Proton Groups from the $B^{11}(d,p)B^{12}$ Reaction*

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(Received April 10, 1950)

Two proton groups observed when boron targets are bombarded with 1.5-Mev deuterons have been identified as arising from the $B^{11}(d,p)B^{12}$ reaction. The Q-values for these groups are 1.136 ± 0.005 and 0.189 ± 0.004 Mev, showing the presence of an excited state in B^{12} at 0.947 ± 0.005 Mev. The reaction energy for the ground-state group is in good agreement with that calculated for the masses and from the B^{12} beta-rays and indicates that the primary mode of decay of B^{12} to C^{12} is between the ground states of these nuclei.

I. INTRODUCTION

THE bombardment of B^{11} with deuterons leads to the formation of radioactive B^{12}. This decays by electron emission to C^{12}, and the beta-ray spectrum has been the subject of several investigations, the most recent of which is that of Hornyak and Lauritsen.[1] These authors find the end point of the B^{12} distribution to be 13.43 ± 0.06 Mev. The shape of the observed distribution is such as to indicate that more than one state of the residual nuclei of B^{12} or C^{12} may be involved in the transformation.

Recently, Hudspeth and Swann[2] have measured, as a function of deuteron energy, the yield of beta-rays from B^{12} formed in the reaction $B^{11}(d,p)B^{12}$. Using photographic plates and range measurements, they have also observed two particle groups which they identify as protons and which they attribute to this reaction. On the basis of this assignment, they have obtained Q-values of 1.25 and 0.15 Mev for the reactions. The relative intensities of these two groups were found to be in the ratio of 1 to 60, the high energy group which is assigned to the reaction leading to the formation of B^{12} in its ground state being the weaker. Hudspeth and Swann conclude that, in the $B^{11}(d,p)B^{12}$ reaction, the B^{12} is usually formed in an excited state at about 1.1 Mev, and that the B^{12} thus formed emits a gamma-ray of this energy before the beta-decay.

We have studied the proton groups emitted from boron targets bombarded by deuterons, using a magnetic spectrometer to analyze the particle groups. We have found two groups of protons that we assign to $B^{11}(d,p)B^{12}$, and the measured Q-values are in approximate agreement with those given by Hudspeth and Swann. However, there is a marked discrepancy between their measurements and ours with regard to the relative intensities of the two groups, our measurements indicating that the ground-state group is about four times as intense as is the one associated with the B^{12} excited state. These measurements and the possible reasons for this disagreement are discussed in the sections that follow.

II. EXPERIMENTAL METHODS AND RESULTS

The apparatus and experimental techniques are essentially the same as those that have been described in a previous paper.[3] The deuteron beam from an electrostatic accelerator and deflecting magnet is directed at a target placed between the pole faces of a large annular magnet. The charged particles emitted at right angles to the incident beam are deflected through 180 degrees and focused in the uniform magnetic field. The particles are recorded on nuclear track plates placed in the focal plane of the magnet so that a series of plates, each exposed at a different field strength, provides a spectrum of the charged particles emitted from the target. As in our previous work, polonium alpha-particles have been used to calibrate the fluxmeter. A similar fluxmeter has been installed in the deflecting magnet used for analyzing the incident deuteron beam, and this is calibrated from measurements on the deuterons elastically scattered from thin foils placed in the target position.

Various measurements and calculations have recently been made that considerably reduce the uncertainties introduced by the conversion from the observed peak positions to the corresponding reaction energies. These new measurements include a precise determination of the angle of observation with respect to the incident beam and will be described in a forthcoming paper on the energies released in a number of nuclear reactions. The results reported here have been treated in the light of these new measurements.

