Energy Levels in B^9 and Be^7 from the Reactions $C^{12}(p,\alpha)B^9$ and $B^{10}(p,\alpha)Be^7$†

J. B. REYNOLDS
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received February 10, 1955)

The energy levels of Be^7 and B^9 have been studied by observation of the alpha-particle spectra resulting from the reactions $B^{10}(p,\alpha)Be^7$ and $C^{12}(p,\alpha)B^9$. Alpha groups were observed corresponding to the ground state of B^9 and an excited state at 2.39±0.08 Mev. Groups were observed corresponding to Be^7 being left in the ground state and excited states of the following energies: 0.49±0.10 Mev, 4.72±0.08 Mev, 6.27±0.10 Mev, 7.21±0.10 Mev, 14.6±0.3 Mev.

I. INTRODUCTION

A STUDY of the energy levels of Be^7 and B^9 has been made by observation of the alpha-particle spectra resulting from the reactions $B^{10}(p,\alpha)Be^7$ and $C^{12}(p,\alpha)B^9$. The (p,α) reaction is often particularly suitable for such studies since in many cases in the light nuclei it is possible to reach final states which are accessible otherwise only by the (p,n) reaction. Although the photographic plate technique for neutron spectroscopy has been most successful, it is still more convenient to deal with reactions in which charged particles are involved if possible. The disadvantage of the (p,α) reaction for such studies is that with a few (notable) exceptions the Q's for such reactions in the light elements are quite highly negative. 18-Mev protons from the Princeton synchrocyclotron, however, are sufficiently energetic to produce the (p,α) reaction in any element.[1]

The alpha-particle spectrometer employed in the experiment is an obvious extension of the differential-range ion chamber of Rutherford *et al.*[2] and seems to have occurred to several workers[3] nearly simultaneously. Its main advantages are good resolution (for a range-measuring device), extreme stability, and lack of sensitivity to any particles except alpha and He^3 particles.

II. EXPERIMENTAL ARRANGEMENT

The scattering chamber in which the experiment was performed has been described by Likely and Franzen.[4] The collimated proton beam passed through the target foil and was collected in a Faraday cup. Total charge collected by the cup during a run was measured and used to normalize data with respect to the incident beam intensity. Alpha particles ejected from the target foil as a result of proton bombardment were received by the detecting apparatus which could be placed at any of 5 ports spaced 30° apart on the scattering chamber. A detailed view of the detection apparatus is shown in Fig. 1. The detector consisted of an air absorption chamber (of known length), in which the air pressure could be varied, followed by a series of three proportional counters. Pulses from counters No. 1 and No. 2 were in coincidence with one another and in anti-coincidence with those from counter No. 3; i.e., only those alphas were counted which traversed the absorption chamber and counters No. 1 and No. 2, but not No. 3. The relative counting rate *vs* pressure in the absorption chamber gives a differential range curve. A "monochromatic" α group (e.g., Po α's) entering the detector results in maximum counting rate when the absorption chamber pressure is such as to make the α's stop in a small region between chambers No. 2 and No. 3. The "line" obtained by plotting counting rate *vs* pressure for such a group is approximately Gaussian in shape and has a full width at half-maximum of ~100 kev.

Figure 2 shows the spectrum obtained from a ThC+C′ source. The peak width (full width at half-maximum) is ~100 kev for the 6.05-Mev group (this peak is actually due to two groups, which has the effect of broadening the peak) and ~140 kev for the 8.78-Mev group. The range of an α group whose energy is to be measured consists of two parts: (1) the known distance traveled in the absorption chamber in air of known pressure, temperature, and humidity and (2) that part of the particle range accounted for by the two mica windows and counters No. 1 and No. 2 which particles also have to traverse. Part (2) is a constant of the apparatus[5] and can be determined by measuring the range of an α group of known energy; e.g., assume the energy of the ThC group (Fig. 2) to be 6.05 Mev and hence to have a range[6] of 4.72 cm. Of this the absorption chamber accounts for (27.7 cm Hg/76.0 cm Hg)×6.87 cm×0.958=2.39 cm, leaving 2.33 cm as residual range accounted for by foils and counters. 27.7-cm Hg is the pressure at which the peak occurs, 6.87 cm is the ab-

† This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.

[1] The (p,d) reaction also can sometimes be used to reach the same final states as are accessible to (p,n) reactions, but for these also the Q is usually highly negative.

