tributed to contamination or to the transition effect. Assuming a 1.5 c.p.m. maximum beta-activity for 400 cm^2 of cadmium metal counted at 5.46 percent efficiency, the variation of minimum half-life with maximum beta-energy can be determined. Effective sample thickness is taken as the range from standard range-energy curves for beta-radiation. Results for betas up to 200 kev are shown in Table V.

Through the kindness of Dr. J. V. Dunworth, researches conducted in 1947 and described in a Ph.D. thesis by S. G. Cohen on the possible orbital capture activity of In^{113} have recently been made available to us. Their data appear to exhibit evidence of the same activity of natural indium which we have investigated. The authors are indebted to the Isotopes Division of the Oak Ridge National Laboratory for the remarkable isotopically enriched indium samples made available to them.

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Proton Groups from the Deuteron Bombardment of Boron*

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Protons emitted when boron enriched to 96 percent B^{10} was bombarded by 3.76-Mev deuterons have been observed at 90° and 0°. Groups corresponding to Q-values of 9.18±0.05, 7.03±0.06, 4.70±0.06, 4.15±0.08, 2.26±0.07, 1.36±0.07, 0.70±0.10, and 0.32±0.10 Mev were found. These have relative intensities at 90° of 1, 0.3, 0.8, 0.6, 16, 13, and 0.8. The intensity of the lowest energy group was not determined, since it was only just distinguishable from the scattered beam. The bombardment of unseparated boron gave no significant results, because of the presence of large amounts of an impurity, probably magnesium as the boride.

I. INTRODUCTION

IT is well known that the study of the particle groups emitted by an element under bombardment gives information concerning the energy levels in the residual nucleus. The reaction $B^{10}(d,p)B^{11}$ is of more than usual interest because of the large energy release, or Q-value, which enables very highly excited levels in the B^{11} nucleus to be observed.

This reaction was first studied by Cockcroft and Walton,[1] and then more carefully by Cockcroft and Lewis,[2] using 550-kev deuterons and unseparated boron isotopes. They observed three proton groups, corresponding to Q-values of 9.14±0.06, 7.00±0.05, and 4.71±0.03 Mev, as corrected by Livingston and Bethe,[3] which they assigned to the $B^{10}(d,p)B^{11}$ reaction. A few years later, a fourth group was found by Pollard, Davidson, and Schultz,[4] having a Q-value of 2.39±0.20 Mev, using 3.1-Mev deuterons from a cyclotron, and again, unseparated isotopes. Although they assigned this group also to the reaction involving B^{10}, its large yield made it seem likely that it was due to $B^{11}(d,p)B^{12}$. Since their resolution was not very good, it was felt that it would be profitable to repeat their work using the separated isotopes now available from Oak Ridge, and the much better resolution possible with our present counting techniques.

II. PROCEDURE

Boron targets having a thickness of about 3 mm of air-equivalent, or 50 kev at our beam energy, were prepared by evaporating the element off a wolfram filament onto a thin (0.04 mil) gold backing in a vacuum of 10^{-5} mm of mercury. It was necessary to replace the filament several times during the evaporation, since the boron reacted with the wolfram to form the rather brittle

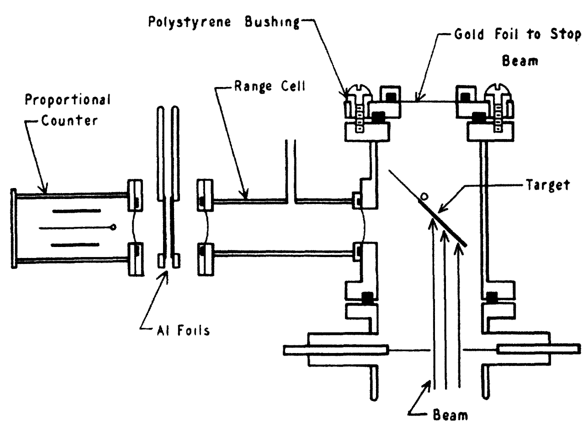

FIG. 1. Schematic diagram of bombardment chamber used. The beam analyzing magnet and slit system have been omitted.

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‡ Assisted by the ONR and AEC.
[1] J. D. Cockcroft and E. T. S. Walton, Proc. Roy. Soc. 144, 704 (1934).
[2] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. 154, 246 (1936).
[3] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 245 (1937).
[4] Pollard, Davidson, and Schultz, Phys. Rev. 57, 1117 (1940).

