Particle Groups from the Alpha-Particle Bombardment of Boron*

ROBERT J. CREAGAN**
*Sloane Physics Laboratory, Yale University,*** New Haven, Connecticut*
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Targets of natural boron and targets of 96 percent boron 10 have been bombarded by 7.45 Mev and 6.64 Mev cyclotron alphas. Seven charged particle groups have been observed. The Q-values calculated from the energy of the various groups have been assigned as follows: $Q_1=4.07$ Mev to the $B^{10}(a,p)C^{13}$ reaction; $Q_2=0.85$ Mev to the $B^{11}(a,p)C^{14}$ reaction; $Q_3=0.31$ Mev to the first excited state of carbon 13 at 3.76 Mev. Other values are: $Q_4=0.07$ Mev; $Q_5=-0.31$ Mev; $Q_6=-1.57$ Mev; $Q_7=-1.76$ Mev with assignments discussed. The assignments were checked with boron 10 targets and proton-gamma-coincidence technique. Gammas were detected by coincident counts from two photo-multiplier tubes observing the same naphthalene crystal. Excited states of carbon 13 were searched for, but not observed, at 0.8 Mev and 3.12 Mev.

INTRODUCTION

THE particles emitted from boron, bombarded by alphas, are the first in which the group structure of nuclear fragments was recognized. The reaction has been studied extensively by use of natural alpha-sources which require poor geometry to give appreciable yields. This led to considerable disagreement as to the energy released in the various possible reactions.[1] The energy released in these reactions is important because it determines the following: (a) the mass difference between boron 10 and carbon 13;[2] (b) the mass difference between boron 11 and carbon 14;[3] (c) the energy level of the first excited state of carbon 13;[1,4] (d) the possibility of the reaction $B^{10}(a,d)C^{12}$;[5,6] For the four reasons listed above it was considered desirable to repeat the experiments with the well-collimated cyclotron beam and consequent possibilities for better geometry and results.

It was considered that the best method for identifying the particle groups due to the $B^{11}(a,p)C^{14}$ reaction was to bombard targets of 96 percent boron 10 and compare results with those obtained by bombarding targets of natural boron.

To verify the existence of an excited state in carbon

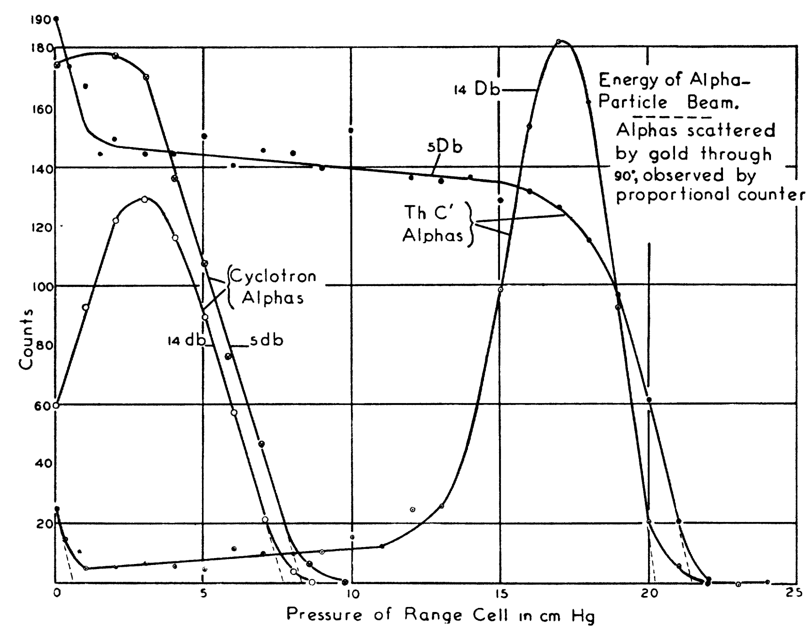

FIG. 1. The number of alpha-particles detected in a proportional counter as a function of the air pressure in a range-cell. Two curves were obtained by scattering cyclotron alphas through 90° by gold foil. The other two curves show the relative range of Th C and Th C′ alphas used for calibration. The 14 db curves count only the highest pulses while the 5 db curves count all pulses.

