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Deuteron Bombardment of Boron Isotopes*†

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The excitation of curve for $B^{11}(d,p)$ has been obtained by observing the intensity of the beta-rays from B^{12} as a function of bombarding voltage from about 0.3 to 1.85 Mev. No resonance structure was observed in this region of bombardment. The yield at 1.47 Mev is approximately 10^7 beta-rays/microcoulomb of deuterons.

The short-range protons which are formed in the above reaction were also observed in photographic plates, and range measurements showed that the Q-value of the reaction is 0.15 Mev. It is believed that this value does not represent the formation of B^{12} in its ground state, however, but in an excited state at about 1.1 Mev. A group believed to be protons of higher energy (corresponding to $Q=1.25$ Mev) but of much lower intensity was subsequently observed.

It was shown, by bombardment of enriched B^{10} and of normal boron, that a gamma-ray of approximately 1.1 Mev energy is associated with the disintegration of B^{11} by deuterons. It is therefore almost certain that this gamma-ray arises from the decay of B^{12} to its ground state. Intensity measurements also indicate that this is the case.

I. INTRODUCTION

THE bombardment of boron by deuterons leads to the following reactions:

$$B^{10}+H^2\rightarrow B^{11}+H^1+Q_1, \tag{1}$$

$$B^{10}+H^2\rightarrow C^{11}+n^1+Q_2, \tag{2}$$

$$B^{11}+H^2\rightarrow B^{12}+H^1+Q_3, \tag{3}$$

$$B^{11}+H^2\rightarrow C^{12}+n^1+Q_4, \tag{4}$$

$$\text{or}\rightarrow 3He^4+n^1+Q_5. \tag{5}$$

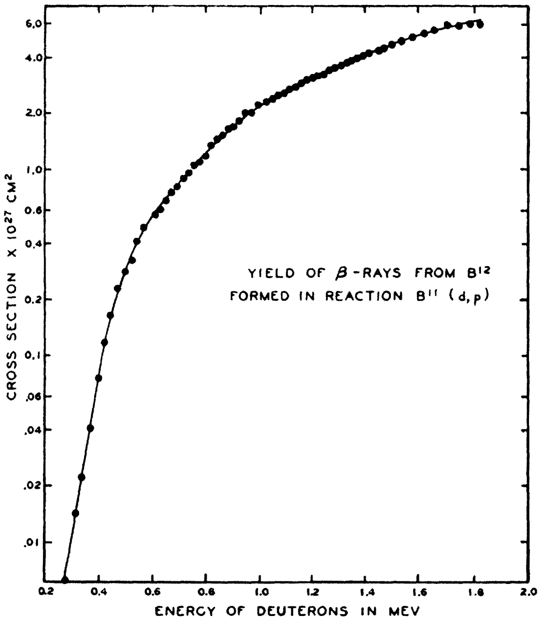

FIG. 1. Yield of beta-rays from boron target under deuteron bombardment. Coincidence counters recorded all beta-rays of energy greater than approximately 2.5 Mev.

The $B(d,\alpha)$ reactions also occur and have been previously studied. Several proton groups have been observed[1,2] from reaction (1). The neutrons emitted in reactions (2), (4), and (5) have been observed[3,4] by both cloud chamber and photographic plates. It has not been possible to correlate all of the observed neutron groups with the disintegration of a specific isotope, although some assignments can be made from calculated limits of the Q-values. The protons from reaction (3) have not heretofore been observed; the reaction has been inferred through observation of beta-rays emitted in the disintegration of B^{12}. The precise mode of decay of B^{12} has not been established in detail, although the end-point of the beta-spectrum has been the subject of numerous investigations.[5–7] Finally, the energies of the gamma-rays which are produced by deuteron bombardment of normal boron have been measured,[8,9] and the origin of all but the gamma-ray of lowest energy (~1.5 Mev) can be deduced.

The reactions which lead to the production of charged particles have been observed[10] by bombarding separated isotopes of boron and the assignment of reactions, except for $B^{11}(d,p)$, has been definitely confirmed.

The purpose of the present investigation was to study the excitation function for reaction (3), and to establish the value of Q_3 by direct observation of the protons; to determine whether the reported ~1.5 Mev gamma-ray is associated with this reaction; and to obtain more information about the decay scheme of B^{12}.

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* Assisted by the Joint Program of the ONR and AEC.

† A preliminary account of some of this work has already appeared: E. L. Hudspeth and C. P. Swann, Phys. Rev. **74**, 1722 (1948).

[1] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **154**, 246 (1936).

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

[3] T. W. Bonner and W. M. Brubaker, Phys. Rev. **50**, 308 (1936).