[2] Rutherford, Ward, and Wynn-Williams, Proc. Roy. Soc. (London) **A129**, 211 (1930).

[3] E.g., J. R. Holt and T. N. Marsham, Proc. Roy. Soc. (London) **A66**, 249 (1953); also used such a scheme in their study of (d,p) reactions.

[4] J. G. Likely and W. Franzen, Phys. Rev. **87**, 666 (1952).

[5] Constant except for the fact that the equivalent of the first mica window varies slightly with the incident α energy. This correction is usually negligible but can be easily made if necessary.

[6] The range-energy curves of H. A. Bethe, Revs. Modern Phys. **22**, 217 (1950), and H. A. Bethe, U. S. Atomic Energy Commission Report BNL-T-7 (unpublished), were used to compute α energies in this work.

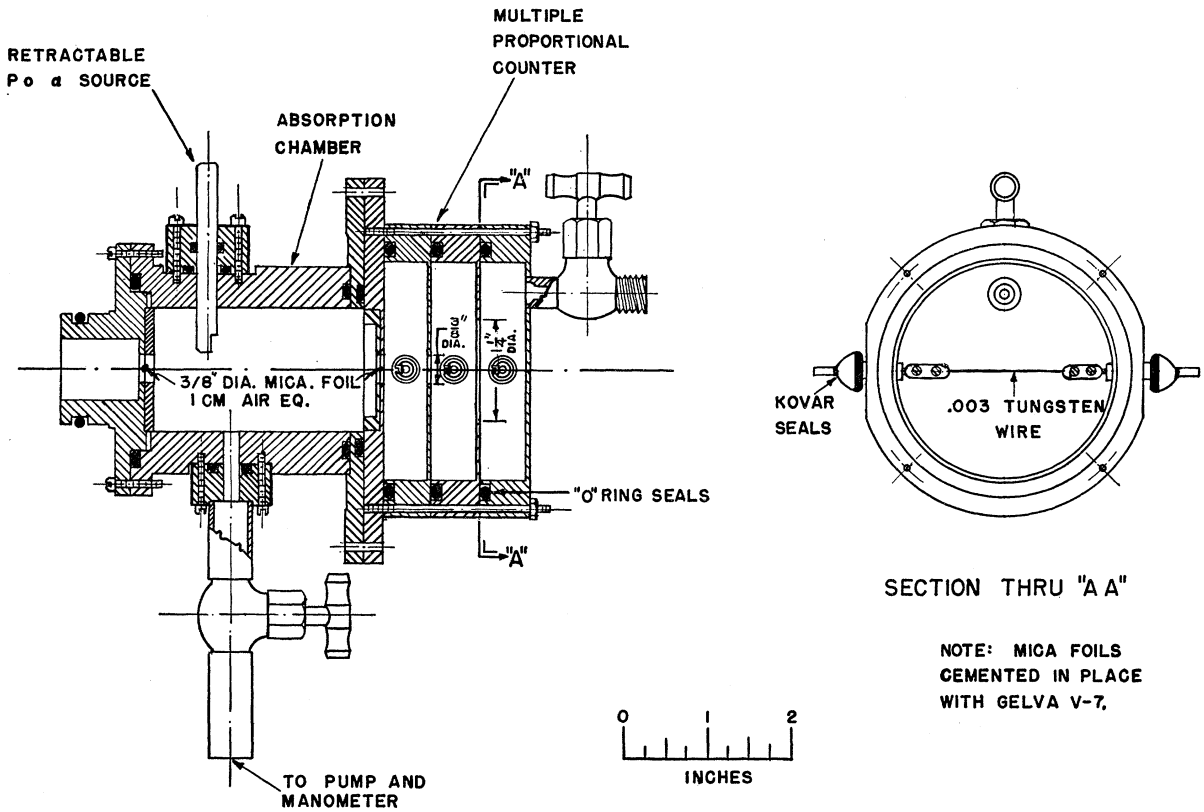

FIG. 1. The alpha-particle detector.

sorption chamber length, and 0.958 is a factor which converts from air at 24.5°C and 40 percent humidity (conditions under which the data were taken) to dry air at 15°C (the conditions for which Bethe's curves were drawn). Using this value for the residual stopping power, one obtains $R=2.33+6.87\times(71.4/76.0)\times 0.958=8.50$ cm as the range of the ThC′ α group. This corresponds to an α energy of 8.76 Mev as opposed to the accepted value of 8.78 Mev.

