tion in heavier nuclei. Preliminary results for the case of Ca^{40} show a striking resemblance to the data of Fig. 9, after adjustment of abscissas on the basis of Eq. (5). It is found, in agreement with other observations,[20,21] that the polarization minimum corresponding to the dip in C^{12} at 27.5° is not completely washed out in the low energy channels, implying that inelastic scattering is competing less strongly in the heavier nucleus. This may simply be a result of the fact that the diffraction pattern is moving into smaller angles, together with the possibility that inelastic scattering is much less dependent on nuclear radius. In any event, we suspect that previously reported strong variations of the large-angle behavior with nuclear mass can be explained by differences in inelastic contributions.

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Energy Levels of Be^9†

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Magnetic analysis of the alpha-particle groups from the deuteron bombardment of boron and of the proton groups from the proton bombardment of beryllium confirms previous work indicating the existence of levels in Be^9 at 2.43 and 3.04 Mev. The energy of the edge of a broad distribution at 1.664-Mev excitation is taken to indicate that it arises from a three-body reaction; the shape of the edge indicates the influence of the Be^8—n interaction.

I. INTRODUCTION

The energy levels of the Be^9 nucleus have been the subject of several recent studies.[1–3] These experiments have been concerned with verifying the results of Moak *et al.*[4] and Almqvist *et al.*,[5] which showed that the $Li^7(He^3,p)Be^9$ and the $B^{10}(t,\alpha)Be^9$ reactions displayed a characteristic edge to the proton and alpha distributions which was interpreted as evidence for a state at 1.8 Mev in Be^9. In addition, the well-known level at 2.428 Mev[6–8] as well as a broad group attributed to a 3.1-Mev state were observed. Lee and Inglis[1] saw alpha groups from the deuteron bombardment of boron which they assigned to Be^9 levels at 1.75 Mev, 2.43 Mev, and 3.02 Mev. However, Gosset *et al.*[2] in a study of the inelastic protons from a Be^9 target carefully measured the edge of a proton distribution, which corresponded to an excitation of 1.675±0.002 Mev. They suggested that these protons, rather than signifying a 1.8-Mev level in Be^9, might be associated with the (p,pn) reaction, since the edge energy corresponded closely to the (γ,n) threshold in Be^9 measured as 1.666±0.002 Mev by the Wisconsin group[9] and as 1.662±0.003 Mev at Notre Dame.[10] The small difference between the edge and the threshold was attributed to a barrier effect. Finally, Rasmussen *et al.*,[3] studying the inelastic scattering of deuterons and alphas from Be^9, again saw a broad distribution with a maximum in the neighborhood of 1.74-Mev excitation, the sharp state at 2.43 Mev, and the broad state at 3.1 Mev. By analyzing the shape of the distribution, these authors attempted to answer the question of whether the 1.74-Mev maximum is a state or the edge of a continuum from the three-body breakup. The present work was undertaken concurrently with the work described in references 2 and 3. It was felt that the use of the broad-range spectrograph,[11] which permits the simultaneous recording of a wide energy range of reaction products,

