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Energy Levels of B^{11} from the $B^{10}(d,p)B^{11*}$ Reaction*

D. M. Van Patter, W. W. Buechner, and A. Sperduto
Physics Department and Laboratory for Nuclear Science and Engineering,
Massachusetts Institute of Technology, Cambridge, Massachusetts

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The proton groups from enriched B^{10} bombarded by 1.51-Mev deuterons have been investigated by means of a magnetic spectrograph of high resolution. Eleven proton groups were assigned to the reaction $B^{10}(d,p)B^{11}$, corresponding to the ground state and ten excited states of B^{11}. Five of these excited states have not been previously reported. At 6.8-Mev excitation of B^{11}, a doublet was observed with a level spacing of 50.0±2.0 kev. The range of excitation of B^{11} covered in these experiments was from 0 to 10.2 Mev.

I. INTRODUCTION

The first investigation of the proton groups from natural boron bombarded by deuterons was made by Cockcroft and Walton.[1] Using range measurements, they found three groups which they attributed to the B^{10} isotope on the basis of mass considerations. Their measurements at 0.55-Mev bombarding energy were repeated with improved accuracy by Cockcroft and Lewis[2] who measured Q-values of 9.14±0.10; 7.00 ±0.10; and 4.71±0.05 Mev,[3] corresponding to the ground state of B^{11} and levels at 2.14 and 4.43 Mev.

Pollard, Davidson, and Schultz[4] bombarded natural boron targets with 3.1-Mev deuterons and found four proton groups by range measurements. They reported Q-values of 9.22±0.2; 7.30±0.3; 5.00±0.2; and 2.39 ±0.2 Mev, corresponding to the ground state of B^{11} and excited states at 1.92, 4.22, and 6.83 Mev.

While the present experiments were in progress, Bateson[5] reported the results of his investigation of the proton groups from enriched B^{10} targets bombarded by 3.8-Mev deuterons. Using range measurements, he found seven groups which he assigned to the $B^{10}(d,p)B^{11}$ reaction, the Q-values being 9.18±0.05; 7.03±0.06; 4.70±0.06; 4.15±0.06; 2.26±0.07; 1.36±0.07; and 0.70±0.10 Mev. This work confirmed the earlier results and indicated new levels in B^{11} at 5.03±0.06; 7.82 ±0.08; and 8.48±0.10 Mev.

The assignment of the proton group with Q-value of 9.2 Mev to the ground-state $B^{10}(d,p)B^{11}$ reaction was shown to be correct by Thirion[6] from his p-γ coincidence measurements on the $B^{10}(d,p)$ proton groups. The excitation curve for the ground-state protons has been measured by Phillips[7] from 0.7- to 2.0-Mev bombarding energy at observation angles of 0, 90, and 135 degrees. Angular distributions of the ground-state protons have been reported by Redman[8] at bombarding energies of 1.06, 1.50, 1.71, 2.36, 3.06, and 3.68 Mev.

Additional information concerning the excited states of B^{11} has been found from other reactions. Ortner and Protiwinsky[9] have reported transitions to the 2.25- and 4.45-Mev levels of B^{11} from the $N^{14}(n,\alpha)B^{11*}$ reaction. Fulbright and Bush[10] have investigated the inelastic scattering of 15.6-Mev protons from natural boron. They found proton groups corresponding to levels at 2.2±0.3; 4.8±0.4; 6.5±0.3; and 7.8±0.4 Mev which could be associated with either B^{10} or B^{11}.

The gamma-radiation from natural boron bombarded by deuterons was first studied by Crane, Delsasso, Fowler, and Lauritsen[11] using a cloud chamber. Improved measurements were later made by Gaerttner, Fowler, and Lauritsen[12] who reported gamma-rays with energies of 1.5±0.2; 2.2±0.3; 4.4±0.3; 6.9±0.4; and 9.1±0.4 Mev at 550- to 850-(peak) kev bombarding energy. Halpern and Crane,[13] also using a cloud chamber, reported gamma-rays of 1.4, 2.4, 4.2, 6.0, and 8.6 Mev at 700-kev bombarding energy.

While the present experiments were in progress, Terrell[14] reported his measurements using a pair spectrometer on the gamma-rays from natural boron and enriched B^{10} bombarded by 1.56-Mev deuterons. He measured gamma-rays of 4.52±0.10; 6.74±0.13; and 9.11±0.18 Mev, assigned to $(B^{10}+d)$, and of 4.5±0.1 Mev, assigned to $(B^{11}+d)$. The thick-target yields of these gamma-rays were approximately 7.2, 7.2, 3.7, and 3.6×10^7 quanta per microcoulomb, estimated for targets of 100 percent separated isotopes. The asymmetrical shape of the peaks of the two lower $(B^{10}+d)$ gamma-rays indicated the possible existence of weaker unresolved gamma-rays of slightly higher energy. The gamma-rays of 1.5 and 2.2 Mev, reported by earlier workers, would probably not have been detected by Terrell because of the low efficiency of the pair spectrometer at these energies.

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* A report of these measurements was given at the 1950 meeting of the Physical Society in Washington, D. C.

[1] J. D. Cockcroft and T. S. Walton, Proc. Roy. Soc. (London) **A144**, 704 (1934).

[2] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **A154**, 246 (1936).

[3] Corrected by M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 245 (1937).

[4] Pollard, Davidson, and Schultz, Phys. Rev. **57**, 1117 (1939).

[5] W. O. Bateson, Phys. Rev. **78**, 337 (1950).

[6] J. Thirion, Comptes rend. **229**, 1007 (1949).

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[9] G. Ortner and G. Protiwinsky, Nature **142**, 807 (1938).

[10] H. W. Fulbright and R. R. Bush, Phys. Rev. **74**, 1323 (1948).

[11] Crane, Delsasso, Fowler, and Lauritsen, Phys. Rev. **46**, 1109 (1934).

[12] Gaerttner, Fowler, and Lauritsen, Phys. Rev. **55**, 27 (1939).

[13] J. Halpern and H. R. Crane, Phys. Rev. **55**, 415 (1939).

[14] J. Terrell, private communication. Also, Bull. Am. Phys. Soc., 26, 12 (1951).

The high ground-state Q-value of 9.2 Mev for the $B^{10}(d,p)B^{11}$ reaction permits the investigation of the excited states of B^{11} over a large region of excitation. Previous investigations of this reaction have indicated the existence of many levels in this region of excitation. It was decided to investigate with a magnetic spectrograph the protons group from B^{10} bombarded by 1.51-Mev deuterons, since this would establish the position of the excited states of B^{11} over the region from 0- to 10-Mev excitation and might indicate some pattern to the level structure. In addition, the high resolution of the magnetic spectrograph would make possible the detection of fine structure of any of the excited states that would not have been resolved by the earlier range measurements.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

The apparatus and experimental procedures were essentially the same as those described in previous papers[15,16] except for some improvements in stabilization and the calculation of Q-values. A beam of deuterons was accelerated by an electrostatic generator and then deflected through 90° by means of a magnet. After passing through a narrow slit, the deuteron beam was directed at a target placed between the pole faces of a large annular magnet. A fraction of the charged particles, emitted from the target in a plane normal to the incident beam, was deflected through 180° in the magnetic field of the annular magnet and recorded on nuclear-track plates. Each plate covered a range in particle momentum of 6 percent, so that, in order to survey a complete spectrum of charged-particle groups, a series of plates was necessary, each plate being exposed at a different field strength.