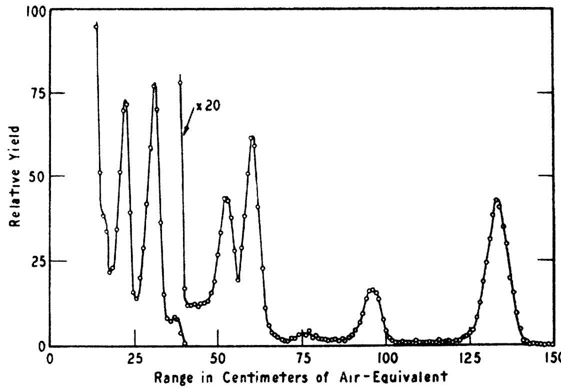

FIG. 2. Protons emitted at 90° when 96 percent B^{10} was bombarded by 3.76-Mev deuterons. The ranges are uncorrected for the change in the stopping power of aluminum with proton energy.

boride. Because of the very high temperature needed to evaporate boron, it was probable that some wolfram was also deposited on the target. There was also the possibility that some of the boron would be oxidized by the residual air in the vacuum chamber where the evaporation was carried out. Since B_2O_3 is much more volatile than boron, it would be deposited very readily on the target, introducing considerable oxygen contamination.

The bombardments were performed in the conventional manner in a chamber built by Martin.[5] The 3.76-Mev deuteron beam emerged from the cyclotron, passed through a slit system and between the pole faces of an analyzing magnet, and impinged on the target, which was held between the arms of a *C*-shaped support. The beam passed through the target and its thin gold backing, between the arms of the *C*, and was stopped in the end plate of the chamber. This was insulated from the rest of the chamber, and was connected to the beam integrating circuit. The protons emitted at 90° to the beam passed out through an exit port covered by a thin aluminum foil, through a range cell, through a set of variable aluminum absorbers, and into a proportional counter. The counting circuits were biased so that only the largest pulses, corresponding to protons at the end of their range, would be recorded. For 0° observation, the target was fastened to the chamber end plate, in front of a window covered with enough gold foil to just stop the beam (about 14 cm of air-equivalent). The bombardment chamber is shown schematically in Fig. 1.

The general procedure was to measure the number of protons as a function of their range emitted from the target. Absorption was added in steps of 1 cm air-equivalent, starting with the minimum amount needed to stop the scattered beam, until a value 10 cm greater than the range of the most energetic proton group was reached. The number of protons emitted with a given range for a constant number of deuterons were thus determined. The run was then repeated in the reverse order, removing the absorbers, and the two results averaged. This method tended to compensate for any slow drifts in the counting level and for the deterioration of the target under bombardment. A total of 18 runs, using 4 different targets were made using the separated B^{10} at 90° observation.[6] A composite of these is shown in Fig. 2. Four runs were also taken with the separated isotope at 0°, and are shown in Fig. 3. Several runs were also taken with commercial unseparated boron, but were of no value because of the large amounts of magnesium present as the boride. In fact, some of the groups due to the impurity were larger than those due to the B^{10}. The contaminant was identified by the presence of a strong 14.8-hour activity in the target, from the $Mg^{26}(d,\alpha)Na^{24}$ reaction.[7]

A total of ten groups can be seen in Fig. 2, some of which are caused by contaminants. The groups with extrapolated ranges of 140, 101, and 65 cm air-equivalent are those reported by Cockcroft and Lewis. The last of these is now seen to be a doublet, which is almost completely resolved. The two at 33 and 25 cm were reported by Pollard, Davidson, and Schultz as one group. The small change in curvature at 18 cm appeared in every run, and so is probably another group. At first it was thought that this small group was due to the energetic alpha-particles from the $B^{10}(d,\alpha)Be^8$ reaction, but further investigation with the counting level set above pulses due to protons of any energy, showed it was due to protons. Finally, another, large yield group can be seen at 16 cm, being just distinguishable from the scattered beam at 14 cm range. The group at 40 cm falls where protons from $C^{12}(d,p)C^{13}$ would be expected, and since its yield varied from run to run by a factor of 50 it is undoubtedly due to this reaction. The very small group at 80 cm is barely twice the neutron background, and is also probably due to an impurity. It has about the right range for the $C^{13}(d,p)C^{14}$ reaction, and its

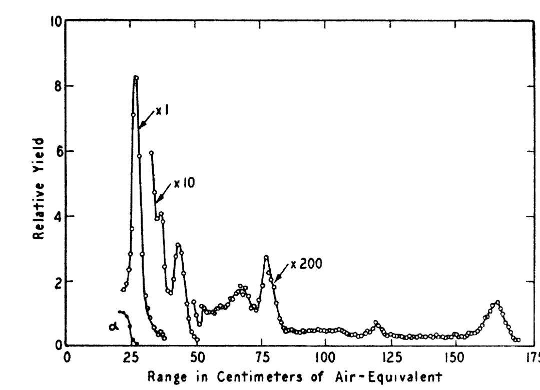

FIG. 3. Protons emitted by the $B^{10}(d,p)B^{11}$ reaction at 0° observation. The ranges are uncorrected for the change in stopping power of gold and aluminum with proton energy. The α-particles from the $B^{10}(d,\alpha)Be^8$ reaction are also shown.