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[1] W. Bothe and H. Maier-Leibnitz, Zeits. f. Physik **107**, 513 (1937).
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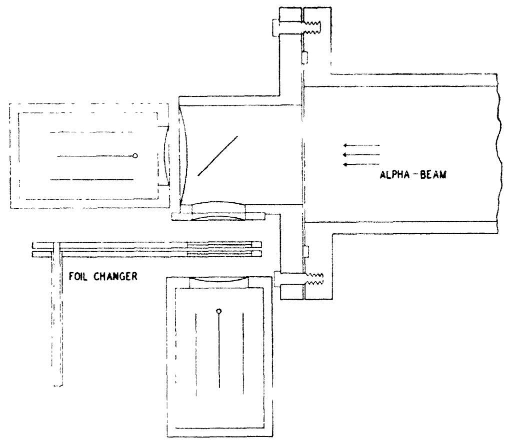

FIG. 2. A typical experimental set-up with the alpha-beam from the cyclotron impinging on the boron target and the emitted protons detected at 0° and 90° by proportional counters. The foil changer allowed range measurements to be made.

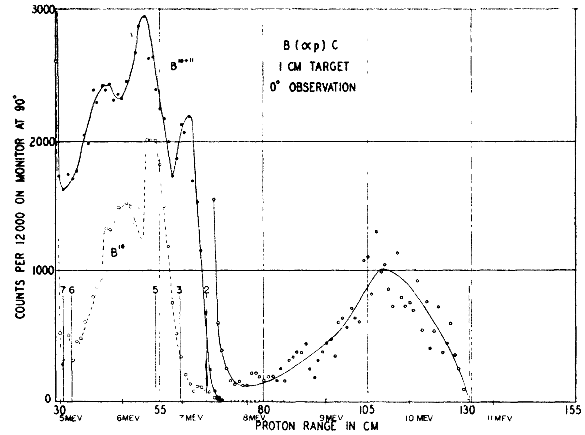

FIG. 3. Proton yield from alpha-particle bombardment of boron targets of separated and unseparated isotopes. Only the largest pulses were counted.

13, observation of proton-gamma-coincidences was considered the best evidence available, on the assumption that the excited state decayed by gamma-emission to the ground state of the residual nucleus. Coincidence technique would also be a check on the $B^{11}(a,p)C^{14}$ reaction end group because no proton-gamma-coincidences should be observed. Similarly the existence of recoil protons from the target could be identified.

PROCEDURE

The energy of the cyclotron alphas was determined in four different experiments: 1. The alpha-beam was passed through a range-cell, picked up by a probe in an evacuated volume, and observed by means of a galvanometer. The range, and hence energy, of the alphas was obtained by varying the air pressure in the range-cell (a pipe through which the alphas pass). 2. The alpha-beam was passed through a range-cell and was observed by a proportional counter at 0°. Calibration of counter depth and basic absorption (minimum amount of absorption in the path of the particles due to vacuum seal foil and foil on counter) was obtained by use of Th C and Th C′ alphas. 3. The alpha-beam was scattered by gold through 90°, passed through a range cell, and observed by a proportional counter. 4. The alpha-beam impinged on an aluminum foil covered with a thin film of vacuum grease and the recoil protons so produced were passed through a range-cell and observed at 0° by a proportional counter.

The various alpha-beam energy measurements gave an extrapolated value of 7.45 Mev with a mean deviation of 0.02 Mev, although the procedure does not warrant error limits smaller than 0.05 Mev. The beam spread at half-height is 0.3 Mev. All values were taken as the extrapolated value of the steepest part of the counts *vs.* range curve. Curves were taken counting all particles (integral curve), and only those particles near the end of their range (differential curve). The result of experimental method 3 above is given in Fig. 1 as an example of the results. The 14 db and 5 db refer to the attenuation introduced between the proportional counter pre-amp and the video amplifier.