The targets employed in these experiments were prepared by the evaporation of metallic boron onto platinum sheets. Both natural boron and boron in which the proportion of B^{10} was increased 96 percent (obtained from Oak Ridge) were employed. The targets used had effective thickness of approximately 5 kilovolts. With the incident deuteron energy held constant at 1.510 Mev, the various particle groups emitted from both the natural boron and the B^{10} enriched targets have been studied over a wide range of analyzing magnet field strengths, enabling the study of proton groups with energies lying between 1.25 and 10 Mev. Since a 1.5-Mev

* This work has been assisted by the joint program of the ONR and AEC.

[1] W. Hornyak and T. Lauritsen, Phys. Rev. 77, 160 (1950).
[2] E. L. Hudspeth and C. P. Swann, Phys. Rev. 76, 1150 (1949).
[3] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. 74, 1569 (1948).

deuteron has approximately the same $H\rho$ as a 3-Mev proton (250 kilogauss centimeters), all the plates exposed at field strengths below this value were covered with thin aluminum foil so as to intercept the deuterons that were elastically scattered by the platinum backing of the target. The thickness of these foils was chosen so that, for the particular energy range for which the plates were exposed, the scattered deuterons were completely stopped. This greatly facilitated the counting of the plates in the low energy region. These foils also completely stop any alpha-particles that may be present as, for example, from $B^{10}(d,\alpha)Be^8$; since, for a given $H\rho$, alpha-particles have a smaller range than do deuterons. Since, for a given $H\rho$, the deuterons have only approximately half the proton energy, such foils do not seriously shorten the proton tracks.

Large numbers of proton groups were observed in the energy interval investigated. By comparing the yields from the natural boron targets with those enriched in B^{10}, all except two of these proton groups could be identified as arising from either the $B^{10}(d,p)B^{11}$ reaction or from reactions involving various contaminants, such as nitrogen, oxygen, and carbon.

The proton spectrum in the region where these two groups occur is shown in Fig. 1. The upper part of Fig. 1 shows the protons observed from the natural boron targets, while the lower part shows the groups observed from the targets enriched in B^{10}. It can be seen that the groups at 167 and 214 kilogauss centimeters with the natural boron targets are completely missing in the lower curve taken from the targets enriched in B^{10}. This would be expected if these groups are due to B^{11}, since the enriched targets contain only 4 percent B^{11}, as compared with 81 percent for the natural boron. The groups at 171 and 190 kilogauss centimeters are increased in intensity by a factor of approximately 5 when the enriched targets are substituted for the natural boron, as would be expected if they are due to $B^{10}(d,p)B^{11}$, since the B^{10} is only 18 percent in the natural boron but is 96 percent in the enriched material. As indicated on the figure, the other groups observed are identified as arising from reactions involving N^{14} and O^{16}. The very intense peak at 216 kilogauss centimeters has been shown one-half size in the figure and is due to the $O^{16}(d,p)O^{17*}$ reaction, the O^{17} being formed in an excited state. The Q-value for this reaction has been previously measured as 1.049 Mev.[4] This group from oxygen is close to, but clearly resolved from, the group from B^{11}.

As a further check on the assignments of these groups, we have measured the shift in position produced by changes in the energy of the incident deuteron beam. Such measurements provide a sensitive check on the proper assignment of a group to a particular isotope, the change in proton energy being independent of the Q for the reaction and depending only on the ratios of the various masses involved and the change in the deuteron energy. For observations made at 90 degrees, the energy of a proton group from $B^{11}(d,p)B^{12}$ will change by an amount equal to ten-thirteenths of the change in energy of the incident deuteron beam, whereas the fraction will be nine-twelfths in the case of a group from $B^{10}(d,p)B^{11}$. This difference is readily measurable with a magnetic spectrometer of the type employed in these experiments. Studies of this type made on the two groups shown in Fig. 1 at 215 kilogauss centimeters are plotted in Fig. 2. The figure shows the position of these groups for both the natural boron and the B^{10} enriched targets at three different deuteron energies. Since the change in energy of the proton group from $O^{16}(d,p)O^{17*}$ is fifteen-eighteenths the change in the deuteron energy, the energy of this group will decrease more rapidly as the incident energy is lowered than will the energy of a proton group from either of the boron isotopes. This effect can be seen in Fig. 2, the group from oxygen having the higher energy at a bombarding energy of 1.674 Mev and the lower energy for 0.700-Mev deuterons. The change in energy of the group from boron

