*, compiled by D. J. Hughes and R. Schwartz, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 1958), 2nd ed.

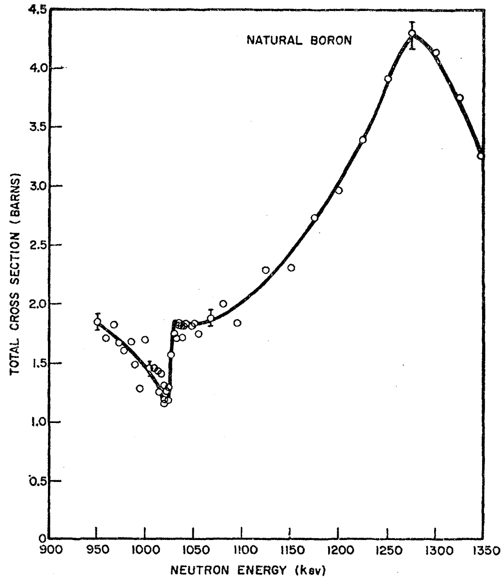

FIG. 2. The total cross section of natural boron as a function of neutron energy.

$B^{12}(n,\gamma)B^{11}$ cross sections are estimated to be $\pm 50\%$. The cross section at thermal energy was found to be 5 ± 3 mb.

Resonances in the capture cross section occur at 430, 1280, and 1780 kev where resonances have previously been observed in the total neutron cross section of B^{11}. As shown in Fig. 1, there is also a well-defined maximum in the capture cross section at about 1030 kev. This does not correspond to a previously observed resonance in the total cross section nor to a known level in B^{12}.

The results of the present measurement of the total cross section of natural boron in the energy region near 1 Mev with an energy resolution of about 4 kev are shown in Fig. 2. An apparent S-wave resonance is seen at 1027 kev and is attributed to B^{11} because the cross-section variation is too large to be produced by B^{10} or by any of the contaminants in the scattering sample.

The observed cross section of B^{11} in this energy region was found to be consistent with an S-wave resonance, most probably produced by a compound nucleus state with $J=1^-$, and a width of 10 ± 4 kev. In analyzing the experimental results to obtain the resonance parameters, potential scattering phase shifts of Willard *et al.*[7] were used.

Assuming that the capture cross sections of Fig. 1 can be represented by a sum of noninterfering Breit-Wigner resonance terms superimposed on a slowly varying background, the radiation widths of the levels were found to be 0.3 ev at 430 kev, 0.3 ev at 1026 kev, 0.2 ev at 1280 kev, and 0.9 ev at 1780 kev, with estimated uncertainties of about 50%. In this analysis the neutron width of the 1027-kev level was taken to be 10 kev: The neutron widths of the other levels were those reported by Bockelman *et al.*[1]

Theoretical estimates were made of the radiation widths of the various levels in B^{12}. Since no observations were made of the gamma rays associated with the radiative capture, it is possible to compare only the total radiation widths with theory. Such a comparison is hampered by uncertainties in the spins and parities of the lower levels to which the excited B^{12} nucleus may decay. Because of these uncertainties, calculations were performed for a number of possible spin assignments of the more important levels.

The radiation widths were first estimated using the formula derived by Weisskopf[8] for single-proton transitions. In this approximation the wave function of this proton is taken to be constant inside the nuclear radius and zero outside. Also, the orbital angular momentum of the proton is assumed to be zero in the final state. For the more general case in which the angular momentum is not zero in the final state, the Weisskopf value was multiplied by a statistical factor. These estimates of the radiation widths are larger than the experimental values by one to two orders of magnitude.

More exact calculations, based on the shell model, were carried out with formulas given by Lane.[9] All the particles in unfilled shells were taken into account by expanding their wave functions in a fractional parentage representation. Reasonable selections were made for the spin, parity, and parentage assignments of the odd-particle states coupled to the core, and several possible assignments for these states were found for which the calculated radiation widths were higher, but within about a factor of 2 of the experimental values. Since the accuracy of the present experiment and the existing data on the states of B^{12} are insufficient to discriminate between different possible spin and parity assignments for these levels, a detailed discussion of these theoretical calculations is not warranted in this paper.

[7] H. B. Willard, J. K. Bair, and J. D. Kington, Phys. Rev. **98**, 669 (1955).

[8] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).

[9] A. M. Lane, Revs. Modern Phys. **32**, 519 (1960).