Boron targets were made by evaporating boron onto gold foils. The gold foils were used to stop the alphas behind the target and thus prevent other nuclear reactions by the alphas. The boron was heated on a tungsten filament in a vacuum (~1 micron) and water-cooled gold (~8-cm air equivalent) was clamped above the filament so as to intercept the evaporating boron. This gave a smooth thin target. Most of the work was done with targets between 0.4 cm and 1-cm air equivalent, assuming that 1.25 mg/cm^2 of boron is equivalent to 1 cm of air. Target preparation was the same for natural boron and the 96 percent boron 10, since they were both in the form of 200 mesh amorphous powder.

The target was bombarded about a meter outside the cyclotron can and the charged particles emitted were observed by proportional counters at 90° and 0° as shown in Fig. 2. A typical run would consist in observing the number of proton counts at 0° as a function of range for a standard number of counts on the counter at 90°.

The absorption was varied by placing different thickness aluminum foils in the path of the protons. The energy of the particles was then determined from the 1937 Cornell range-energy diagrams.

The proportional counters were so biased that only those particles near the end of their range would record. This is possible because of the increased ionization per cm of path near the end of the particle range (Bragg curve) which produces a larger pulse in the proportional counter.

The results of the 0° and 90° observations are given in Fig. 3 and Fig. 4 respectively. The results obtained by putting a 1.13 cm aluminum foil in the incident alpha-beam to lower the energy of the beam is given in Fig. 5.

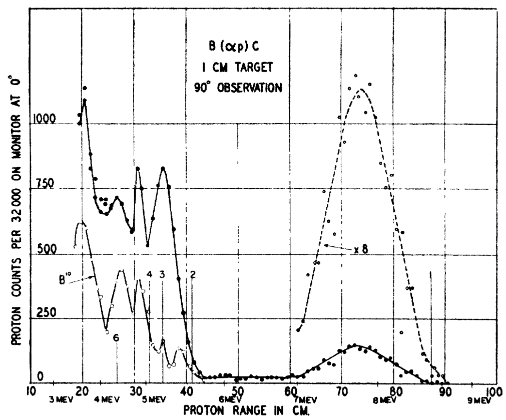

FIG. 4. Proton yield from alpha-particle bombardment of boron targets of separated and unseparated isotopes. Only the largest pulses were counted.

By extrapolation, the ranges of the various groups are determined and by using the standard Q-value equation, the energy released in the nuclear reaction is determined.

The bombardments were performed with boron 10 and natural boron targets.

To observe gammas emitted in coincidence with protons, protons are detected at 0° and gammas are detected at 90° as shown in Fig. 6. The iron shield around the photo-multiplier was necessary because of the stray magnetic field of the cyclotron deflector magnet. Both photo-multipliers observed the same crystal and only coincident counts from both were taken as gamma-counts. This served to lower the background noise counts from each photo-multiplier by the factor $2Tn_1n_2=A$; where A is the number of accidental counts observed when n_1 and n_2 random counts are fed into the respective inputs of the coincidence circuit. The resolving time T of the coincidence circuit[7,8] used in this experiment was 2.5 10^{-7} seconds. The video amplifiers[9,10] used have a 4-megacycle band width. Typical background in the cyclotron room for $1\times1\times2.5$ cm naphthalene crystal with no cyclotron beam is 28 coincident counts per minute. For the weak alpha-particle beam used, typical counting rates were 5000–10,000 coincident counts per minute. Naphthalene crystals were used after earlier attempts with calcium fluoride and polystyrene had proven unsatisfactory. 931A photo-multiplier tubes were used, with approximately 150 volts for the first stage and 75 volts for subsequent stages. It was hoped that this arrangement might allow noise pulses introduced in later stages to be biased out. No great difference was observed. Dry-ice cooling was used more as a temperature stabilizer than as a low temperature device, and satisfactory results were obtained with no cooling. The output of the photo-multiplier tube was fed to a 6AK5 cathode follower, then to a 6J6 cathode follower (Fig. 7), which was matched to the 75-ohm cable leading from the cyclotron to the control room where the video amplifier with a 75-ohm resistor input was located. The two cathode followers in cascade gave a better amplification and impedance match between the photo-multiplier tube and the 75-ohm amplifier input than could be obtained with one tube.