The momentum of the charged-particle groups was determined from measurements of the magnetic field and their radii of curvature. The magnetic field measurements were calibrated from the measured radius of curvature of polonium alpha-particles. The value of Hr for polonium alpha-particles, used as an absolute standard, was 3.3159×10^5 gauss cm[17,18] (absolute emu), which is accurate to 0.02 percent. The incident deuteron energy was determined from the observation of deuteron groups elastically scattered from C^{12} and O^{16} nuclei in a thin Formvar target.

Several small corrections[19] were applied to the Q-values calculated for a 90° angle of observation. These corrections took into account:

(1) A small measured departure of the median angle of observation from 90°;

(2) The effect of the finite angle of acceptance (±0.2° about the median angle) of the detector and the finite size of the deuteron beam striking the target;

(3) The approximation in using the nonrelativistic Q-equation for calculation;

(4) The effect of increased mass of residual nucleus when in an excited state.

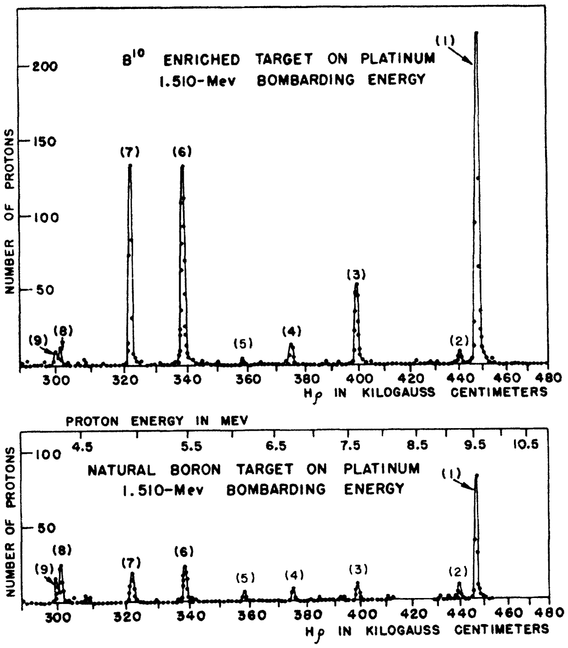

FIG. 1. Proton groups observed from targets of enriched B^{10} and natural boron bombarded by 1.51-Mev deuterons.

The targets used for the $B^{10}(d,p)$ reaction were prepared by the evaporation from a carbon crucible of metallic boron onto 10-mil platinum sheets. Both natural boron and boron enriched to 96 percent B^{10} were used. (The enriched boron was obtained from the Stable Isotopes Division, AEC, Oak Ridge.) These targets had an effective thickness of about 10 kev for the $B^{10}(d,p)B^{11}$ ground-state reaction.

The survey of the proton groups at 90° from these targets was made at 1.51-Mev bombarding energy. In order to observe proton groups with energies of less than 3 Mev, it was necessary to eliminate the deuterons elastically scattered from the platinum backing of the target. This was accomplished by covering the nuclear-track plates with an aluminum foil sufficiently thick to stop the deuterons but thin enough to allow the protons to be recorded. However, this method had some disadvantages. Any variation in the effective thickness of the aluminum foils caused a large variation in the residual range of the proton tracks. This meant that the selection of tracks to be counted could not be so strict, and, therefore, tracks caused by alpha-contamination on the plates could not be eliminated so readily. In addition, any pinholes in the foils allow small numbers of deuterons to be recorded, and these also could not be completely eliminated from the counting

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[15] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. 74, 1569 (1948).

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

[17] G. H. Briggs, Proc. Roy. Soc. A157, 183 (1936).

[18] W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. A145, 250 (1934).

[19] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. 81, 747 (1951).

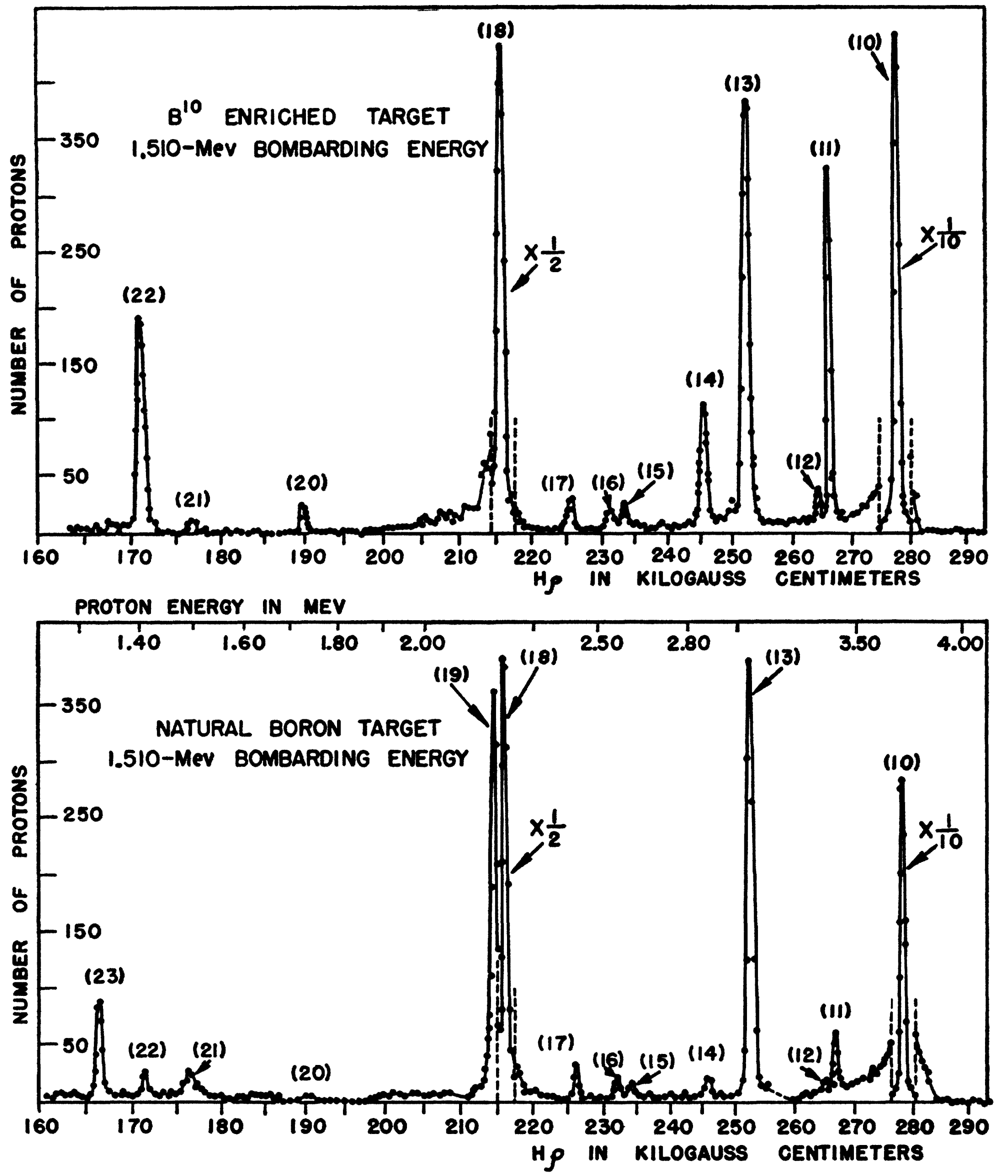

FIG. 2. Proton groups observed from targets of enriched B^{10} and natural boron bombarded by 1.51-Mev deuterons.

of the proton tracks. The result of these effects was an appreciable background between proton peaks. It was found to be impracticable to use this method for the detection of proton groups with energies of less than 1.3 Mev.