[4] C. F. Powell, Proc. Roy. Soc. **181**, 344 (1942).

[5] D. S. Bayley and H. R. Crane, Phys. Rev. **52**, 604 (1937).

[6] Frank L. Hereford, Phys. Rev. **74**, 574 (1948).

[7] Hornyak, Dougherty, and Lauritsen, Phys. Rev. **74**, 1727 (1948).

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

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

[10] C. L. Smith and E. B. M. Murrell, Proc. Camb. Phil. Soc. **35**, 298 (1939).

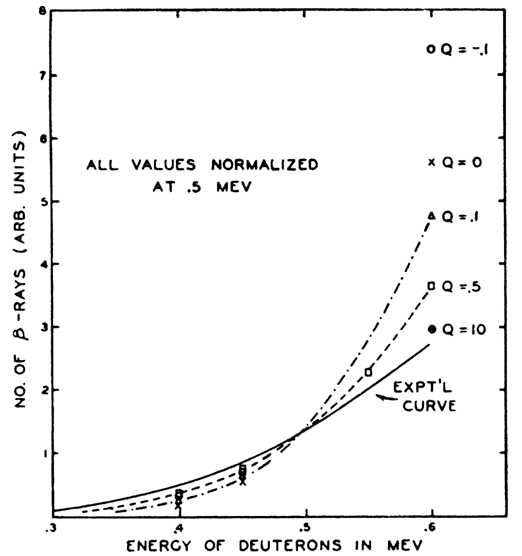

FIG. 2. Family of curves showing attempt to fit the theoretical formula to the observed excitation curve for $B^{11}(d,p)$ up to 0.6-Mev bombarding energy.

II. THE EXCITATION CURVE FOR $B^{11}(d,p)$

The bombardment of boron with deuterons leads to the formation of a radioactive isotope which decays with the emission of beta-rays of maximum energy 13.43 Mev[7] and with a half-life of 0.02 seconds. The endpoint of the beta-ray spectrum has been examined carefully by several investigators, one of whom[6] worked with the apparatus in this laboratory. The excitation function has already been observed[5] in the region up to about 0.6 Mev, and it was our purpose to carry this to higher voltage.

Thin targets of elemental boron and of boron trioxide were used in most of this work; these were made by evaporation of the compound in a vacuum. Thickness of the targets was determined by weighing them on a microbalance; a typical thickness was about 25 kev. The beta-rays were detected by coincidence counters. Before producing coincidences, the beta-rays penetrated the target backing, the first counter, and the wall and cylinder of the second counter. This added to a total of 1.3 g/cm^2, which is sufficient to stop all beta-rays whose energy is below about 2.5 Mev.

The excitation curve which we obtained is shown as Fig. 1. The cross section which is plotted is the cross section for the production of beta-rays of energy greater than 2.5 Mev; beta-rays of lesser energy were absorbed before reaching the second counter. Rough checks with a single counter showed that only a relatively small fraction of the beta-rays had energy less than this amount, as one would expect from the shape of the beta-ray spectrum. The excitation curve displays no resonance characteristics, but only a rather rapid rise in yield with increase in bombarding voltage. This is in contrast to $Li^7(d,p)$ which leads to the radioactive nucleus Li^8; three resonances in this reaction have been observed[11] up to a bombarding voltage of 1.4 Mev. (These resonances were also observed in the course of the present work; this was done simply as a check on our operation.) The excitation energy of the intermediate C^{13} nucleus as formed by $B^{11}(d,-)$ is, over the range of bombardment which we employed, between 18.7 and about 20.5 Mev. The excitation level of Be^9 as formed by $Li^7(d,-)$ is, for zero bombarding energy, at 16.66 Mev, and the three resonance levels found just above this value are only about 0.3 Mev apart. Since C^{13} is a heavier nucleus and since it is formed in a higher state of excitation, it seems likely that any resonance structure would not be resolved in our experiments. Indeed, the states are apparently so close together that we observe only a smooth increase in yield of B^{12} with bombarding voltage, although we believe that maxima separated by as little as about 15 kev could have been located. The work of Fünfer[12] has indicated 22 excitation levels in the region between 12.7 and 16.7 Mev, the higher ones being only about 120 kev apart, so that our failure to observe any resonance structure is not surprising. The excitation curve is flattening rather rapidly in the vicinity of our maximum bombarding voltage.