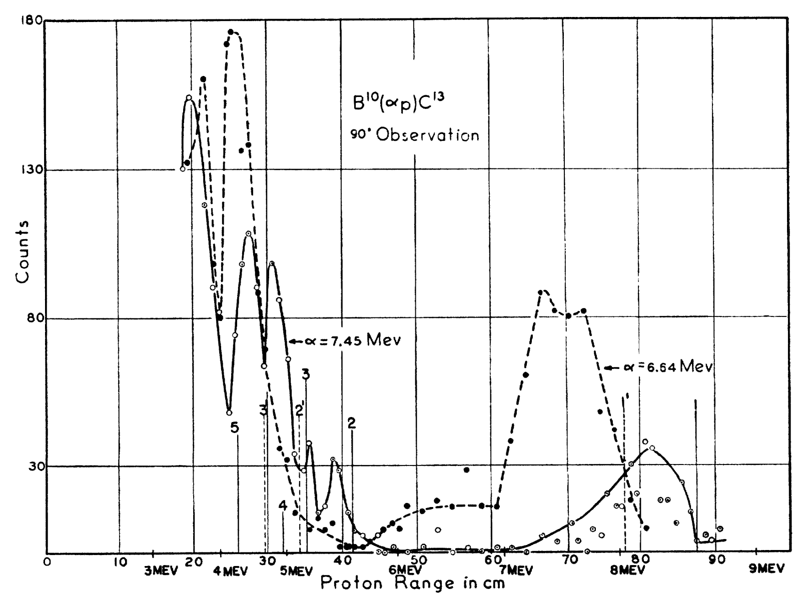

FIG. 5. Proton yield from alpha-particle bombardment of boron targets of 96 percent boron 10 at two different energies of the incident alphas.

[7] H. L. Schultz and E. C. Pollard, Rev. Sci. Inst. **19**, 617 (1948).
[8] B. B. Benson, Phys. Rev. **73**, 7 (1948).
[9] H. L. Schultz, Phys. Rev. **69**, 689 (1946).
[10] B. B. Benson, Rev. Sci. Inst. **17**, 533 (1946).

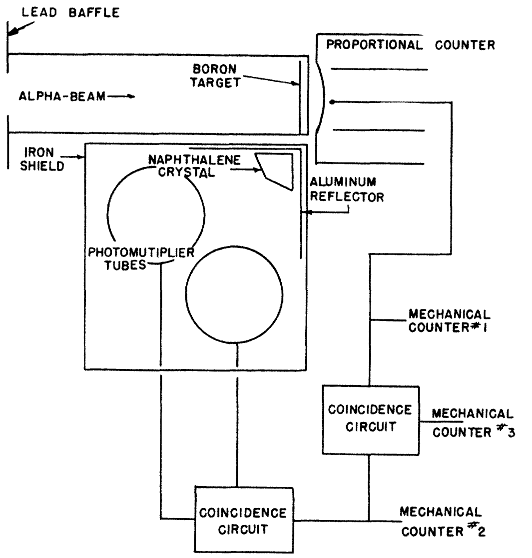

FIG. 6. Experimental arrangement for observing proton-gamma-coincidences emitted from a boron target bombarded by alpha-particles. The protons are detected in a proportional counter and the gammas are detected in a naphthalene crystal which is observed by two 931A tubes in coincidence.