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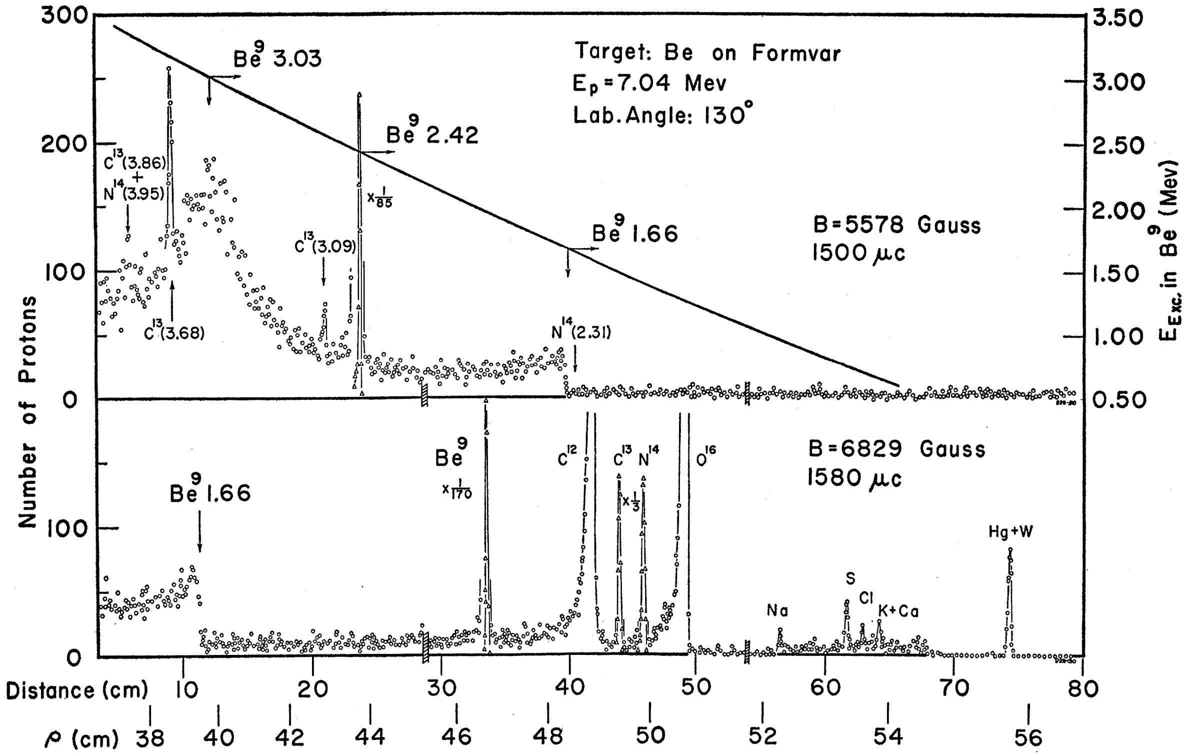

FIG. 1. Spectrum of protons inelastically scattered from a Be target. The number of proton tracks in a ½-mm strip across the exposed zone of the plate is plotted against distance along the plate. The solid line in the upper portion of the figure graphs excitation energy in Be^9 against distance along the plate.

might be profitably used to obtain with reasonable accuracy the shape of the distributions involved.

II. EXPERIMENTAL METHODS AND RESULTS

A. $Be^9(p,p)Be^9$

For a study of the beryllium levels via inelastic proton scattering, thin targets of beryllium evaporated onto Formvar were used. Protons were accelerated in the MIT-ONR electrostatic generator. The charged particles emitted were analyzed in momentum by the broad-range spectrograph and recorded in three NTA 50-micron emulsions 10 inches long placed end to end along its focal surface. The magnetic field was measured by a resonance fluxmeter. A previous publication[12] describes the experimental arrangement in greater detail.

Figure 1 shows the proton count for an incident energy of 7.04 Mev with the spectrograph set at 130 degrees. The number of tracks, of length expected for protons, per ½-mm strip across the exposed zone is plotted as a function of a distance scale assigned to the plates by means of index marks referred to the plate-holder. The calibration of distance *versus* radius of curvature was accomplished by means of polonium alpha particles as well as by judicious use of elastic peaks. The lower portion of the figure displays a set of peaks caused by elastic scattering from the beryllium film, from the carbon and oxygen in the supporting Formvar layer, and from a variety of contaminants either in the beryllium or acquired during the process of target making. The beryllium peak was too intense to be counted at this exposure; the curve shown is the result of a 150-microcoulomb exposure obtained at the same magnet settings immediately following the primary exposure.

At a distance of $d=11$ cm, the edge of a continuous distribution of protons is seen, superimposed on a background attributed to slit-edge scattering. In a following exposure, the bombarding energy was held constant and the magnetic field changed so as to center the expected 3.1-Mev peak on the third photographic plate, where the solid angle of the spectrograph is largest. The results of this exposure are shown on the top half of Fig. 1. The edge is again seen clearly, this time at $d=40$ cm. The point at which the edge intersects the background can be located with good accuracy in both of these exposures. By using an input energy calculated from the Be^9 elastic peak, the relativistic Q value is computed to be -1.664 ± 0.005 Mev, in excellent agreement with the (γ,n) threshold.[9,10]

In order to identify the peaks, another exposure was made at 7.01 Mev and 40 degrees. At this forward angle,

[12] Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. 91, 1502 (1953).