It was thought that we could, by following the procedure of Rumbaugh, Roberts, and Hafstad[13] for

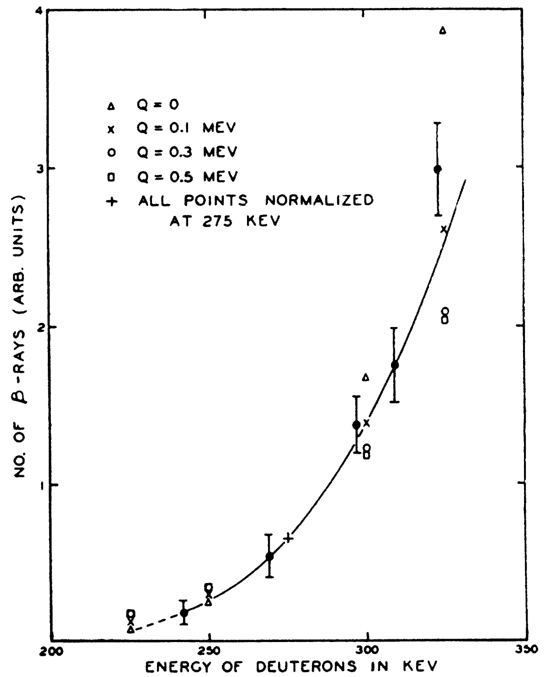

FIG. 3. The $B^{11}(d,p)$ excitation curve in the very low energy region. Over this restricted interval, the formula gives the best fit for $Q=0.1$ Mev, although no "good fit" is obtained.

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[11] Bennett, Bonner, Richards, and Watt, Phys. Rev. **71**, 11 (1947).

[12] E. Fünfer, Ann. d. Physik **35**, 147 (1939).

[13] Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938).

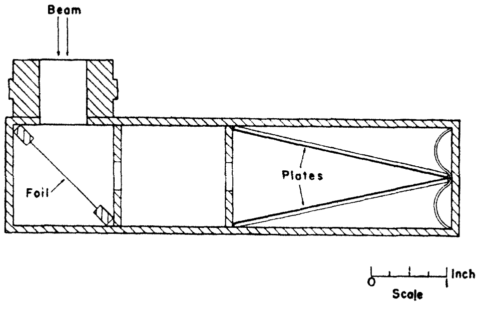

FIG. 4. Diagram of the camera employed for the detection of scattered particles and particles of transmutation. This was used for detection of the short-range protons from the reaction $B^{11}(d,p)$.

the case of Li^8 formation, deduce a Q-value for the $B^{11}(d,p)$ reaction by the shape of the excitation curve. In our case, we have

$$E_p=(13/12)Q+(11/12)E_d,$$

where E_p is the energy of the emitted proton and E_d is the energy of the bombarding deuteron; energies are computed in the center of mass system. We assume also[13] that the cross section may be expressed[13,14] as

$$\sigma=Kv_d^{-1}\exp(-2\pi zZ\alpha cv_d^{-1})\exp(-2\pi zZ\alpha cv_p^{-1}), \quad (6)$$

where K is a constant, v_d and v_p are relative velocities for the deuteron and proton, z and Z are the nuclear charges involved, c is the velocity of light and α the fine-structure constant. Over a region of many close levels this formula might apply with enough precision to yield the value of Q (or, explicitly, of v_p). An attempt was therefore made, as shown in Fig. 2, to fit our data to Eq. (6) by assuming various values of Q; points were arbitrarily normalized at 0.5 Mev. This procedure led to no "good fit," and we accordingly sought to fit the data over a more limited region. The results are shown in Fig. 3, with points normalized at 275 kev. While the fit is in no case very accurate, it appeared that the value of Q is about 0.1 Mev. Using this as an estimate, we calculated what range the protons would have at various bombarding voltages; in this way it was possible to devise an experiment (Section III) and to select a satisfactory bombarding voltage for observation of the protons.

The $B^{11}(d,p)$ reaction has often been used as a beta-ray source, and the yield at low bombarding voltage has been reported.[5] We found that the yield of beta-rays from a thick target of elemental boron, bombarded at 1.47 Mev, is approximately 10^7 particles/microcoulomb of deuterons.

III. OBSERVATION OF PROTONS FROM $B^{11}(d,p)$

In view of the anticipated short range of the protons emitted in $B^{11}(d,p)$, it was thought advisable to avoid an effort to bring them out of the vacuum system and into a counter through foils. It appeared that detection would be most straightforward by the use of photographic plates, and a small and simple "camera" was built. This is illustrated in Fig. 4.

The deuteron beam struck a thin target of elemental boron which was evaporated onto a very thin (150 $\mu g/cm^2$) aluminum leaf. The leaf was supported on a brass frame and was placed at 45° to the bombarding beam. Two Eastman NTB photographic plates, with emulsions 50μ thick, were placed at 90° to the bombarding beam and were set so that particles struck them at a grazing angle of about 10°.