RESULTS

The results of the study of group structure are illustrated in Figs. 3–5. The observed group structure corresponds to the following Q-values:

The longest proton group observed, designated group 1, gives a Q-value of 4.07 Mev with a mean deviation of 0.14 Mev for six determinations. This is a rough measure of the accuracy of the experimental values, although errors could exist to 0.2 Mev because of equipment and technique. The Q_1 value agrees well with the $Q=4.03$ Mev calculated from Mattauch's table of mass spectrographic data.[11] There seems to be a noticeable asymmetry in the yield of the end group at 90° and 0° with a ratio of 5 in favor of the 90° observation, if the yield is normalized in each direction with respect to the other groups. The predicted half-width of the end group was 1.07 Mev on the basis of energy-spread of incident alphas and the target thickness, while the experimentally determined half-width was 0.95 Mev. This agreement of the half-width of the end group, plus the fact that no dip occurred in the peak (except statistical fluctuations), are reasons for doubting the existence of an excited level in the carbon 13 nucleus at 0.8 Mev.[1]

The next longest proton group gives $Q_2=0.85$ Mev which has been assigned to the $B^{11}(\alpha,p)C^{14}$ reaction[2] giving a mass difference between boron 11 and carbon 14 of 2.9940 mass units. The identity of the group was verified by bombarding 96 percent boron 10 targets. The group has a ratio of 13 between yield with natural boron and boron 10 targets (see Fig. 3).

[11] J. Mattauch and S. Flugge, *Nuclear Physics Tables* (Interscience Publishers, Inc., New York, 1946).

The next group: $Q_3=0.31$ Mev has been assigned to the first excited state of carbon 13 because it appears with separated and unseparated isotope targets. This indicates the first excited state of carbon 13 is 3.76 Mev above the ground state, in contrast to results published by other experimenters[1,4] who have given 0.8 Mev and 3.12 Mev, respectively, as the first excited state. Because of this disagreement, the proton spectrum in the pertinent ranges was studied intensively; however, the groups were not found.

The next group: $Q_4=0.07$ Mev has been assigned to the next excited state of carbon 13 at 4 Mev above ground level.

The next group gives a Q-value of -0.31 Mev if protons are assumed. If the group is assumed to consist of deuterons from the reaction $B^{10}(\alpha,d)C^{12}$ the Q-value equals 1.55 Mev; a number in good agreement with the $Q=1.45$ Mev predicted by mass differences.[11] Deuteron emission in this reaction has been suggested,[5] and deuterons have been observed in cloud chamber work.[6] Data obtained by W. Bothe[12] at various angles and energies and ascribed to protons, gives the same mean deviation for Q-values when deuterons are assumed.

Group six: $Q_6=-1.57$ Mev is very weak and was observed only at 0° because of the basic absorption at 90°. If assigned to carbon 13 it implies an excited state at 5.64 Mev.

Group seven: $Q_7=-1.76$ Mev is apparently due to recoil protons observed at 0°. This assumption would specify an incident alpha-beam of 7.72 Mev, but it is considered that faulty extrapolation occurred due to basic absorption which masked all but the tail end of the recoil protons. This assumption, if true, would exclude the 5.9 Mev excited state of carbon 13.

For further verification of group assignments, proton-gamma-coincidence observations were made. The results are given in Table I. The lack of coincidences at 120 cm absorption indicates: (a) that the circuits are operating so that spurious coincidences are minimized, since only 2 coincidences were observed in two hours of cyclotron running time despite the high electrical noise background commonly found in cyclotron operation; (b) that this group has no associated gammas and hence implies a residual carbon 13 nucleus in a ground state;

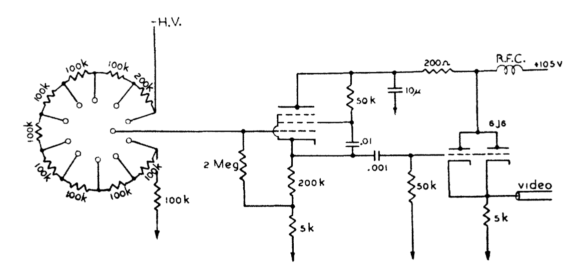

FIG. 7. A pre-amp for a 931A scintillation counter. The cathode resistor for the 6J6 cathode follower is a 75-ohm resistor in the input of the video amplifier.