In order to investigate proton groups with energies less than 1.3 Mev, targets were prepared by the evaporation of natural boron and enriched B^{10} onto a thin film of Formvar. This type of target with a thin backing has the advantage that the full length of the proton tracks can be recorded and is particularly useful for the investigation of proton groups which occur at *Hr* values lower than any of the deuteron groups elastically scattered from the nuclei of the target and backing. Such a target was not used for the original survey, because it was considered doubtful that it would withstand beam bombardment. However, it was found that boron targets evaporated onto Formvar films did survive for long exposures to the beam. Proton groups in the energy range from 0.45 to 1.45 Mev were investigated with these targets. It was also possible to observe the deuteron groups elastically scattered from the B^{10} and B^{11} nuclei in these targets.

In this work, a number of alpha-particle groups was also observed. Studies of these groups are reported in separate publications.

III. RESULTS

With the incident deuteron energy held constant at 1.51 Mev, a survey was made of the proton groups of energies 1.3 to 10.5 Mev emitted from targets of enriched B^{10} and natural boron on platinum backings.

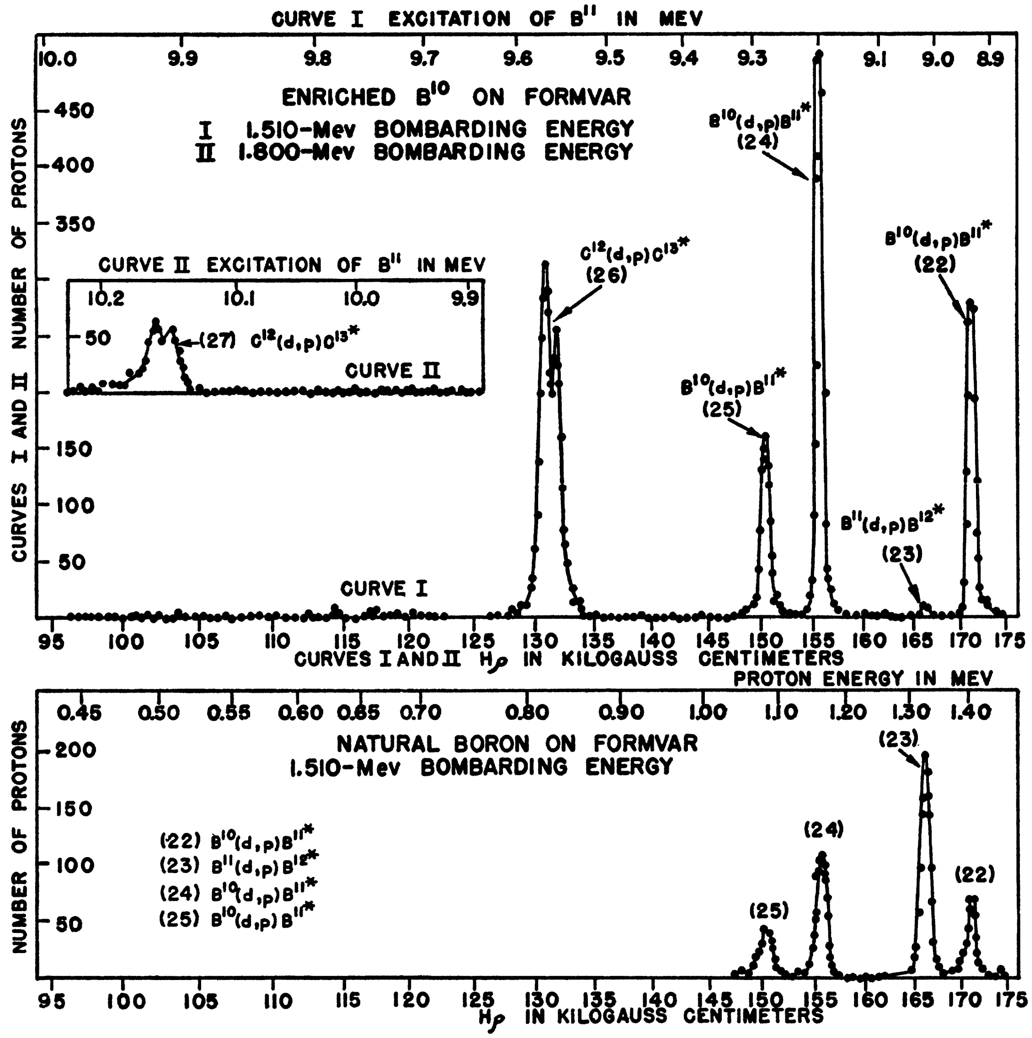

FIG. 3. Proton groups observed from targets of enriched B^{10} and natural boron on Formvar backings bombarded by 1.51- and 1.80-Mev deuterons.

The proton groups with energies 1.3 to 3.0 Mev were observed by means of nuclear-track plates covered with thin aluminum foils. The results of this survey are shown in Figs. 1 and 2. The yields of the proton groups from the two boron targets have been normalized to the same beam bombardment and area counted on the nuclear-track plates.

The enriched B^{10} and natural boron targets were prepared by similar evaporations, and it was expected that the two targets would be about equal in thickness. To verify this, the yield of the $B^{10}(d,p)B^{11}$ ground-state proton group was measured from each target and was found to be a factor of 4.5 greater from the enriched B^{10} target (96 percent B^{10}) than from the natural boron target (19 percent B^{10}). The ratio of the isotopic abundances of B^{10} in the two targets was 5.0. Hence, the thicknesses of the two boron targets were found to be equal within 10 percent. The target thickness was estimated from the half-widths of the lower energy proton groups (20), (22), and (23) and was found to be approximately 10 kev for the $B^{10}(d,p)B^{11}$ ground-state reaction.

The survey was extended to lower proton energies using an enriched B^{10} target evaporated onto a thin film of Formvar. This survey covered a range of proton energies from 1.45 to 0.45 Mev at a bombarding energy of 1.51 Mev, which corresponded to a region of excitation of B^{11} from 8.9 to 10.0 Mev. The results are shown in the upper curve of Fig. 3. From the half-widths of the observed proton peaks, the target thickness was calculated to be 9 kev for the $B^{10}(d,p)B^{11}$ ground-state group. It can be seen that the background between peaks has been reduced considerably compared with the survey of Fig. 2. This improvement was made possible by the use of thin Formvar backing, which eliminated the necessity of using aluminum foils to observe the proton groups. The survey of Fig. 3 was not extended below a proton energy of 0.45 Mev, because at this energy the proton track length became so short that it was difficult to distinguish the proton tracks from the continuous background on the nuclear-track plates.

In order to investigate possible proton groups corresponding to higher excitations of B^{11}, the bombarding energy was raised to 1.800 Mev, and a survey was made for proton groups corresponding to a region of excitation of B^{11} from 9.9 to 10.2 Mev. The results of this survey are shown in the insert of Fig. 3.