Only a very brief exposure (a few microcoulombs of bombardment) was sufficient to get a satisfactory number of tracks on the plates. With a bombarding voltage of 1.67 Mev, two groups of particles, with mean range of 14.3 and 18.9 microns, were observed; the first group corresponds to the scattered deuterons and the

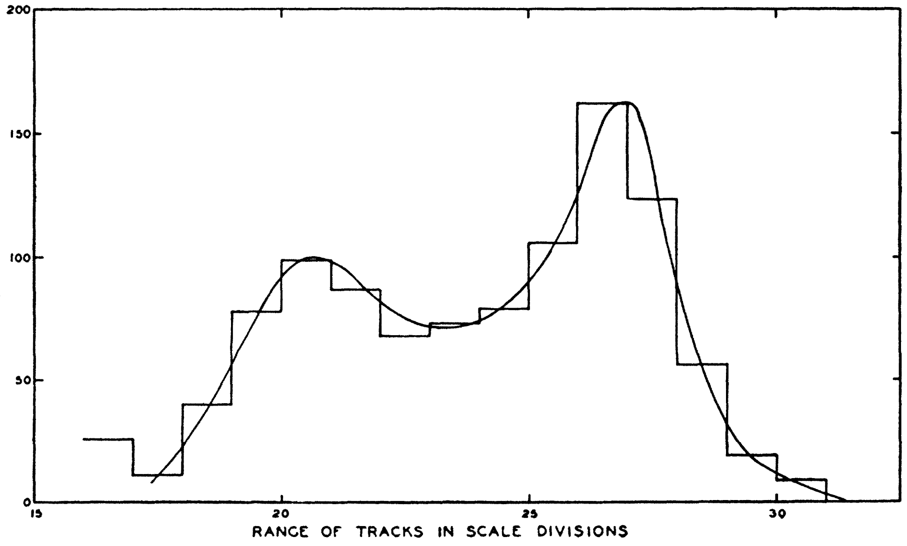

FIG. 5a. Spectrum of particles observed in photographic plate. Peaks at approximately 21 and 27 scale divisions (14.7 and 18.9 microns) represent scattered deuterons and protons from the reaction $B^{11}(d,p)$, respectively.

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[14] G. Breit, Phys. Rev. 34, 817 (1929).

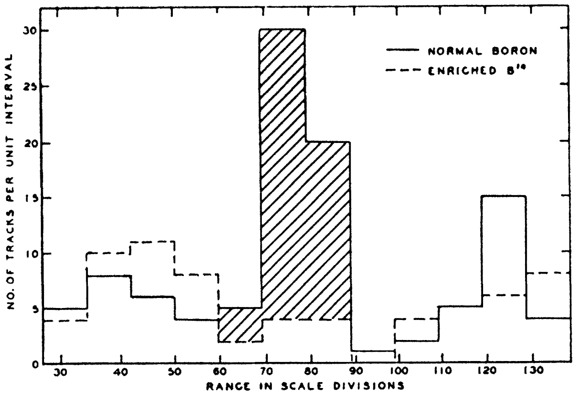


FIG. 5b. Spectrum of particles observed in the region between 30 and 130 scale divisions (21 to 91 microns). The shaded area represents a group which apparently arises from the bombardment of B^{11}; it is interpreted as a proton group associated with the formation of B^{12} in its ground state. This group is about 1/60 as intense as the group of range 27 scale divisions (Fig. 5a). (The range scale is distorted in this plot of equal energy intervals.)

second is ascribed to the protons from the reaction $B^{11}(d,p)$. The results of these observations are shown in Fig. 5a, where number of tracks per unit interval is plotted as a function of length of tracks in scale divisions of the eyepiece used in our microscope. The eyepiece was calibrated by use of a substage micrometer and it was found that 1 scale division is equal to 0.70 microns. The plot in Fig. 5a represents the results of three observers; each observer found two well-defined maxima, and most of the high-energy tail appeared in only one set of observations.

A control run was made by bombarding a plain aluminum foil, and the spectrum shown in Fig. 6 was obtained. The main peak at about 21.5 scale divisions (15.1 microns) represents the deuterons which have been elastically scattered through approximately 90° before falling on the photographic plate. The groups at 6.25 and 11.0 scale divisions represent the tracks produced by protons from diatomic and triatomic ions which were scattered in like manner; these ions were brought onto the aluminum target as the generator built up voltage after a spark. All of the groups may be used to determine something of the range-energy relation for particles of these low energies in the photographic emulsion. The maxima in Figs. 5a and 6 representing scattered deuterons do not correspond precisely in energy, but this is of course due to the fact that deuterons scattered by boron have, on the average, only about 78 percent as much energy as those scattered from aluminum. The slightly greater width of the groups in Fig. 5a is ascribed to the thickness of the boron film.