The constructional details of the counters are shown

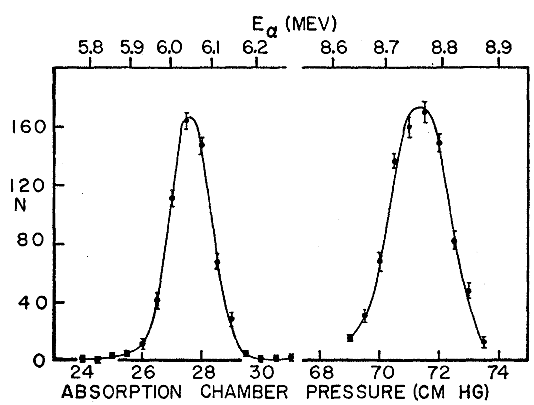

FIG. 2. Alpha-particle spectrum from a ThC+C′ source. N is the anticoincidence counting rate in arbitrary units.

in Fig. 1. The counters were filled to ~5 cm Hg with a 2 percent CO_2 in argon mixture. The circuitry was of standard design; Model 100 amplifiers set at about full gain were used for the α pulses which were then fed to integral discriminators, the outputs of which went to a conventional coincidence-anticoincidence circuit. The counters were operated with ~750 v on the central wires and gave ~50 v pulses from the model 100 amplifiers.

Variation of setting of the discriminator associated with counter No. 3 by as much as 20 percent did not appreciably shift the position of an α peak. Drifts in discriminator settings amounted to less than 1–2 percent over intervals long compared to the time required to take a spectrum. In practice, discriminator No. 2 was set to take pulses well above noise but well below the α pulse height due to ~5-Mev α's traversing counter No. 2. Discriminator No. 3 was set one-half as high as No. 2. Discriminator No. 1 was slightly below the maximum value it could have without reducing the height of an α peak. With this setting, the apparatus was insensitive to any particles except He^3 and He^4.

The energy of the incident proton beam was measured by determining the range in aluminum of protons scattered out of the incident beam at 90° by a thin polythene foil. The accurate proton range-energy results

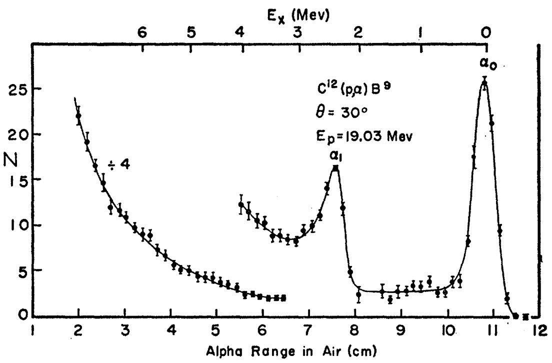

FIG. 3. Spectrum of alpha particles observed at 30° as a result of the bombardment of C^{12} with 19 Mev protons. N is the relative anticoincidence rate per unit of integrated beam current. E_x is the excitation energy of the final B^9 nucleus for the given alpha range.

of Bichsel and Mozley[7] were used in determining proton energies.

The line widths of α groups resulting from proton bombardment (Fig. 3 and following) are approximately 300 kev. Contributing factors to this are mainly cyclotron beam energy spread, target foil thickness, and finite angle subtended by the detector.

The absorption chamber was not operated at pressures greater than atmospheric. Alpha groups whose range was greater than the length of the absorption chamber were studied by inserting aluminum foils of appropriate thickness into the alpha-particle path. The spectra of Figs. 3–7 are plotted as a function of alpha range in air, the total amount of material traversed by the alphas having been converted to an equivalent amount of air at 76 cm Hg and 15°C. Absorption chamber pressure was read on a mercury manometer which was calibrated by use of a cathetometer.

III. RESULTS FOR $C^{12}(p,\alpha)B^9$

This reaction was observed using targets of 0.5 mg/cm² polythene foil and also with targets of (~0.2 mg/cm²) lampblack on a platinum backing.

Figures 3 and 4 are typical of the alpha spectra obtained from the reaction. Data were also taken at 60°

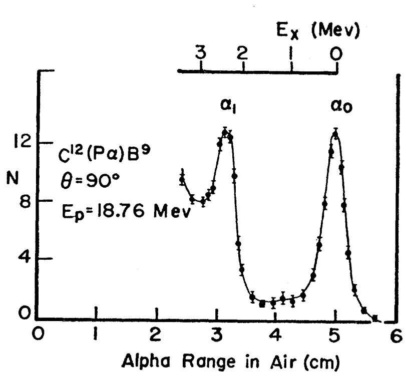

FIG. 4. $C^{12}(p,\alpha)B^9$ alpha spectrum at 60° in the laboratory system.