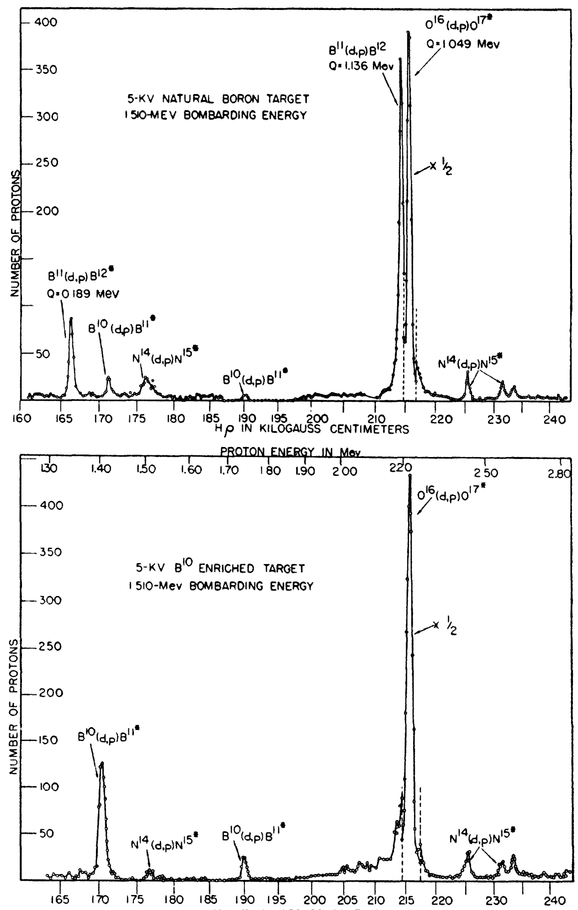

FIG. 1. Proton spectrum from natural boron and B^{10} enriched targets in the energy interval from 1.30 to 2.80 Mev. Incident deuteron energy is 1.510 Mev.

[4] Buechner, Strait, Sperduto, and Malm, Phys. Rev. 76, 1543 (1949).

shows conclusively that it arises from the $B^{11}(d,p)B^{12}$ reaction; on the basis of this assignment the Q-values calculated for this group, for each of the three bombarding energies, agree to about 1 kilovolt. If the boron group shown on the curve for 1.674-Mev deuterons had been due to $B^{10}(d,p)B^{11}$, it would have appeared at the position shown by the dotted curve in the figure for the natural boron targets at 0.700-Mev deuteron energy. Figure 2 also shows that this peak for boron is absent from the measurements taken on the B^{10} enriched target.

These measurements allow the calculation of the energies released when B^{12} is formed in its ground state and in an excited state. The Q-values obtained are 1.136 ± 0.005 Mev and 0.189 ± 0.004 Mev, respectively. This leads to a value of 0.947 ± 0.005 Mev for the energy of the excited state of B^{12} involved in these reactions. An energy-level diagram of B^{12} is shown in Fig. 3, the excitation curve shown for the $B^{11}(d,p)B^{12}$ reaction being that determined by Hudspeth and Swann for the yield of the disintegration electrons.

The above values for the Q-values have not been corrected for the effect of possible surface contaminants. In general, it is possible to measure the thickness of surface layers, which consist principally of carbon and oxygen, by observations on the intensities of the groups from the $C^{12}(d,p)C^{13}$ and $O^{16}(d,p)O^{17}$ reactions. In the present case, it appears that oxygen is distributed throughout the target; since the boron was evaporated from a graphite crucible, this is also true for carbon. Hence, it is not possible to distinguish the effect of a surface layer in this way. However, the close concordance of results taken over a considerable time interval, together with the good agreement between the Q-values obtained at widely different bombarding energies, indicates that the effect of surface contaminants which would lead to somewhat low Q-values is not serious in these experiments.