At 1.51-Mev bombarding energy, a partial survey was made of proton groups with energies of 1.05 to 1.45 Mev emitted from a natural boron target evaporated onto a thin film of Formvar. This survey was made to verify the assignment of proton groups (24) and (25) to the reaction $B^{10}(d,p)B^{11*}$, and the results are shown in the lower curve of Fig. 3. The target thickness was calculated to be about 14 kev for the $B^{10}(d,p)B^{11}$ ground-state reaction. In order to compare the results from the natural boron target with those from the enriched B^{10} target, a measurement was made of the yield of the $B^{10}(d,p)B^{11}$ ground-state proton group from both targets. The proton groups shown in the lower curve of Fig. 3 have been normalized in such a way as to make the ratio of the yields of the $B^{10}(d,p)B^{11}$ proton groups from the natural and enriched B^{10} targets equal to the ratio of isotopic abundances of B^{10} in the two targets.

In the surveys shown in Figs. 1–3, a total of twenty-seven proton groups was distinguished. Of these groups, fourteen have been attributed to various target contaminants; the remainder, to either the $B^{10}(d,p)$ or $B^{11}(d,p)$ reactions. The evidence for the assignment of all of these groups is outlined in the following paragraphs.

The fourteen proton groups that have been assigned to contaminants of C^{12}, C^{13}, N^{14}, O^{16}, and Si^{28} will be considered first. In Fig. 2, the intense group (10) corresponds to the $C^{12}(d,p)C^{13}$ ground-state reaction. The Q-value of this group from the boron targets was calculated to be 2.712 Mev, in agreement with the most recent Q-value of 2.716±0.005 Mev for the $C^{12}(d,p)C^{13}$ reaction.[19] The yield of this group was a factor of about 1.5 greater from the enriched B^{10} target, indicating the presence of slightly more carbon contamination on this target. The high intensity of this group (a factor of 10 greater than any other observed group) was possibly due to the fact that the boron targets were evaporated from a carbon crucible. However, it has been found that carbon occurs as a surface contamination on all targets and usually increases with beam bombardment.

In Fig. 3, the proton groups (26) and (27), observed from the enriched B^{10} target on Formvar, had measured Q-values of -0.366 and -0.969 ± 0.010 Mev when assigned to the reaction $C^{12}(d,p)C^{13*}$. Both of these groups are double, evidently arising from a layer of carbon on the surface of the target and from the carbon in the thin Formvar backings. The Q-value of group (26) agreed with the published value[16] of -0.370 ± 0.003 Mev for the proton group corresponding to the 3.10-Mev level in C^{13}.

In the previous investigation of the $C^{12}(d,p)C^{13*}$ reaction made in this Laboratory,[16] the proton group (27) was not observed, because that survey did not extend to so high an excitation of C^{13}. If this group is assigned to the $C^{12}(d,p)C^{13*}$ reaction, it would correspond to an excited state of C^{13} at 3.686±0.011 Mev. This result is in excellent agreement with the value of 3.677±0.005 Mev found by Malm and Buechner[20] from an investigation of the $N^{15}(d,\alpha)C^{13*}$ reaction. However, this result does not agree with the value of 3.91 Mev report by Heydenburg *et al.*[21] from their investigation of the $C^{12}(d,p)C^{13*}$ reaction. This discrepancy apparently has been accounted for by recent results of Rotblat[22] who finds two levels in C^{13} at 3.7 and 3.9 Mev from the $C^{12}(d,p)C^{13*}$ reaction.

In Fig. 1, proton group (4) has been assigned to the ground-state $C^{13}(d,p)C^{14}$ reaction. This group evidently originated from the 1.1 percent of C^{13} occurring in the natural carbon contamination of the targets, and its yield was slightly higher from the enriched B^{10} target. The Q-value of this group was calculated to be 5.940 Mev, in agreement with the value[23] of 5.948±0.014 Mev measured from enriched C^{13} targets.

In Fig. 2, the two intense proton groups (13) and (18) occur from all targets and have been attributed to O^{16}. The Q-values of these groups from the boron targets agreed within 5 kev with the measured values of 1.917±0.005 Mev[19] and 1.049±0.007 Mev[19] for the $O^{16}(d,p)$ reaction. These groups had about equal intensities from both the boron targets, in agreement with the assignment to a target contaminant.

In addition to the expected proton groups from contaminants of carbon and oxygen, the surveys shown in Figs. 1 to 3 indicated eight additional weak groups which were of about equal intensity from both the boron targets. Six of these groups, (2), (8), (9), (16), (17), and (21) were attributed to the $N^{14}(d,p)$ reaction, corresponding to the ground state and five excited states of N^{15}. The assignment of these groups was aided by the recent accurate measurements[24] of the $N^{14}(d,p)$ proton groups. The Q-values of all the six groups from the boron targets agreed within 8 kev with the results found by Malm and Buechner. The ratio of the yield of these groups from the enriched B^{10} and natural boron targets varied from 0.5 to 1.5, indicating approximately equal amounts of nitrogen contamination on both targets. In the lower curve of Fig. 1, the N^{15} doublet, peaks (8) and (9), is clearly resolved and corresponds to a level separation of 26±2 kev, in agreement with the value previously reported.[24] It has been found that $N^{14}(d,p)$ and $N^{14}(d,\alpha)$ groups are observed from all targets, and their possible presence must always be considered, particularly for investigations of reactions with low yields.

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[21] Heydenburg, Inglis, Whitehead, and Hafner, Phys. Rev. **75**, 1147 (1949).

[22] R. G. Thomas, private communication.

[23] Sperduto, Holland, Van Patter, and Buechner, Phys. Rev. **80**, 769 (1950).

[24] R. Malm and W. W. Buechner, Phys. Rev. **80**, 771 (1950).

The remaining two weak proton groups (5) and (15) have been assigned to the $Si^{28}(d,p)Si^{29*}$ reaction. The presence of these groups was unexpected, and at first it was thought that they originated from a small amount of silicon (less than 2 percent) in the boron material. However, recent investigations of other reactions have indicated silicon contamination on all targets. It is now considered probable that the silicon contamination appears during the evaporation of the targets, evidently from the silicon oil used in the vacuum system of the evaporator.

The proton groups (5) and (15), if assigned to the $Si^{28}(d,p)Si^{29*}$ reaction, have measured Q-values of 4.95 ± 0.02 and 1.31 ± 0.02 Mev. These values are in agreement with the recent values of 4.97 ± 0.01 Mev and 1.31 ± 0.01 Mev measured from SiO_2 targets.[25]

In their investigations of the $N^{14}(d,p)$ reaction at 1.420-Mev bombarding energy, Malm and Buechner[24] also found $Si^{28}(d,p)$ groups, the most intense of which were those corresponding to peaks (5) and (15). It is certain that other $Si^{28}(d,p)$ groups were present in the surveys covered in the three figures; however, they were evidently not sufficiently intense to be detected.

