equation,

$$\frac{d}{du}\left\{(1-u^2)\frac{dU_0}{du}\right\}+\left(\beta_0-\frac{1}{1-u^2}\right)U_0=0, \quad (11)$$

is appropriate for both U_0 and V_0.

Equation (10) has already been solved by Page and Adams[10] for small, real values of k. Their solution is also valid for a small, imaginary k, but unfortunately, the magnitudes of k for the specimens of this study were in the order of a few thousand. Another method,[11] however, has proved fruitful for the case of large but real values of k, and it offers possibilities which we hope to pursue soon. The fact that k may be complex due to magnetic hysteresis, is not expected to help matters.

The authors wish to thank Mr. R. V. Dyba for his capable assistance in the experimentation.

[10] L. Page and N. I. Adams, *Electrodynamics* (D. Van Nostrand Company, Inc., New York, 1940), Sec. 80.

[11] Stratton, Morse, Chu, and Hutner, *Elliptic Cylinder and Spheroidal Wave Functions* (John Wiley and Sons, Inc., New York, 1941).

PHYSICAL REVIEW VOLUME 84, NUMBER 5 DECEMBER 1, 1951

The Alpha-Particle Disintegration of Beryllium*

WILLIAM O. MCMINN, M. B. SAMPSON, AND V. K. RASMUSSEN
Physics Department, Indiana University, Bloomington, Indiana

(Received August 27, 1951)

The disintegration of Be^9 by 21.7-Mev alpha-particles has been studied with observations of the emitted particles made at various angles. Q-values of -6.92, -7.87, -8.57, and -10.74 Mev were found for the $Be^9(\alpha, p)B^{12}$ reaction giving levels in B^{12} at 0.95, 1.65, and 3.82 Mev. Two groups of deuterons from $Be^9(\alpha, d)B^{11}$ were found giving a level in B^{11} at 2.18 Mev. A third group, if assigned to this reaction would give a level in B^{11} at 0.65 Mev. The inelastic scattering $Be^9(\alpha, \alpha')Be^{9*}$ gives a level in Be^9 at 2.63 Mev.

I. INTRODUCTION

THE charged particle groups produced in the bombardment of thin beryllium films with 21.7-Mev alpha-particles have been investigated by determining their ranges in aluminum absorbers. A preliminary report has been made of some of the results of this investigation which were obtained with apparatus where the angle between the beam direction and the axis of the detecting system was 90°.[1] This report presents the results from observations of the particles emitted in various directions with respect to the direction of the incident particles. This permits the more certain assignment of a group to a definite reaction. The occurrence of the $Be^9(\alpha, d)B^{11}$ reaction is revealed, which was not suspected in our earlier work.

The results of proton scattering experiments by several investigators indicate the lowest excited state of Be^9 to be about 2.42 Mev.[2] Van Patter *et al.* assign two groups obtained by magnetic analysis of the products of the deuteron bombardment of boron to the $B^{11}(d, \alpha)Be^9$ reaction.[3] The Q-values obtained indicate an excited state of Be^9 at 2.422 ± 0.005 Mev.

No excited state below 2.1 Mev has been reported for B^{11}. This level has been obtained from the $B^{10}(d, p)B^{11}$ reaction as 2.138 ± 0.014 Mev by Van Patter *et al.*[4] Li and Whaling[5] have reported a tentative value of 2.107 ± 0.017 Mev from the $C^{13}(d, \alpha)B^{11}$ reaction.

Hudspeth and Swann[6] found a level in B^{12} at about 1 Mev from the deuteron bombardment of boron. Buechner *et al.*,[7] using the same reaction, got a value of 0.947 ± 0.005 Mev. Bockelman[8] found a resonance in the neutron cross section of boron for neutrons of 0.43 Mev which he attributed to the formation of B^{12}. This energy gives a level in B^{12} at 3.70 Mev.