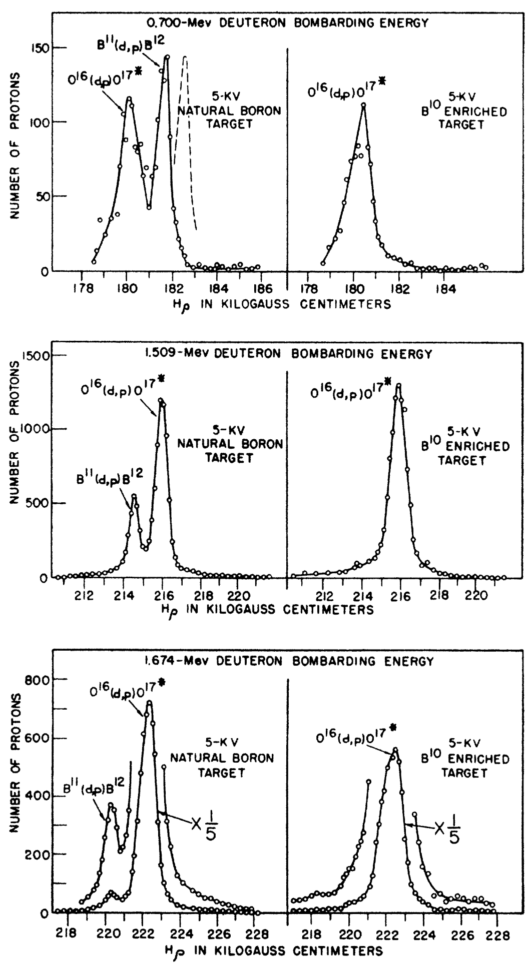

FIG. 2. Proton groups from $B^{11}(d,p)B^{12}$ and $O^{16}(d,p)O^{17*}$ for different incident deuteron energies.

III. DISCUSSION

The curves in Fig. 1 show that the proton group from $B^{11}(d,p)B^{12}$ is about four times an intense as that from $B^{11}(d,p)B^{12*}$ at a bombarding energy of 1.510 Mev. As has been mentioned, Hudspeth and Swann report that, at a deuteron energy of 1.68 Mev, the low energy group is 60 times as intense as the group corresponding to the ground-state reaction. We have not made a detailed study of the variation of yields of these groups as a function of bombarding energy, but the data shown in Fig. 2 indicate that the intensity of the ground-state group is not sensitive to bombarding energy in the range from 1.50 to 1.67 Mev. Such a large change in the relative intensity of the groups would not be expected over such a short energy interval, and it is possible that the discrepancy between the two sets of measurements can be explained as being caused by other factors.

In the measurements of Hudspeth and Swann, the group of particles attributed to the $B^{11}(d,p)B^{12*}$ reaction is more intense than and has a slightly longer range than a group identified as being due to deuterons elastically scattered from a target prepared by the evaporation of boron onto a thin aluminum foil. Their curve indicates that the scattering from the boron is only a small fraction of the scattering from the target. Thus, their interpretation indicates that the protons from $B^{11}(d,p)B^{12*}$ are much more numerous than the deuterons elastically scattered from the boron. We have made measurements on the relative intensities of the protons from $B^{11}(d,p)B^{12*}$ and the elastically scattered deuterons, the targets being formed by the evaporation of boron onto a thin Formvar foil. We find that deuterons elastically scattered from boron are approximately six times as intense as protons from $B^{11}(d,p)B^{12*}$. It appears probable that, in the work of Hudspeth and Swann, the more intense peak having a slightly greater range may be due to a scattering of deuterons from some target contamination of higher atomic number rather than to protons from the boron. It has been suggested by Dr. Hudspeth[5] that such a con-

[5] E. L. Hudspeth, private communication.

taminant might be either wolfram or tantalum from the ribbons used for the boron evaporation, and measurements on the relative ranges of the two groups tend to confirm this interpretation. Since the elastic scattering varies as the square of the atomic number, only a small amount of wolfram or tantalum would be required to produce this group, and we have found that small amounts of these elements are usually deposited on targets prepared by evaporation from such ribbons.