The proton group (15) was a factor of 1.7 more intense from the enriched B^{10} target; and, since it occurred in a region corresponding to the Q-value of 1.35 ± 0.07 Mev reported by Bateson[5] for the $B^{10}(d,p)B^{11*}$ reaction, it was considered necessary to eliminate the possibility that part of this peak might be a $B^{10}(d,p)B^{11*}$ group. In order to do this, the bombarding energy was lowered from 1.508 to 1.197 Mev, and the change in proton energy of group (15) was measured as 281.5 ± 2.5 kev. The expected shift in energy of a $Si^{28}(d,p)$ group would be 279.6 ± 2.7 kev, while a $B^{10}(d,p)$ group would shift 232.8 ± 2.3 kev. Since no proton group appeared at a position expected for a $B^{10}(d,p)$ group at 1.197-Mev bombarding energy, it was concluded that the assignment of group (15) to the $Si^{28}(d,p)Si^{29*}$ reaction was correct.

It might appear that the presence of as many as fourteen groups due to contaminants could jeopardize the investigation of the $B^{10}(d,p)$ groups. However, the high resolution of the magnetic spectrograph enabled the proton groups to be well separated and permitted accurate comparison of the Q-values of these groups to known Q-values. In addition, the ratio of the yield of these groups from the enriched B^{10} and natural boron targets was never greater than a factor of 1.7, while all the groups assigned to the $B^{10}(d,p)$ reaction were 3 to 6 times more intense from the natural boron target.

The remaining thirteen proton groups found in the surveys were attributed either to the $B^{10}(d,p)$ or the $B^{11}(d,p)$ reactions. Of these, groups (19) and (23) were much more intense from the natural boron target and were assigned to the isotope B^{11}, as has been previously reported.[26] The remaining eleven proton groups (1), (3), (6), (7), (11), (12), (14), (20), (22), (24), and (25) were approximately a factor of 5 more intense from the enriched B^{10} target (96 percent B^{10}) than from the natural boron target (19 percent B^{10}) and were attributed to the B^{10} isotope.

In Fig. 1, the intense proton group (1) had a measured Q-value of 9.235 ± 0.011 Mev, in agreement with the value of 9.24 Mev predicted from masses[27] for the $B^{10}(d,p)B^{11}$ ground-state reaction and with previous measured values[2,4,5] of 9.14 ± 0.10; 9.22 ± 0.2; and 9.18 ± 0.05 Mev. An additional confirmation of this assignment was obtained from the measurement of the shift in energy of this proton group when the bombarding energy was changed from 1.380 to 1.506 Mev. The observed energy change was 91 ± 2 kev, compared to the value of 95 ± 5 kev expected for a $B^{10}(d,p)$ proton group.

The positions of groups (3) and (6) agreed with $B^{10}(d,p)B^{11*}$ proton groups already reported by previous workers. Both of these groups were a factor of 4 to 5 more intense from the enriched B^{10} target. These groups corresponded to excited states at 2.138 ± 0.014 and 4.459 ± 0.014 Mev, in agreement with the values of 2.15 ± 0.06 and 4.48 ± 0.06 Mev reported by Bateson.[5]

The next proton group (7) shown in Fig. 1 was 5 times more intense from the enriched B^{10} target and had a measured Q-value of 4.201 ± 0.008 Mev, corresponding to an excited state of B^{11} at 5.034 ± 0.014 Mev. This measurement confirms the result of Bateson,[5] who found a previously unreported proton group corresponding to a level in B^{11} at 5.03 ± 0.06 Mev.

In Fig. 2, two proton peaks (11) and (12) were assigned to the $B^{10}(d,p)B^{11*}$ reaction and correspond to a doublet in B^{11} with a level spacing of 50.0 ± 0.6 kev. Both of these groups were 3 to 4 times more intense from the enriched B^{10} target; however, this ratio was subject to uncertainty in the case of peak (12), because of its weak intensity compared to the background in this region. The more intense group (11) corresponds to an excited state in B^{11} at 6.758 ± 0.013 Mev, which has already been reported[4,5] at 6.83 ± 0.2 and 6.92 ± 0.08 Mev. The proton group (12) was a factor of 10 less intense than group (11) at 1.51-Mev bombarding energy and has not been previously reported. This doublet would not have been resolved by the range measurements used by earlier investigators. Because of theoretical interest in such doublets,[28] it was important to be certain of the identification of proton group (12). Further investigations were made of this group which resulted in the unambiguous assignment of group (12) to the reaction $B^{10}(d,p)B^{11*}$. These results will be described in detail in a succeeding section.

The next proton group, (14), assigned to the $B^{10}(d,p)B^{11*}$ reaction, was a factor of 5 more intense from the enriched B^{10} target. This group has a Q-value

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[26] Buechner, Van Patter, Strait, and Sperduto, Phys. Rev. **79**, 262 (1950).

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[28] D.R. Inglis, Phys. Rev. **78**, 616 (1950).

TABLE I. Energy levels in B^{11}.

Peak number	Reaction	Ratio of yields[a]	Approx[b] $d\sigma$	*Q*-value (Mev)	Level in B^{11} (Mev)
(1)	$B^{10}(d,p)B^{11}$	4.9	2.	9.235±0.011	0
(3)	$B^{10}(d,p)B^{11*}$	3.7	0.4	7.097±0.009	2.138±0.014
(6)	$B^{10}(d,p)B^{11*}$	5.2	1.2	4.776±0.008	4.459±0.014
(7)	$B^{10}(d,p)B^{11*}$	4.9	1.0	4.201±0.008	5.034±0.014
(11)	$B^{10}(d,p)B^{11*}$	3.8	2.	2.477±0.007	6.758±0.013
(12)	$B^{10}(d,p)B^{11*}$	3.	0.2	2.427±0.007	6.808±0.013
(14)	$B^{10}(d,p)B^{11*}$	5.0	1.2	1.937±0.006	7.298±0.012
(20)	$B^{10}(d,p)B^{11*}$	6.	0.3	0.667±0.005	8.568±0.012
(22)	$B^{10}(d,p)B^{11*}$	3.6	5.	0.309±0.005	8.926±0.012
(24)	$B^{10}(d,p)B^{11*}$	4.4	8.	0.045±0.005	9.190±0.012
(25)	$B^{10}(d,p)B^{11*}$	4.1	4.	−0.041±0.005	9.276±0.012
	$B^{10}(d,d)B^{10}$	—	35.	0	
	$B^{10}(p,p)B^{10}$		57.	0	

[a] Ratio of yields from enriched B^{10} and natural boron targets.
[b] Approximate differential cross section at 90° in millibarns per atom per steradian.

of 1.937±0.006 Mev, corresponding to an excited state at 7.298±0.012 Mev. Bateson[5] has reported a $B^{10}(d,p)$ group with a *Q*-value of 1.36±0.07, which is considerably lower than our value. However, Bateson was not able to resolve his $B^{10}(d,p)$ proton group from the $O^{16}(d,p)O^{17*}$ proton group with a *Q*-value of 1.049. In view of the otherwise excellent correspondence between the present results and those of Bateson, it appears possible that group (14) was not observed in his experiments. At the 3.8-Mev bombarding energy used in his work, the energy of the proton group from $O^{16}(d,p)O^{17*}$ ($Q=1.049$ Mev) would be such as to give a *Q*-value of 1.42 Mev if mistakenly assigned to $B^{10}(d,p)B^{11}$. It appears possible that the presence of such a $O^{16}(d,p)O^{17*}$ group in Bateson's range measurements could account for the above discrepancy in *Q*-values.