II. EXPERIMENTAL METHOD

The charged particles produced in the alpha-particle bombardment of beryllium were detected with a proportional counter biased to count particles only near the end of their paths. Corrections were made for variations in the beam intensity by monitoring the current which was collected after passing through the thin target foil. A current integrator circuit was used for this purpose.[9]

The beam energy was determined by measuring the ranges of the alpha-particle groups elastically scattered

* Supported by the joint program of the ONR and AEC.

[1] McMinn, Sampson, and Bullock, Phys. Rev. **78**, 296 (1950).

[2] K. E. Davis and E. M. Hafner, Phys. Rev. **73**, 1473 (1948); E. H. Rhoderick, Proc. Roy. Soc. (London) **201**, 348 (1950); Browne, Williamson, Craig, and Donahue, Phys. Rev. **83**, 179 (1951).

[3] Van Patter, Sperduto, Huang, Strait, and Buechner, Phys. Rev. **81**, 233 (1951).

[4] Van Patter, Buechner, and Sperduto, Phys. Rev. **82**, 248 (1951).

[5] C. W. Li and W. Whaling, Phys. Rev. **82**, 122 (1951).

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

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

[8] C. K. Bockelman, Phys. Rev. **80**, 1011 (1950).

[9] H. T. Gittings, Rev. Sci. Instr. **20**, 325 (1949).

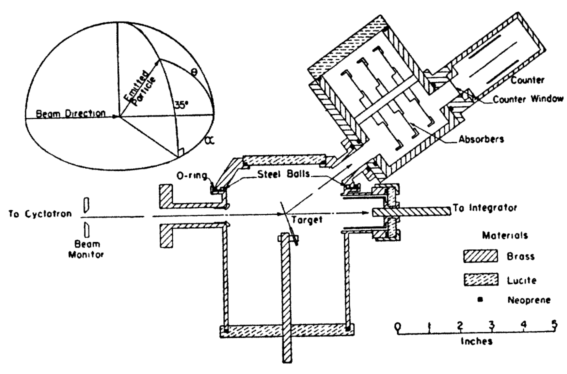

FIG. 1. Apparatus for observing reaction particles at various angles with respect to the cyclotron beam. $\cos\theta = \cos\alpha \cos 35°$.

from the beryllium and from known contaminating elements in the target.

The mean range in aluminum of a group of particles which gave a peak in the curve of number of particles detected *versus* aluminum absorption was obtained by adding a correction described below to the total aluminum absorption, including the counter window, at the peak A correction was made for the energy lost in the target.

The range-energy data of Livingston and Bethe[10,11] was used to construct mean range *versus* energy relations for protons, deuterons, and alpha-particles in aluminum, for use in this experiment. Conversion of mean ranges in aluminum to equivalent ranges in air was made with the factor 1.52 mg/cm^2 Al = 1 cm air, and with the correction curves in Livingston and Bethe.

The correction, r, to be added to the absorption at a peak of the yield curve in order to obtain the mean range of the group responsible for the peak was regarded as a constant for all ranges, for a given type of particle as discussed by Holloway and Moore.[12]

III. APPARATUS AND PROCEDURE

Figure 1 represents the apparatus consisting of a target chamber, system of aluminum absorbers, and a proportional counter which was used to observe the reaction particles emitted at various angles θ with respect to the direction of the cyclotron alpha-particle beam. The variable angle chamber is designed to allow θ to be varied between 35° and 145°. The figure shows the counter in its most forward (35°) position. The angle θ is changed by rotating the head of the target chamber which rests upon a ring of $\frac{1}{8}$-inch steel balls and carries the absorber chamber and counter. A greased rubber O-ring around the edge of the target chamber head seals the vacuum.

The aluminum absorbers which are interposed between the target and the counter are mounted in stacks over $\frac{9}{16}$-inch holes in three wheels. Each wheel carrying the absorbers is rotated and positioned by a pawl and ratchet wheel arrangement which is actuated by an electromagnet. The unit absorbers were cut from a roll of 1.1 mg/cm^2 aluminum foil. Each set of absorbers was weighed to 0.1 mg/cm^2.