[12] W. Bothe, Zeits. f. Physik 63, 381 (1930).

(c) that the 0.8 Mev excited state is improbable, because it would have contributed coincidences at 120 cm absorption. The naphthalene would be more efficient for a 0.8 Mev gamma than it would be for higher energy gammas which it later detects as coincidences.

The low coincidence rate at 62 cm absorption confirms Q_2 as belonging to a ground state transition and hence to $B^{11}(\alpha,p)C^{14}$. The few coincidences observed can be accounted for by overlapping of the adjacent group as apparent from Fig. 3.

The 7.2 coincidences observed per 10^4 protons at 51 cm further substantiate the assignment of group 3 to an excited state of carbon 13 at 3.76 Mev and because of lack of coincidences at greater ranges it seems highly probable that this is the first excited state, since the naphthalene detector would be more efficient (Klein-Nishina formula) for lower energy gammas associated with a lower energy level.

The large coincidence rate at 41 cm and 44 cm absorption does not confirm the assumption that group five consists of deuterons, but rather implies that most of the particles are protons belonging to an excited state of carbon 13. The overlapping of groups in this region makes definite assignment of coincidences difficult.

The lack of coincidences at 30 cm absorption strengthens the assumption that group seven is due to recoil protons.

The data is given in Table I with two different counter settings because, while it was necessary to accept most pulses (semipeaked proportional counter) to get reasonable statistics for the end group, it also seemed desirable to bias the counter to accept only the largest pulses (peaked proportional counter) so as to separate the proton groups for better assignment of coincidences.

Because of the possible existence of a proton group due to an excited level of carbon 13 at the same range as the protons from the $B^{11}(\alpha,p)C^{14}$ end group, proton-gamma-coincidences were observed with a boron 10 target. The results were similar to those given in Table I, and indicate no excited state at the range in question. The data was taken with protons observed at 90° and gammas observed at 30°. The solid angle of the counters was different at the different angles and no attempt was made to look for angular correlation of the proton gamma-coincidences.

TABLE I. Results of the proton-gamma-coincidence observation of the alpha-particle bombardment of boron. Semipeaked proportional counter

Absorption	Number of runs	Number of protons	Approximate total time	Total number of coin.	Expected change coin.	Genuine coin.	Genuine coin. per 10^4 protons
Semipeaked proportional counter							
30 cm	7	69,600	34 min.	23	8.4	14.6	2.10
34	5	51,200	24	26	5.4	20.6	4.02
41	7	70,400	36	39	8.7	30.3	4.27
44	9	109,200	49	80	13.8	66.2	6.08
51	7	83,100	35	55	9.6	45.4	5.45
62	6	70,400	48	18	9.0	9.0	1.28
120	19	17,700	117	2	0.9	1.1	0.65
Peaked proportional counter							
30 cm	1	6,400	347 sec.	1	0.18	0.82	1.28
34	1	6,400	293	2	0.31	1.70	2.66
41	1	6,400	307	3	0.26	2.74	4.29
44	1	6,400	235	3	0.35	2.65	4.15
51	1	6,400	186	5	0.40	4.60	7.20
62	1	6,400	257	1	0.37	0.63	0.98

All results quoted in this paper have been repeated at least three times on different days and with equipment dismantled in between runs.

The over-all experimental efficiency of the naphthalene detector was about 1 percent, calculated on the assumption that one gamma is associated with each proton associated with a residual nucleus in an excited state. This is in qualitative agreement with a 4 percent efficiency calculated on the basis of the Klein-Nishina formula and consideration of crystal volume.

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