In Fig. 2, the weak proton group (20) was assigned to the reaction $B^{10}(d,p)B^{11*}$. The yield of this group was about 6 times greater from the enriched B^{10} target; however, this ratio was not very accurate because of its very low intensity from the natural boron target. The *Q*-value of this group was measured as 0.667±0.005 Mev, in good agreement with a $B^{10}(d,p)$ *Q*-value of 0.70±0.10 Mev first reported by Bateson.[5] Additional evidence for the assignment of this group was obtained from a measurement of the change of proton energy when the bombarding energy was changed from 1.507 to 1.800 Mev. The observed shift in proton energy was 218.1±1.2 kev. The expected shift is 219.1±2.1 kev for a $B^{10}(d,p)$ group, whereas the expected shifts for $Be^9(d,p)$ and $B^{11}(d,p)$ groups are 212±2 and 225±2 kev, respectively. This result shows that this proton group can be assigned only to a target of mass 10.

In Figs. 2 and 3, there is indicated an intense proton group (22) assigned to $B^{10}(d,p)B^{11*}$. This group was found to be 3 to 6 times more intense from enriched B^{10} targets as compared with natural boron targets. The *Q*-value of this group was calculated to be 0.309±0.005 Mev, corresponding to an excited state of B^{11} at 8.926 ±0.012 Mev. Prior to these experiments, this $B^{10}(d,p)$ group had not been reported. However, since the first report[29] of these results, Bateson[30] has found a $B^{10}(d,p)$ group with a *Q*-value of 0.32±0.10 Mev, in excellent agreement with the present work.

The remaining two intense proton groups (24) and (25), shown in Fig. 3, were a factor of 4 to 5 more intense from the enriched B^{10} target on Formvar. In addition, these proton groups were single, as compared with the two $C^{12}(d,p)$ groups (26) and (27) which were double, indicating that proton groups (24) and (25) originated from the target material. In view of this evidence, these groups were assigned to the $B^{10}(d,p)$ reaction, with *Q*-values of 0.045±0.005 and −0.041 ±0.005 Mev, corresponding to excited states in B^{11} at 9.190±0.012 and 9.276±0.012 Mev. These two $B^{10}(d,p)$ groups have not been reported previously and would not have been observed by Bateson, as they would have been obscured by elastically scattered deuterons.

The results of the surveys indicated the presence of eleven $B^{10}(d,p)$ groups, corresponding to the ground state of B^{11}, and ten excited states, five of which have not been previously reported. These results are summarized in Table I. The position of the levels found agreed with earlier results, while the proton groups corresponding to the new B^{11} levels would not have been observed by earlier workers (except for the group with a *Q*-value of 0.309 Mev which has been confirmed by Bateson). In the region of excitation of B^{11} from 0 to 6.31 Mev, no additional groups were found with an intensity greater than 0.1 the intensity of the ground-state group. Only 3 percent of the total region was obscured for groups of this intensity by the intense $C^{12}(d,p)$ and $O^{16}(d,p)$ contaminant groups, since none of the groups had a half-width greater than 30 kev. It is considered improbable that any $B^{10}(d,p)$ groups that had an intensity greater than 0.05 the intensity of the ground-state group were missed in the surveys.

As was previously mentioned, the doublet of proton groups (11) and (12) was investigated further in order to make certain of the assignment of the weak group (12) to the $B^{10}(d,p)B^{11*}$ reaction. The doublet was observed at bombarding energies of 1.510, 1.649, and 1.811 Mev, and the results are shown in Fig. 4. From these curves, it was first possible to check the assignment of the intense member of the doublet (11) from the observed change in proton energy of 225.1±2 kev for a change in bombarding energy of 301±3 kev. The expected change in proton energy for a $B^{10}(d,p)$ group would be 225.5±2.1 kev, indicating that the assignment of group (11) to the $B^{10}(d,p)B^{11*}$ reaction was correct.

Once the assignment of group (11) to the $B^{10}(d,p)B^{11*}$ reaction was established, measurement of the spacing between groups (11) and (12) at the three bombarding energies provided a sensitive method of establishing the

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[29] W. W. Buechner and D. M. Van Patter, Phys. Rev. **79**, 240 (1950).

[30] W. O. Bateson, private communication. Also, Phys. Rev. **80** 982 (1950).

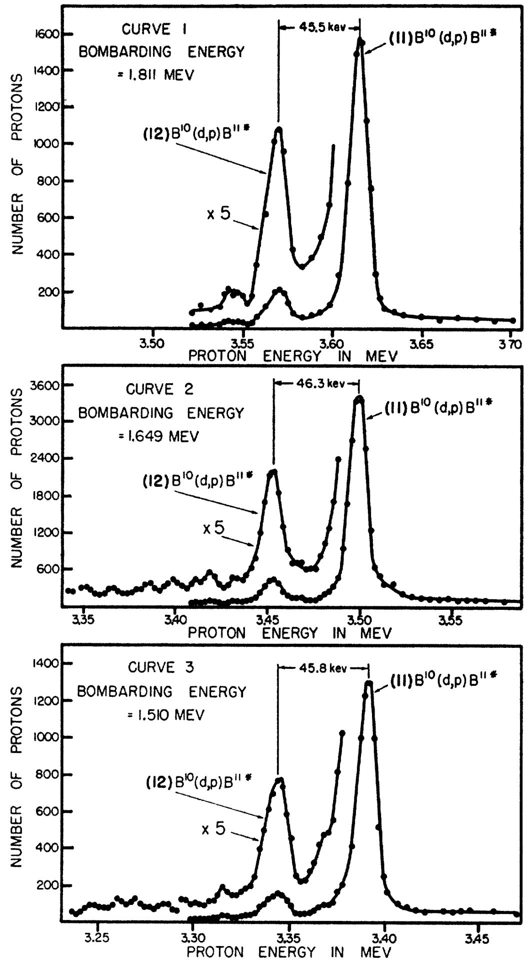

FIG. 4. $B^{10}(d,p)B^{11*}$ doublet observed at bombarding energies of 1.51, 1.65, and 1.81 Mev.

target mass responsible for the less intense group (12). The difference in proton energy of groups (11) and (12) was measured as 45.8±2.0; 46.3±2.0; and 45.5±2.0 kev at bombarding energies of 1.509, 1.649, and 1.811 Mev. These results indicated that the spacing remained constant within 0.5±2.0 kev. If the target mass responsible for group (12) had been one unit different than that responsible for group (11), then the spacing between groups would have changed by 6 to 7 kev when the bombarding energy was changed from 1.509 to 1.811 Mev. It is concluded that both groups (11) and (12) could be assigned unambiguously to the $B^{10}(d,p)B^{11*}$ reaction. In the curves of Fig. 4, there is some evidence for proton groups with intensities less than 0.01 the intensity of group (11); however, none of these groups remained at a constant spacing from the doublet members at the different energies. Hence, there was no evidence for additional structure to the doublet with an intensity greater than 0.09 the intensity of the weaker member (12). At the three bombarding energies, group (11) was a factor of 10, 10, and 8 more intense than group (12). The separation of these two proton groups corresponds to a level separation in B^{11} of 50.0±2.0 kev.