Following the bombardments of normal boron and of the aluminum foil, we obtained some enriched B^{10} (96 percent) from Oak Ridge. As a further check (to exclude the possibility that the protons we observed represented a strong group which might be produced by $B^{10}(d,p)$), we bombarded a target of the enriched B^{10}. The proton group observed in the bombardment of normal boron was not present.

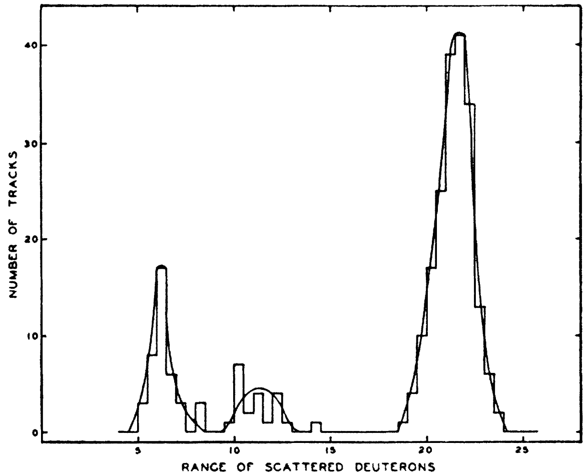


FIG. 6. Spectrum of the 1.68-Mev deuterons scattered from a thin aluminum foil. Secondary peaks are due to diatomic and triatomic beams which appeared when generator built up voltage after a spark.

It is known[10] that the reaction $B^{11}(d,\alpha)Be^9$ yields particles of 4.5 cm range, and these would lie close to the group which we observed at 27.0 scale divisions. That the latter group could not consist of α-particles, however, was proved by performing our observations at lower bombarding voltage. The resultant change in position of the group at 27.0 scale divisions showed that it could not be associated with $B^{11}(d,\alpha)$.

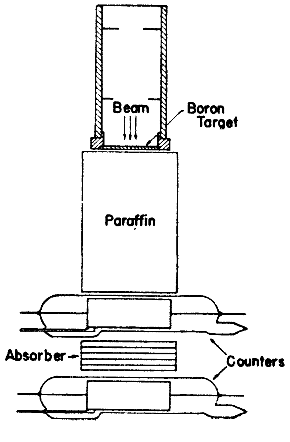
From the position of the longer range group in Fig. 5a, one may calculate the mass of B^{12} as it is produced in this reaction. A range of 27.0 scale divisions (18.9 microns) corresponds to a range in air of 3.76 cm, indicating a proton of energy 1.37 Mev. The mean energy of the impinging deuterons is taken as 1.6 Mev. Then, since

$$Q=(M/M_{B^{12}})E_p^{90^\circ}-[(M_{B^{12}}-M_d)/M_{B^{12}}]E_d,$$

one has

$$Q=0.15 \text{ Mev.}$$

FIG. 7. Diagram of the arrangement used for coincidence absorption measurements. The paraffin was of sufficient thickness to absorb the beta-rays emitted in B^{12} decay.



Although the only prominent groups of particles which we observed on examination of our plates are those shown in Fig. 5a, we concluded from subsequent information (Section IV) that a Q-value of 0.15 is probably associated with an excited state of B^{12}.

Indeed, taking the mass of B^{12} as 12.01927 (calculated from $Q=0.15$ Mev) and of C^{12} as 12.00382,[15] one finds that the $B^{12}-C^{12}$ decay should evolve a total energy of 14.5 Mev. It is known that the end point of the beta-ray spectrum, accurately determined[7] by a spectrometer, lies at 13.43 ± 0.06 Mev, and hence approximately 1.1 Mev remains to be accounted for in the transition. It seemed likely therefore that the group at 27 scale divisions (Fig. 5a) was produced by protons which left B^{12} in an excited state. (For other possibilities, see Section V.) If this state of excitation were at 1.1 Mev, then we should expect a probability that the reaction $B^{11}(d,p)$ may yield longer range protons than those at 27 scale divisions; the Q-value for this case should be 0.15 Mev+1.1 Mev, or 1.25 Mev.