The proportional counter was constructed with a 5-mil tungsten wire inside a copper cylinder 1 inch in diameter and $1\frac{1}{8}$ inches long. Counter windows of 1 mil and 0.7-mil aluminum foil were used. The counter was filled with argon and CO_2 in the ratio 12:1 to a total pressure of 13 cm Hg. The outer cylinder of the counter limited the directions of particles entering the counter to a maximum of 3.5° from the axis of the counter.

A model 100 pulse preamplifier was used, followed by three stages of amplification. The amplified pulses were discriminated against according to pulse height by a Schmidt circuit.

It was desirable to have target foils free of heavy contaminations to prevent the scattering of more energetic alpha-particles. The foils were prepared by evaporation in vacuum in an apparatus suggested by the method of H. Smith for making beryllium foils.[13] Granulated beryllium was heated in a graphite crucible with a solid bottom by electron bombardment from a heated tungsten filament below the crucible. 800 watts was sufficient to evaporate the beryllium. The beryllium was collected on 3-mil sheet steel, from which it was separated by flexing. The films used for targets weighed approximately 1 mg/cm^2. Tungsten evaporated from the filament was prevented from condensing on the collector by having the collector in the shadow of the crucible. Aluminum and lead were detected in the experiment from scattered alpha-particle groups, and their presence in the metal used for evaporation was determined by spectroscopic analysis. Carbon which was deposited on the targets during bombardment, and oxygen were other contaminants revealed by scattered alpha-particle groups.

The residual range, r, of alpha-particles in the counter was determined with thorium groups of known range. The residual range for protons was determined by an auxiliary experiment in which a gas target composed of water vapor and hydrogen was bombarded with alpha-particles and the ranges of both the scattered alpha-particles and of the recoil hydrogen nuclei were observed A counter having $r = 1.5$ mg/cm^2 Al for alpha-particles had a residual range of 1.6 mg/cm^2 Al for protons by this determination. A value of r for deuterons was approximated by adding 0.2 mg/cm^2 Al to r for protons. This is approximately the difference in the distances from the end of the range to the peaks of the specific ionization curves for the two hydrogen isotopes.

The investigation of the products of the alpha-

[10] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 261 (1937).
[11] H. A. Bethe, Revs. Modern Phys. **22**, 213 (1950).
[12] M. G. Holloway and B. L. Moore, Phys. Rev. **58**, 851 (1940).
[13] H. Smith, J. Sci. Instr. **26**, 378 (1949).

particle bombardment of beryllium was begun by making runs over the entire range of emitted particles at a given angle, and repeating this for several angles. The alpha-particle groups scattered from beryllium and from known contaminating elements in the targets were used to calculate the beam energy at each angle of observation. The mean beam energy calculated for each angle was used in the calculations of Q-values corresponding to the observed particle groups under assumptions of different reactions. Later observations were made of the positions of peaks of particular interest over as great a range of angles as was possible. During these observations frequent checks were made on the beam energy by observations of the position of the beryllium scattered alpha-particle peak.

IV. RESULTS

Figure 2 shows absorption curves which were obtained at the least angle θ (35°) obtainable with the apparatus. The shorter range curve is an absorption curve for alpha-particles. This was obtained with a counter voltage of -410 volts. The curve for longer ranges (beyond the range of the scattered alpha-particles) was obtained with the same discriminator bias setting and with the counter at -620 volts which permitted counting of protons and deuterons. Figure 2 is typical of the absorption curves obtained. Proton and deuteron peaks were not located where they occurred over a large background of alpha-particles.