[7] H. Bichsel and R. F. Mozley, Phys. Rev. **94**, 764(A) (1954).

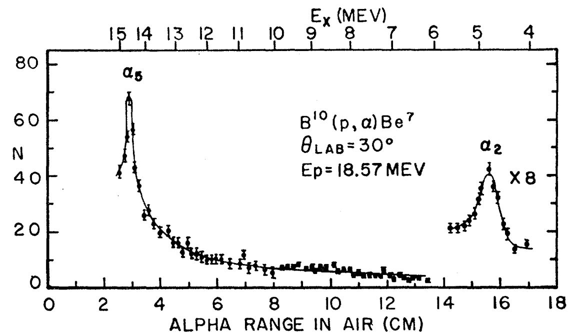

FIG. 5. $B^{10}(p,\alpha)Be^7$ alpha spectrum at 30° in the laboratory system.

and 120° with similar results. Alpha groups resulting in B^9 being left in its ground state (α_0) and an excited state (α_1) are seen at all angles. The ratio of the number of α's in α_1 to the number in α_0 appears to be about the same at 30°, 90°, and 120° and somewhat lower at 60°.

The group α_0 appears not to have a strong variation in differential cross section as a function of angle. The average differential cross section for α_0 for the five angles observed ($E_p \sim 18$ Mev) is 3 ± 1 mb/sterad.

Previous information on the B^9 ground state has been obtained by the $Be^9(p,n)$ and $B^{10}(\gamma,n)$ reactions.[8] Using the mass values assigned by Li *et al.*,[9] one obtains for the Q of the $C^{12}(p,\alpha)B^9$ (ground state) reaction a value of -7.56 ± 0.03 Mev. The average of two determinations at $0=60°$ and one at 90° in the present experiment gave $Q=-7.58\pm0.1$ Mev. The Q difference, ΔQ, for (p,α) reactions leading to the B^9 ground state and the observed excited state was found to be 2.39 ±0.08 Mev. This may be compared with the value obtained by Ajzenberg and Buechner[10] who, by studying neutron groups from the reaction $B^9(p,n)B^9$, obtain the value 2.37 ± 0.04 for ΔQ.

No evidence was found for other α-particle groups. The minimum α energy detected was ~3 Mev. At 30°

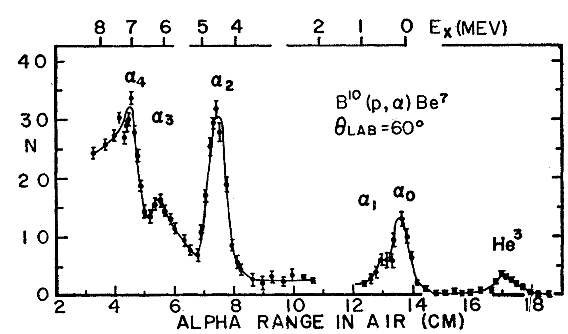

FIG. 6. $B^{10}(p,\alpha)Be^7$ alpha spectrum at 60°.

[8] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).
[9] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).
[10] F. Ajzenberg and W. W. Buechner, Phys. Rev. **91**, 674 (1953).

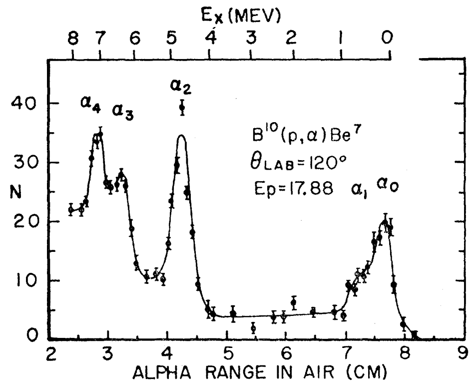

FIG. 7. $B^{10}(p,\alpha)Be^7$ alpha spectrum at 120°.

in the laboratory, this α energy would correspond to the B^9 nucleus being excited by about 7.9 Mev. The mirror image of the reported 6.8-Mev level[7] in Be^9 was not observed.