The three $B^{10}(d,p)$ proton groups (22), (24), and (25) correspond to excited states in B^{11} at 8.93, 9.19, and 9.28 Mev, all of which are above the threshold at 8.64 Mev for alpha-emission to Li^7. The half-widths of these proton groups in the surveys shown in Figs. 2 and 3 were about 15 kev, which were attributed chiefly to the effects of target thickness. This assumption was shown to be correct when proton groups (22) and (23) were measured from a much thinner target of natural boron on Formvar, as shown in the upper curve of Fig. 5. In addition, the deuteron groups scattered elastically from the B^{10}, B^{11}, and C^{12} nuclei in the target backing were observed, as shown in the lower curve of Fig. 5. From this curve, the target thickness was estimated to be 2.8 kev for the $B^{10}(d,d)B^{10}$ process, and 2.0 kev for the $B^{10}(d,p)B^{11*}$ proton group (22). The observed half-width of the $B^{10}(d,p)$ group (22) was 5.9 kev. After subtraction of the spreads due to target thickness and instrumental factors, an upper limit of 3.7 kev was found for the natural width of proton group (22). This result indicates an upper limit of 4 kev for the 8.93-Mev excited state of B^{11}.

From the surveys shown in Figs. 1, 2, and 3, it was possible to estimate the relative intensities of the

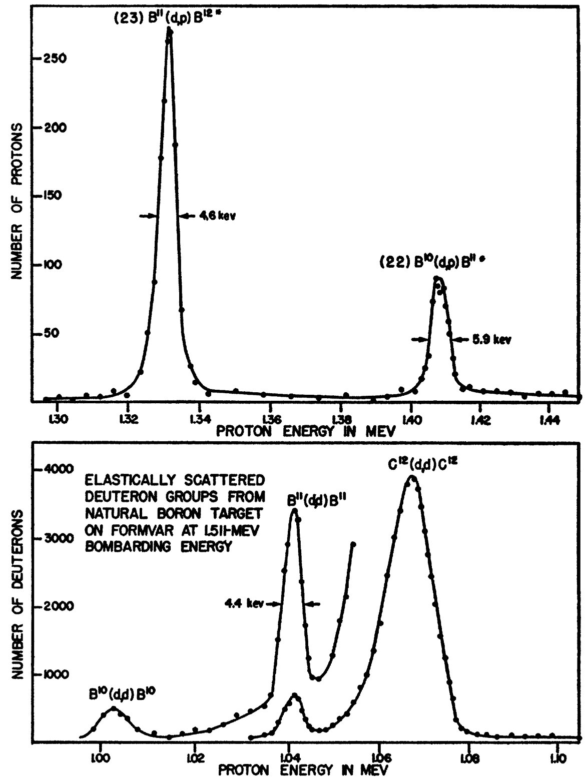

FIG. 5. Proton and deuteron groups observed from a thin target of natural boron on a thin Formvar backing bombarded by 1.51-Mev deuterons.

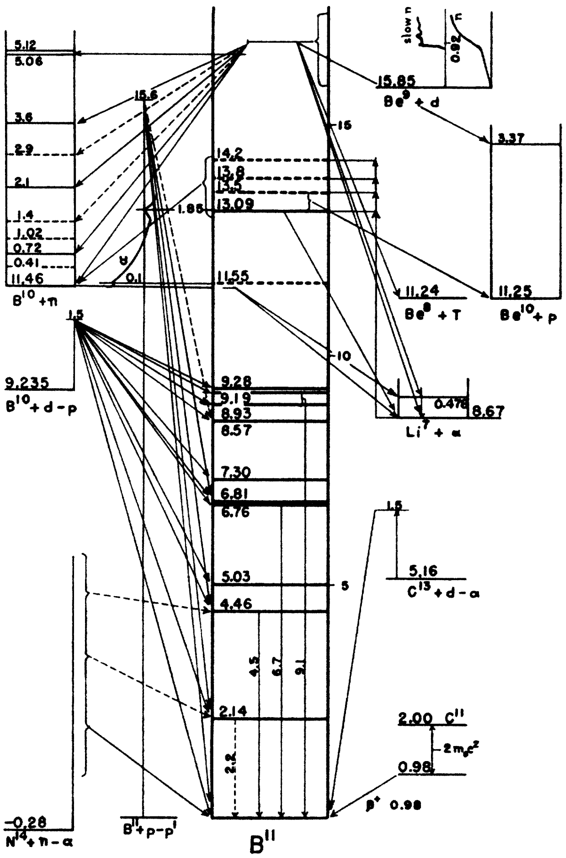

FIG. 6. Energy-level diagram for B^{11}.

various $B^{10}(d,p)$ proton groups at 1.51-Mev bombarding energy. In addition, the $B^{10}(d,d)B^{10}$ and $B^{10}(p,p)B^{10}$ groups elastically scattered from the enriched B^{10} target on Formvar were observed. At 1.51-Mev bombarding energy, the following relative intensities were observed:

$$B^{10}(d,p)B^{11}:B^{10}(d,d)B^{10}:B^{10}(p,p)B^{10}=1.0:17:27.$$

For various reasons, we consider these relative intensities to be accurate to only approximately 50 percent.

If Rutherford scattering is assumed for 1.510-Mev protons scattered from B^{10} at a laboratory angle of 90°, it is possible to estimate the differential cross section for the $B^{10}(p,p)B^{10}$ process as 57 millibarns per atom per steradian. Using this assumption, estimates were made of the differential cross sections for the $B^{10}(d,p)$ proton groups, as indicated in Table I. The accuracy of the differential cross sections calculated by this method cannot be stated since the validity of assuming Rutherford scattering is not known.

IV. CONCLUSIONS

The results of this investigation indicate that eleven $B^{10}(d,p)$ proton groups have been observed at 1.51-Mev bombarding energy, corresponding to the ground state and ten excited states of B^{11}. Five of these excited states at 6.81, 7.30, 8.93, 9.19, and 9.28 Mev have not been reported previously. Two proton groups were found with an intensity ratio of about 10:1, corresponding to a doublet in B^{11} at 6.8-Mev excitation with a level separation of 50.0±2.0 kev. A level diagram of B^{11}, incorporating these results, is shown in Fig. 6.

The Q-values found for the $B^{10}(d,p)$ groups are summarized in Table I. The results of this investigation are in good agreement with previous results, particularly with recent work of Bateson.[5] In the comparison of our results with those of Bateson, the only Q-value in serious disagreement is that of 1.937±0.006 Mev, compared with the value of 1.36±0.07 Mev reported by Bateson. This discrepancy can be accounted for by the presence of oxygen contamination in the range measurements of Bateson.