[5] A. B. Martin, Phys. Rev. **71**, 127 (1947).

[6] 96 percent B^{10} was obtained from Oak Ridge.

[7] No analysis of the boron used was available. According to the suppliers, Eimer and Amend, New York, New York, the probable impurities were traces of the alkalies and one or two percent magnesium, as the boride.

TABLE I. Q-values from the reaction $B^{10}(d,p)B^{11}$.

Present work 90° (Mev)	90° yield	0° (Mev)	Excitation (Mev)	Buechner and Van Patter (Mev)
9.18 ± 0.05	1	9.07 ± 0.15	0	9.232 ± 0.011
7.03 ± 0.06	0.3	6.90 ± 0.15	2.15 ± 0.05	7.091 ± 0.009
4.70 ± 0.06	0.8	4.57 ± 0.15	4.48 ± 0.06	4.775 ± 0.006
4.15 ± 0.08	0.6	4.04 ± 0.20	5.03 ± 0.07	4.199 ± 0.006
2.26 ± 0.07	16	2.30 ± 0.20	6.92 ± 0.07	2.480 ± 0.006
				(2.430 ± 0.007)
1.36 ± 0.07	13	1.50 ± 0.20	7.82 ± 0.07	1.935 ± 0.005
0.70 ± 0.10	0.8	0.81 ± 0.20	8.48 ± 0.10	0.667 ± 0.004
0.32 ± 0.10	large		8.86 ± 0.10	0.311 ± 0.004
				(0.046 ± 0.010)
				(-0.038 ± 0.010)

yield seemed to vary in the same way as that of the 40 cm group, although this is not certain, because of the poor statistics of this group.

Since the two large groups at 25 and 33 cm fall almost exactly where the two from the $O^{16}(d,p)O^{17}$ reaction would appear, it is possible that they are not caused by boron at all. Their very large yield makes it unlikely that they were due to surface contamination, but, as mentioned above, it was possible that the target consisted mostly of the oxide, rather than the elemental boron. To check this possibility, several runs were made at 0°. The energy of the emitted protons depends on the angle relative to the beam at which they are observed, and the change in energy from 90° to 0° observation is fairly dependent on the mass of the target nucleus, especially for light elements. Thus, the groups at 25 and 33 cm at 90° would move out to 34 and 47 cm at 0° if due to boron, but only to 32 and 43 cm if due to oxygen. While the data taken at 0° was not as accurate as that at 90° due to the uncertainty of the range-energy relation in the gold necessary to stop the beam, it is still evident from Fig. 3 that the two groups were due to boron. The high background at long range in the 0° runs was due to the gold needed to stop the beam, being from either the $Au^{197}(d,p)Au^{198}$ reaction, or from $N^{14}(d,p)N^{15}$, from air occluded in the foil.

The extrapolated range of each of the groups was determined from each run and converted to mean range by a procedure due to Motz and Humphreys.[8] This method takes into account the inhomogeneity of the beam, angle and range straggling, target thickness, and the finite range interval detected by the counter. The range in aluminum was corrected for the change in stopping power with the proton velocity, as shown in Livingston and Bethe.[3] A small correction was also made for the counter depth; that is, the distance a proton had to enter the counter in order to be recorded. Where two groups were not completely resolved, the shape of the shorter ranged one was estimated by reflecting the outer edge of the longer ranged one about a vertical line through its peak and subtracting. From the calculated mean range, the mean energy of each group was determined, using the Cornell 1937 relation. From these, and the mean energy of the beam, the Q-value of each group was calculated. They are shown, together with the corresponding levels in the B^{11} nucleus, in Table I. The Q-values obtained from the 0° runs are also given for comparison, although they are not as accurate. The agreement with the results of Cockcroft and Lewis, and Pollard, Davidson, and Schultz is very good, where they can be compared. The levels in B^{11} check within the experimental errors with those found by Fulbright and Bush[9] from the inelastic scattering of protons, who found levels at 2.2 ± 0.3, 4.8 ± 0.4, 6.5 ± 0.3, and 7.8 ± 0.4 Mev. This work can also be compared with the very precise results of Buechner and Van Patter[10] which have been included in Table I. The agreement is good, except for the groups having Q-values of 2.26 and 1.36 Mev. These fall on top of the two oxygen groups, and so may have been distorted somewhat. The three groups in parentheses could not have been detected by our method. That having a Q-value of 2.430 Mev could not have been resolved with our beam width of 250 kev from that at 2.480 Mev. The other two lie within the scattered beam, where we cannot work.

In conclusion, it gives me great pleasure to thank Dr. Ernest C. Pollard for suggesting this problem and for his helpful discussions while directing this research.

[8] H. A. Motz, thesis, Yale University, 1949.

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

[10] W. W. Buechner and D. M. Van Patter, Phys. Rev. **79**, 240 (1950). I am greatly indebted to Dr. Van Patter for sending me his results prior to publication.