The two levels in B^9 discussed here have also been studied by the writer[11] by the reaction $B^{10}(p,d)B^9$. An analysis of the deuteron angular distributions indicates negative parity and spin $>\frac{1}{2}$ for both states.

The groups α_0 and α_1 are superimposed on a continuous alpha-particle background, the origin of which is not certain. Its most likely source is from the reaction $C^{12}(p,p')C^{12*}$ followed by $C^{12*}\rightarrow 3\alpha$. The Q for this reaction is -7.27 Mev as opposed to -7.56 Mev for the $C^{12}(p,\alpha)B^9$ (ground state) reaction. This is consistent with the fact that the alpha continuum appears to start somewhere under the α_0 peak. The high-energy part of this continuum cannot arise from B^9(ground)$\rightarrow p+2\alpha$ for which the Q is 281 kev or from Be^8(ground)$\rightarrow 2\alpha$ for which $Q=90$ kev. It is, of course, possible that the continuum comes from decay of excited states of either B^9 or Be^8.

IV. EXPERIMENTAL RESULTS: $B^{10}(p,\alpha)Be^7$

The B^{10} target consisted of a thin ($\sim$0.2 mg/cm^2) evaporated layer of enriched (97 percent) B^{10} on an 0.2-mil platinum backing. The evaporation was performed by Dr. W. Franzen to whom the writer is indebted for supplying the target.

Figures 5, 6, and 7 show the alpha spectra for θ (lab system) equal to 30°, 60°, and 120°, respectively. The group α_2 corresponds to a level in Be^7 previously seen only by Thomson[12] in a study of the reaction $Li^7(p,n)Be^7$. The groups α_3 and α_4 correspond to levels the existence of which was previously inferred from the observation of resonances in the reaction[7] $Li^6(p,He^4)He^3$. α_5 corresponds to a level not previously observed in Be^7.

[11] J. B. Reynolds and K. G. Standing, Phys. Rev. **95**, 639 (1954).

[12] D. M. Thomson, Phys. Rev. **88**, 954 (1952).

It should be noted that the reactions $B^{10}(p,He^3)Be^8$ and $B^{11}(p,\alpha)Be^8$ can also take place. The group α_5 is ten times as intense as any of the others and, since the B^{11} content of the foil is 3 percent, the cross section for a $B^{11}(p,\alpha)$ reaction giving this group would have to be 300 times as large as for the $B^{10}(p,\alpha)$ reactions leading to $\alpha_0-\alpha_4$. Since α_5 was only observed at one angle, the possibility of it being a He^3 group cannot be excluded. However, the only other He^3 group observed was that leaving Be^8 in the ground state and it was quite weak. It is shown in Fig. 6 labeled "He^3."

The identification of α_0, α_1, and α_2 as resulting from $B^{10}(p,\alpha)Be^7$ is certain and the identification of α_4 and α_5 as resulting from the same reaction is quite certain. Table I summarizes the energy level diagram of Be^7 as determined by the experiment.

The Q for the reaction giving α_0 has been accurately measured[7] and was taken to be 1.15 Mev. The excitation energies of Table I were calculated by assuming this value for the ground state Q; e.g., the Q for the reaction leading to α_0 was *measured* to be 1.07 Mev. An exception

TABLE I. Experimentally determined excitation energy in Be^7 for observed alpha-particle groups.

Group	Excitation energy, E_x (Mev)
0	0.08±0.10
1	0.49±0.10
2	4.72±0.08
3	6.27±0.10
4	7.21±0.10
5	14.6 ±0.3

to this was α_1, for which the excitation energy was calculated relative to the measured ground state Q.

In all cases except α_5, the experimental uncertainty in a single determination of E_x was estimated to be ±0.15 Mev. This represents uncertainty in determining beam energy, angle of observation, and range of alpha particles. To obtain the values shown in Table I, various independent determinations of E_x were averaged, the error being correspondingly reduced.

The group "He^3" of Fig. 6 was identified as such by comparing its experimental Q value of -0.60 Mev [assuming the reaction $B^{10}(p,He^3)Be^8$(ground)] with that of 0.53 Mev calculated from the mass values of Li *et al.*

The differential cross section for the $B^{10}(p,\alpha)$ reaction leading to α_3 is ($E_p\sim$18 Mev) 1.6±1 mb/sterad.

ACKNOWLEDGMENT

It is a pleasure to acknowledge the advice and encouragement of Dr. P. C. Gugelot during the course of the experiment.