With this possibility in mind, we re-examined our previously exposed plates in search of such a group. The results of this search are shown in Fig. 5b, where tracks of range between approximately 30 and 130 scale divisions are plotted. It is known that the production of alpha-particles from $B^{10}(d,\alpha)2\alpha$ gives rise to a continuous distribution of particles which tend to obscure any peaks produced by particles from the bombardment of normal boron, but it has been previously shown[10] that no particles of range greater than approximately 4.5 cm are formed in bombardment of B^{11} by deuterons of 0.55 Mev energy. It is apparent from Fig. 5b that a group of particles at approximately 77 scale divisions in range may be attributed to the bombardment of B^{11}. This group, under the conditions of Smith and Murrell's experiments,[10] could correspond to their group at 2.8 cm, which they ascribe to carbon contamination of their targets, although the specific reaction is not given. There is evidence for its appearance in their bombardment of both B^{10} and B^{11}, although at their bombarding voltage the 2.8 cm peaks are superposed on an intense background and hence interpretation is difficult.

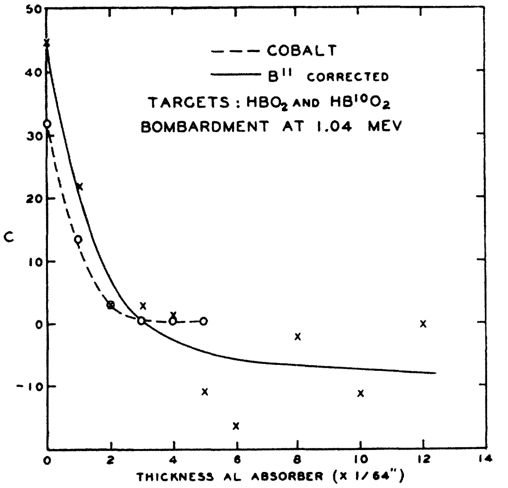


FIG. 8. The "B^{11} corrected" curve was obtained by subtracting (after normalization) the coincidence absorption curves obtained with targets of normal B_2O_3 and of $B_2{}^{10}O_3$. The resultant curve is compared with a coincidence absorption curve obtained from the gamma-rays emitted by Co^{60}.

We believe, therefore, that the group at 77 scale divisions is a proton group of energy approximately 2.35 Mev, which is what one would expect if it arises from the reaction $B^{11}(d,p)$ and if it has a Q-value, as seems probable, of 1.25 Mev. The primary source of error in the 2.35 Mev measurement lies in our lack of an accurate range-energy relationship for these emulsions; this is probably not in error by more than 8 percent at this energy. The number of tracks in the group shown at 2.35 Mev is 50; in an equal area of the photographic plate, approximately 3000 tracks were found in the proton group of Fig. 5a. It therefore appears that the excited state of B^{12} at 1.1 Mev is formed approximately 60 times as often as the ground state (observation at 90°, bombarding voltage 1.67 Mev). More accurate data, preferably with highly enriched B^{11}, should be obtained to confirm these results.

We have made an attempt to estimate the total yield of short-range protons and to correlate this number with the emission of the beta-rays from B^{12}. The number of protons recorded on the photographic plate is considerably more than would be expected from the yield data previously obtained by the observation of the beta-rays with coincidence counters. This could be due to the fact that the protons observed at 90° do not represent the "average yield" as a function of angle, while the beta-rays are of course emitted isotropically. We hope to investigate this point in more detail.

IV. GAMMA-RAYS PRODUCED BY DEUTERON BOMBARDMENT

The gamma-rays which are emitted when boron is under bombardment by deuterons have been observed by Gaerttner, Fowler, and Lauritsen[8] and by Halpern and Crane.[9] The first group reports gamma-rays of 1.5, 2.2, 4.4, 6.9, and 9.1 Mev, while Halpern and Crane report 1.4, 2.4, 4.2, 6.0, and 9.1 Mev, in generally satisfactory confirmation. These gamma-rays may be accounted for directly by correlating them with known excited states of product nuclei, except in the case of the gamma-ray at about 1.5 Mev. It has been speculated[2, 8] that this gamma-ray is associated with the reaction $B^{11}(d,p)$, and that it is involved in the decay-scheme of B^{12}; it may be associated[2] also with transitions between two excited levels (5.8 to 4.4 Mev) in the B^{11} formed in $B^{10}(d,p)$. We thought it worth while to determine definitely whether it was associated in any case with the bombardment of the B^{11} rather than the

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[15] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947).

B^{10} isotope. Rough examinations were made of the "average absorption coefficient" in several absorbers of the radiation produced by bombardment of normal boron and of enriched (96 percent) B^{10}. Indications were that the low energy radiation was from the normal target. Interpretation of such data is always difficult, however, and we therefore shifted our attention to coincidence-absorption experiments.