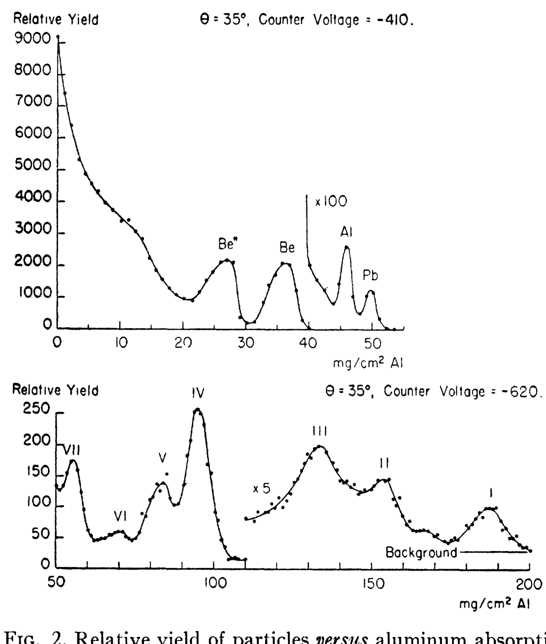

FIG. 2. Relative yield of particles *versus* aluminum absorption, obtained in the alpha-particle bombardment of a thin beryllium film. $E_\alpha = 21.84$ Mev. $\theta = 35°$. The mean range in aluminum of a group is obtained by adding to the absorption at the peak of the curve the weight of the counter window (6.2 mg/cm² Al) and r. The continuous distribution of α-particles at shorter ranges may be attributed to the breakup of C^{12*} or to $Be^9(\alpha, \alpha'n)Be^8$.

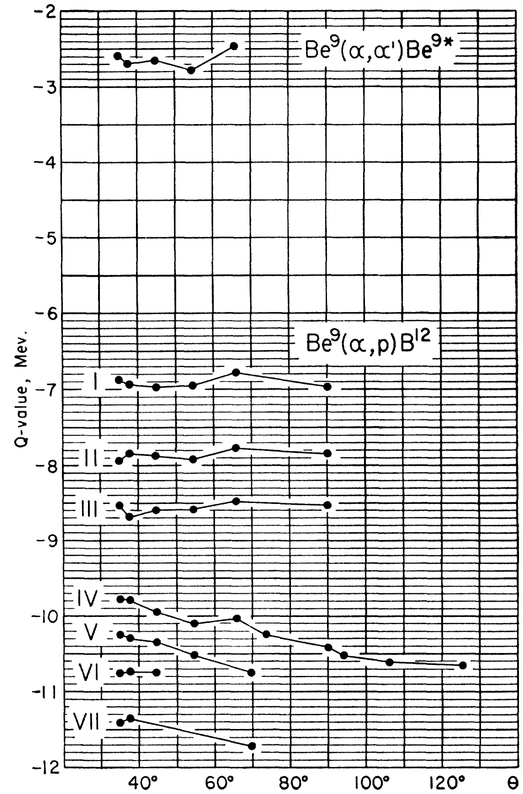

FIG. 3. Q-values for inelastic scattering of alpha-particles from beryllium, and for the reaction $Be^9(\alpha, p)B^{12}$.

The alpha-particle absorption curves for different angles, like Fig. 2 for $\theta = 35°$, represented two strong groups of alpha-particles of about equal intensity. These groups were elastically and inelastically scattered from beryllium. Peaks about 1/100th as high as the beryllium peaks rose at greater ranges than the beryllium elastic scattering peak. These small peaks were due to scattering by contaminating elements. The Q-values calculated for inelastic scattering from beryllium are plotted at the top of Fig. 3.

Seven peaks due to proton and deuteron groups appear in the absorption curve shown in Fig. 2. These seven groups, which are given roman numerals in Fig. 2, were observed at several angles. The results of the observations are presented in Fig. 3 where Q-values calculated under the assumption that the groups are proton groups from the $Be^9(\alpha, p)B^{12}$ reaction are plotted against angle. The horizontal trend of the points for Groups I, II, and III in Fig. 3 suggest that the correct reaction has been assumed. This is supported in the case of Group I by the reasonable agreement between the mean of all the experimentally determined Q-values for the group (-6.92 Mev) and the value -7.01 Mev calculated from the mass tables of Mattauch and Flammersfeld.[14] The experimental Q-values for Groups I

[14] J. Mattauch and A. Flammersfeld, *Isotopic Report, Special Issue*, Z. Naturforsch (1949).