Additional evidence that this peak was probably caused by deuterons scattered by a surface contaminant, rather than by protons from boron, is provided by the fact that it was observed to disappear when a target enriched with B^{10} was bombarded. As can be seen from Fig. 1, the proton group from $B^{11}(d,p)B^{12*}$ is close to a group from $B^{10}(d,p)B^{11*}$. It is unlikely that these two groups would have been resolved in the experiments of Hudspeth and Swann, and it can be seen that the latter group is of considerable intensity when observations are made from a target enriched in B^{10}. These two groups, shown in Fig. 1 for a bombarding energy of 1.51 Mev, would also be somewhat closer together at the higher bombarding energy used in their experiments.

The data in Fig. 2 for a natural boron target at a bombarding energy of 1.674 show the very considerable intensity of the protons from oxygen contamination, as compared with those from $B^{11}(d,p)B^{12}$. It is possible that the measurements of Hudspeth and Swann in this energy region were complicated by the presence of this group from oxygen. That oxygen may have been present in considerable amounts is indicated by the presence of the unidentified higher energy group in their data. This group has approximately the range and relative intensity which would be expected for the protons from $O^{16}(d,p)O^{17}$. The Q-value for this reaction is 1.925 Mev,[4] and we find that, at these bombarding energies, its intensity is approximately half that of the group from $O^{16}(d,p)O^{17*}$.

The measured Q-value for the $B^{11}(d,p)B^{12}$ reaction allows the calculation of the $B^{11}-B^{12}$ mass difference.

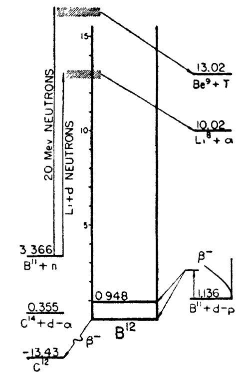

FIG. 3. Energy-level diagram for B^{12}. Energies in Mev.

From this value, together with the mass[6] of B^{11}, and from Hornyak and Lauritsen's value for the end point of the beta-decay from B^{12}, we calculate the mass of C^{12} to be 12.00376. This calculated value agrees with the value otherwise obtained,[6] the difference being within the probable errors of the masses of B^{12} and C^{12}. It thus appears that the primary process in the beta-decay is a direct transition from the ground state of B^{12} to the ground state and, with less probability, to one or more of the excited states of C^{12}.

We are indebted to Dr. E. L. Hudspeth and Mr. C. P. Swann for correspondence regarding their results. We are also indebted to Mr. W. Tripp, Miss C. O'Brien, and Mrs. H. Andrews for their assistance in connection with the reading of the photographic plates.

Note added in proof.—Since the above results were submitted for publication, McMinn, Sampson, and Bullock [Phys. Rev. **78**, 296 (1950)] have reported proton groups from the reaction $Be^9(\alpha,p)B^{12}$, using 21.94-Mev cyclotron alpha-particles and range measurements. They find proton groups with Q-values of -7.02, -8.06, -8.93, and -11.11 Mev, corresponding to the ground state of B^{12} and excited states at 1.04, 1.91, and 4.09 Mev. Since no probable errors were given for these results, we conclude that the value for the first excited state of B^{12} at 1.04 Mev is in reasonable agreement with our result of 0.947 Mev. No search has been made for a proton group from the $B^{11}(d,p)B^{12}$ reaction corresponding to an excited state in B^{12} at 1.91 Mev.

[6] J. Mattauch and A. Flammersfeld, Isotopic Report, Special Issue, Zeits. f. Naturforsche, 1949.