The technique of measuring the range of the secondary electrons produced by gamma-radiation has been frequently used[16] and will not be described here. The arrangement of apparatus is shown in Fig. 7. About 3 in. of paraffin was placed between the target and the coincidence counters; this is sufficient to stop all of the beta-rays which are emitted by B^{12}. Observations of number of coincidences as a function of absorber thickness were made with targets of normal boron and of enriched (96 percent) B^{10}. Before we had obtained boron in elemental form, we also made observations with HBO_2 and oxides of titanium and zinc, data from the oxide targets being used to correct for effects from oxygen.

The range of secondaries produced by the gamma-rays of highest energy (9.1 Mev) would be a maximum of 1.9 cm (48/64 in.) in aluminum, and of course the other radiation would yield numerous secondaries of shorter range. By comparing the shapes of the curves obtained with normal and with enriched boron, however, we hoped that the source of the ~1.5 Mev radiation might be determined.

Figure 8 shows the result of a comparison of the coincidence absorption curves for the gamma-radiation emitted by normal and by enriched B^{10} under deuteron bombardment. The boron in each case was in the form of a thick target of HBO_2. A target of TiO_2 was bombarded also, and the "oxygen correction" was thus ascertained; the number of coincidences from oxygen was only about 10 percent (at 1.05 Mev deuteron energy) of the total number from $HB^{10}O_2$ at the smallest absorber values. After making the oxygen correction, it was found that, in the case of normal boron, the number of coincidences observed beyond about 10/64 in. Al absorber could be ascribed almost entirely to the B^{10}-content of normal boron. (This could not be strictly true, since part of the high energy-radiation is known to come from the bombardment of B^{11}. The number of coincidences produced by this radiation is negligible, however, compared with the total number of coincidences observed with small thicknesses of absorber.) Hence the data were "normalized" at 10/64 in. Al absorber. It was then possible to determine the value of "B^{11} corrected," which is plotted in Fig. 8. This rather indirect approach would have been unnecessary if we could have obtained highly enriched B^{11}, but only B^{10} was available in concentrated form. This particular method of obtaining the net effect of B^{11} explains why the ordinates associated with solid line of Fig. 8 could drop to negative values.

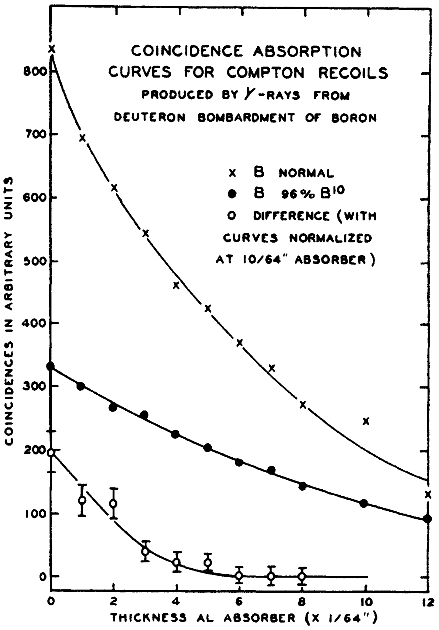

FIG. 9. Coincidence absorption curves obtained from gamma-rays produced by deuteron bombardment of normal boron and of enriched B^{10}, both in elemental form. The difference curve is also plotted, and again shows that a gamma-ray of energy ~1.3 Mev is associated with the bombardment of B^{11}.

It was concluded that a gamma-ray of ~1.5 Mev energy was emitted when B^{11} is bombarded by deuterons. In order to get a closer check on this value, we replaced our target by a source of Co^{60}; this isotope emits two gamma-rays of energies slightly over 1.1 and 1.3 Mev. The end point of the absorption curve for the secondary electrons produced by the 1.3 Mev radiation should lie between 4/64 in. and 5/64 in. Al absorber. It appears that the radiation attributed to B^{11} under deuteron bombardment is very close to this value. The relative position of the two curves, as shown in Fig. 8, is strongly dependent on the accuracy of the corrections applied in obtaining the "B^{11}-corrected" curve. The shapes of the two curves are very similar for the smallest values of absorber thickness, and the γ-rays from Co^{60} and from "B^{11}-corrected" are obviously of approximately the same energy. It is thought (see Section IV) that the energy of the γ-ray represented by the "B^{11}-corrected" curve should be 1.1 Mev.