The positions of the energy levels of B^{11} established by this investigation can be used to assign some of the gamma-radiations observed from boron bombarded by deuterons.[12–14] The gamma-rays of 4.52, 6.74, and 9.11 Mev, assigned by Terrell[14] to $(B^{10}+d)$, appear to be in good agreement with the excited states of B^{11} at 4.46, 6.76, and either 8.93 or 9.19 Mev. It appears probable that these gamma-rays can be assigned to the $B^{10}(d,p)B^{11*}$ reaction, although the possibility that some may arise from the $B^{10}(d,n)C^{11*}$ reaction cannot be ruled out. However, the measured energies of these gamma-rays appear to be in better agreement with the levels of B^{11} than with those of C^{11}. In addition, Terrell found indications of gamma-rays of slightly higher energy than the 4.41- and 6.74-Mev gamma-rays, which could correspond to the 5.03- and 6.81-Mev excited states of B^{11}. The gamma-rays of 6.9- and 9.1-Mev excitation, observed by Gaerttner, Fowler, and Lauritsen,[12] from natural boron bombarded by deuterons were previously ascribed to the $B^{11}(d,n)C^{12*}$ reaction. In view of the above results, it appears that these gamma-rays should be assigned to the $B^{10}(d,p)B^{11*}$ or $B^{10}(d,n)C^{11*}$ reactions. This assignment is in agreement with the observation of Hudspeth and Swann[31] that most of the radiations greater than 2 Mev from $(B+d)$ are from B^{10} rather than from B^{11}. The gamma-ray of 4.4 Mev, observed by Gaerttner *et al.*,[12] from $(B+d)$ can be assigned to both $B^{10}(d,p)$ and $B^{11}(d,n)$ inasmuch as Terrell finds a gamma-ray of 4.5±0.1 Mev from $(B^{11}+d)$ in addition to the gamma-ray of 4.46 Mev from $(B^{10}+d)$. The gamma-ray of 2.2 Mev, observed by Gaerttner *et al.*, can be assigned to both the $B^{10}(d,p)$ and $B^{10}(d,n)$ reactions.

The positions of the levels of B^{11} established in this investigation are shown in the level diagram of Fig. 6. There was no indication of additional $B^{10}(d,p)$ proton groups with an intensity greater than 0.1 the intensity of the ground-state $B^{10}(d,p)B^{11}$ group in a region of excitation of B^{11} from 0 to 10.22 Mev. The intense $C^{12}(d,p)$ and $O^{16}(d,p)$ groups obscured 3 percent of the total region for groups of intensity less than 0.1 the

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[31] E. L. Hudspeth and C. P. Swann, Phys. Rev. 76, 1150 (1949).

intensity of the ground-state $B^{10}(d,p)$ group. The levels of B^{11} found by this investigation appear to be in four groups, with a wide separation of about 2.3 Mev between groups.

For increasing excitation of B^{11}, the number of excited states in each group increases in order from one to four with an over-all spread of about 0.5 to 0.7 Mev for the components of the three higher groups. The fact that no additional levels of B^{11} were found for excitations of 9.3 to 10.2 Mev is in agreement with this pattern.

The next higher level occurs at 11.5-Mev excitation, corresponding to a possible resonance[32] in the $B^{10}(n,\alpha)Li^7$ reaction at a neutron energy of 0.1 Mev. This excited state could correspond to a component of a fifth group of excited states. It would be of interest to examine the yield of the $Li^7(\alpha,\gamma)B^{11}$ reaction starting at low alpha-energies,[33] since resonances would be expected corresponding to the levels of B^{11} at 8.93, 9.19, and 9.28 Mev. An extension of this experiment to higher alpha-energies might establish the position of the next higher excited state of B^{11}.

The background between the $B^{10}(d,p)$ proton groups, corresponding to excited states of B^{11} at 8.93, 9.19, and 9.28 Mev, was less than 0.03 the intensity of these proton groups and could be accounted for by a small amount of alpha-contamination on the nuclear-track plates. In addition, an upper limit of 4 kev was found for the half-width of the 8.93-Mev level of B^{11}, although no proton groups were found corresponding to a region of excitation of 950 kev above the 9.28-Mev level. Therefore, there was no indication of any overlapping of levels or of uniform spacing of levels up to an excitation of B^{11} of 10.2 Mev.

It is of interest to compare the excited states of mirror nuclei of odd mass number. The mirror nuclei, Li^7 and Be^7, each have one low-lying state at 478 and 431 kev, respectively, the positions of which appear to correspond. The mirror nuclei, C^{13} and N^{13}, have excited states at 3.10, 3.68, and 2.34 and 3.52 Mev, respectively. Although the positions of these states do not agree experimentally,[34] their comparison is complicated by the fact that the two excited states of N^{13} are virtual to proton emission, while those of C^{13} are not. Thomas[35] has taken this fact into account and, by a theoretical analysis, has shown that the levels of C^{13} and N^{13} do, in fact, correspond.

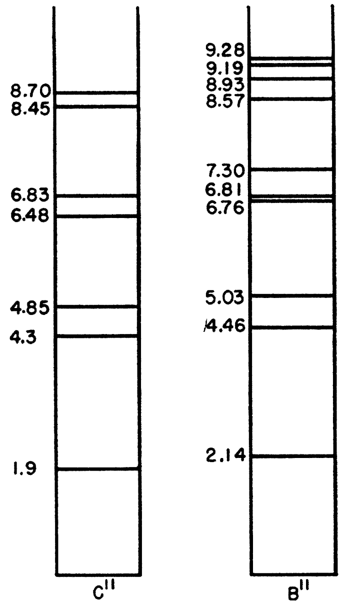

FIG. 7. Comparison of the excited states of C^{11} and B^{11}.

A comparison of the mirror nuclei of B^{11} and C^{11} is not thus complicated. All excited states of B^{11} below 8.6-Mev excitation are bound, while those up to 11.2 Mev are not virtual to proton or neutron emission. Similarly, excited states of C^{11} below 7.5 Mev are bound, while those below 8.7 Mev are not virtual to proton emission. It is of particular interest to compare the states excited by the mirror reactions of $B^{10}(d,p)B^{11}$ and $B^{10}(d,n)C^{11}$.

An extensive survey of the states of C^{11} from the $B^{10}(d,n)C^{11}$ reaction has recently been reported by Johnson,[36] who finds levels at 1.90, 4.30, 4.85, 6.48, 6.83, 8.45, and 8.70 Mev. A comparison of these C^{11} levels with the levels of B^{11} reported here is shown in Fig. 7, where the striking similarity of the two level schemes can be seen. A doublet in C^{11} of 50 kev, corresponding to that of B^{11} at 6.8 Mev, could not have been resolved by Johnson in his measurements of the $B^{10}(d,n)C^{11}$ neutron groups. The levels of C^{11} are consistently lower by about 0.2 Mev (except in one case where the difference is 470 kev). This could be accounted for by the additional coulomb energy in C^{11}. A discussion of the level schemes of mirror nuclei has been recently presented by Richards.[37] It is concluded that the level schemes of B^{11} and C^{11}, as known at present, correspond up to 9-Mev excitation and that the result provides the best example to date of the agreement of the excited states of two mirror nuclei.

We are glad to acknowledge the generous cooperation of our colleagues at the High Voltage Laboratory. We are particularly indebted to Mr. W. A. Tripp and Mrs. C. A. Bryant for their careful work in counting on the photographic plates.

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[32] Goldsmith, Ibsen, and Feld, Revs. Modern Phys. **19**, 259 (1947).

[33] Since this manuscript was prepared for publication, Toppel, Roys, and Bennett, Phys. Rev. **81**, 316 (1951) have reported the observation of three resonances in the thick-target yield curve of the gamma-radiation from Li^7 bombarded by alpha-particles. The positions of these resonances are in excellent agreement with the three levels in B^{11} as determined in the present experiment.

[34] D. M. Van Patter, Phys. Rev. **76**, 1264 (1949).

[35] R. G. Thomas, Phys. Rev. **80**, 136 (1950).

[36] V. R. Johnson, Phys. Rev. **81**, 316(A) (1951).

[37] H. T. Richards, Phys. Rev. **81**, 308 (1951).