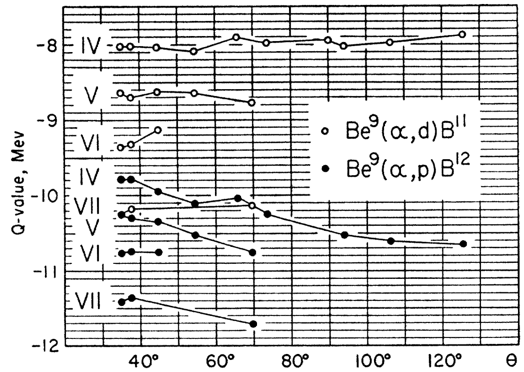

FIG. 4. Q-values under the two assumptions of the $Be^9(\alpha, p)B^{12}$ reaction and the $Be^9(\alpha, d)B^{11}$ reaction.

and II under the assumption of the $Be^9(\alpha, p)B^{12}$ reaction indicate an excitation of B^{12} of 0.95 Mev. This value agrees with the results of others. Group III corresponds to an excited state of B^{12} of 1.65 Mev under this assumption.

Figure 4 compares the Q-values calculated for Groups IV, V, VI, and VII under the two assumptions of $Be^9(\alpha, p)B^{12}$ and $Be^9(\alpha, d)B^{11}$ reactions. The points for these groups in Fig. 3 are replotted in Fig. 4. Comparison of the trends of the Q-values with angle favors the assignment of Groups IV, V, and VII to the $Be^9(\alpha, d)B^{11}$ reaction, and the assignment of Group VI to the $Be^9(\alpha, p)B^{12}$ reaction.

The assignment of Group IV to the (α, d) reaction is supported by the reasonable agreement between the mean of all our Q-values for this group (-8.01 Mev) and the value -8.07 Mev calculated from the mass table. The experimental Q-values for Groups IV and VII assuming the $Be^9(\alpha, d)B^{11}$ reaction indicate an excited state of B^{11} at 2.18 Mev. This excitation is in reasonable agreement with the results of other. The assignment of Group V to the $Be^9(\alpha, d)B^{11}$ reaction is favored by the results of this experiment which are represented in Fig. 4. The assignment is made tentatively since the indicated excited state of B^{11} at 0.65 Mev has not been found in the experiments of others.

Group VI is assigned from the incomplete data represented in Fig. 4 to the $Be^9(\alpha, p)B^{12}$ reaction. This assignment indicates an excited state of B^{12} at 3.82 Mev which may be compared with the value 3.70 Mev indicated by Bockelman's work.

The assignment of the reaction particle groups to (α, p) and (α, d) reactions involving contaminating elements in the targets was investigated and found to be much less likely than the above assignments.

Table I gives the reaction assignments which are proposed for the groups observed in this investigation, the relative intensities of the groups, and the calculated Q-values and excited states.

TABLE I. Reaction assignments, Q-values, and excited states.

Reaction	Group	Relative intensity*	Q-value Mev	Excited state Mev
$Be^9(\alpha, \alpha')Be^{9*}$	α'	1	-2.63 ± 0.15	2.63 ± 0.15
$Be^9(\alpha, d)B^{11}$	IV	20	-8.01 ± 0.05	0
	V	12	-8.66 ± 0.10	(0.65 ± 0.10)
	VII	10	-10.19 ± 0.10	2.18 ± 0.10
$Be^9(\alpha, p)B^{12}$	I	1.0	-6.92 ± 0.05	0
	II	1.2	-7.87 ± 0.05	0.95 ± 0.05
	III	2.0	-8.57 ± 0.05	1.65 ± 0.05
	VI	4.5	-10.74 ± 0.10	3.82 ± 0.10

* The intensity of the inelastically scattered alpha-particle group is compared with the intensity of the elastically scattered alpha-particle group. The intensities of the proton and deuteron groups are compared with the intensity of Group I. Averages are given because the relative intensities did not vary with angle by more than the experimental uncertainty. No determination of the angular dependence of the intensity of a given group was made.