After the completion of the work with HBO_2, we were supplied with enriched B^{10} (96 percent) in elemental form; this was prepared from the $CaF_2 \cdot BF_3$ complex by Dr. W. B. Keighton, who had previously prepared the HBO_2. This made it possible to repeat our observations without the background effect produced by the presence of oxygen. The results are shown graphically in Fig. 9. Complete absorption curves for the secondaries produced by deuteron bombardment of B^{10} and of normal boron are plotted, and a point-by-

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[16] A general discussion may be found by Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. **20**, 236 (1948).

point subtraction (after normalization, with correction for the B^{10} content of normal boron) yielded a resultant curve which again showed the presence of the low energy gamma-ray; it is accordingly attributed, as before, to the bombardment of B^{11}.

We had previously determined (Section II) the yield of beta-rays from the decay of B^{12} formed in $B^{11}(d,p)$, and we therefore sought to measure the yield of the $\sim$1.5 Mev gamma-radiation. The efficiency of the counters was determined by observing radiation from the Co^{60}, and was found to be 0.9 percent. We had also determined the coincidence rate, at various absorber thicknesses, produced by secondary electrons associated with the Co^{60} gamma-radiation (with correction for the gamma-gamma coincidence rate of this element). It was thus possible to show that the intensity of the $\sim$1.5 Mev gamma-radiation produced when B^{11} is bombarded by deuterons was of approximately the same intensity as the beta-rays from B^{12}, produced in the same bombardment. This means that this gamma-ray is quite intense compared to the others emitted at our bombarding voltage. This agrees roughly with the results previously observed by Gaerttner, Fowler, and Lauritsen[8] at a bombarding voltage of 550 to 850 kev peak; Halpern and Crane,[9] using a bombarding voltage of 700 kev maximum found that the most intense line was at 4.2 Mev. We sought therefore to get information of the type shown in Fig. 9 at different bombarding voltages. No quantitative conclusion can be drawn from our data except to state that the ratio of intensities of the $\sim$1.5 Mev gamma-ray and the 4.2 Mev gamma-ray does not seem to change so markedly with bombarding voltage as the reported results would indicate. We were able to show that the excitation curve for the production of low energy radiation was of the same shape as the yield function for B^{12} (see Fig. 1) up to 1.05 Mev bombarding voltage; the fact that the intensities were found to be approximately the same, however (see preceding paragraph), is of more significance, since the excitation curves for most of the products of boron disintegration are probably quite similar in this region.

V. DECAY SCHEME OF B^{12}

It appears that the gamma-ray of $\sim$1.5 Mev discussed in the preceding section could very well be of 1.1 Mev energy and that it comes from the decay of B^{12} (usually formed in an excited state) to its ground state. The nucleus B^{12} may then decay by beta-emission either to the ground state of C^{12} or to one of the known excited levels of C^{12}. (It does not seem likely that it ever decays to an excited level in C^{12} at 1.1 Mev, since no level is known or expected in this region.)

In order to get more information on these points, we have made a search for β-γ-coincidences in B^{12} decay.

The beta-rays were detected by two counters and the gamma-rays with a third counter; all three of the counters fed into a triple coincidence circuit. The experiment is complicated by the fact that effects of gamma-rays associated with the disintegration of B^{10} are several times as intense as those associated with the disintegration of B^{11}; furthermore, gamma-gamma-coincidences which can occur in the former case must be taken into consideration. After increasing resolving time to a limit of less than 10^{-7} second, we could detect no β-γ-coincidence rate which was more than about one-third as great as that which would be expected from our previous measurements of the intensity of the beta-rays, assuming that these are in coincidence with gamma-emission. The small coincidence rate can probably be accounted for, within experimental error, by uncertainties in the gamma-gamma-coincidence rates, efficiency of counters, measurement of resolving time, and chance coincidences; part of it may also be due to true β-γ-coincidences which sometimes occur when B^{12} decays from its ground state to an excited state of C^{12}.

Generally satisfactory conclusions appear to be the following: The B^{12} formed in the $B^{11}(d,p)$ reaction is usually in an excited state at 1.1 Mev, but may be (in approximately 1/60 of the cases) in its ground state. The low energy gamma-ray observed in the bombardment of B^{11} by deuterons has a measured energy which is consistent with 1.1 Mev. It further appears that B^{12} subsequently decays primarily to the ground state of C^{12}, although our observations do not preclude the possibility that decay also takes place to excited levels of C^{12}; indeed, a small net β-γ-coincidence rate indicates that this may sometimes be the case.

These conclusions agree with cloud-chamber experiments,[5] which have indicated that no appreciable number of γ-rays is emitted following the decay of B^{12}. Additional evidence for the postulated transitions could be furnished by utilizing counters in a search for delayed gamma-emission (by stopping bombardment periodically and searching for gamma-rays), as has been pointed out[8] previously, and by a new search for beta-gamma coincidences with highly enriched targets of B^{11}.

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