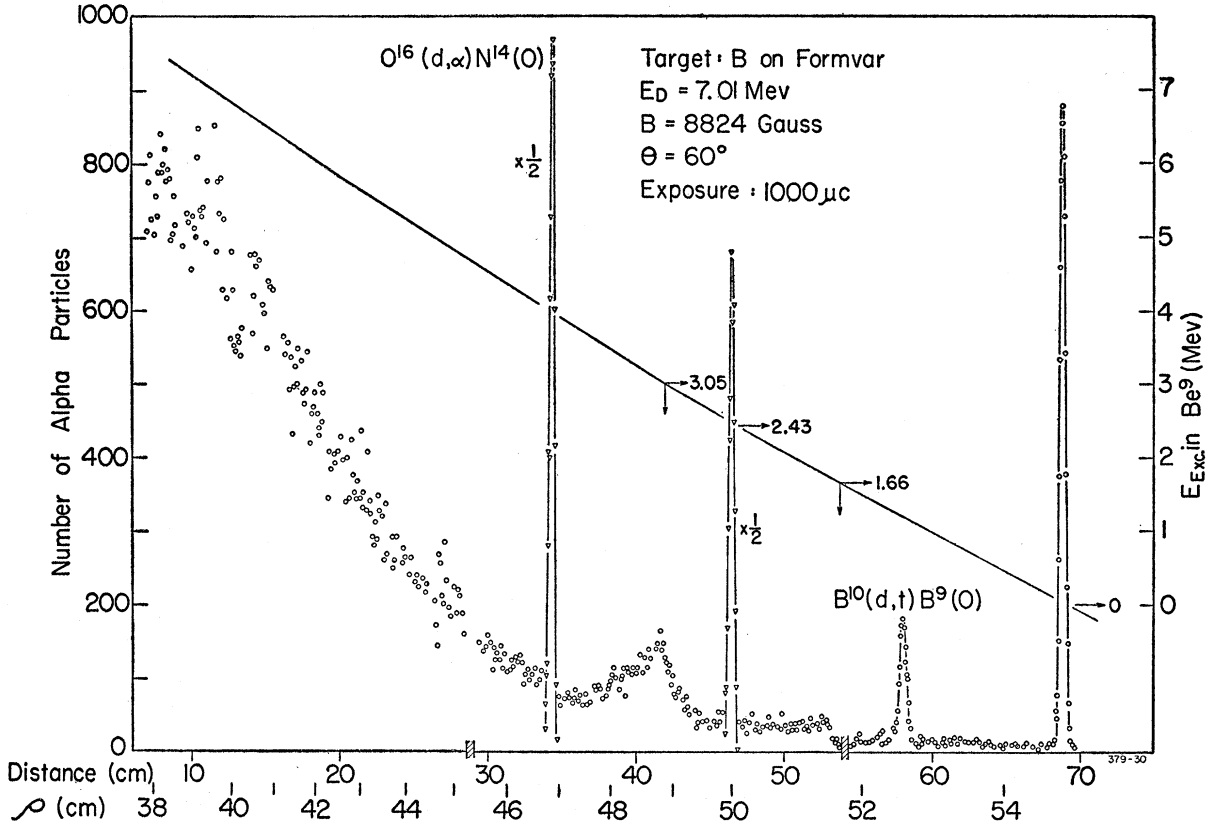

FIG. 2. Spectrum of alpha particles plus tritons emitted from a boron target under deuteron bombardment. The number of tracks of length expected for alpha particles in a ½-mm strip across the exposed zone of the plate is plotted against distance along the plate. The solid line graphs excitation energy in Be^9 against distance along the plate.

the instrumental scattering was worse so that the edge could not be located with as good an accuracy. However, it and the other peaks were observed, and the following identifications justified. The peak at $d=28$ cm in the upper part of Fig. 1 is the well-known Be^9 state, the excitation energy of which is here measured as 2.434 ±0.005 Mev, in agreement with the work of reference 7. The peak of the broad group ($d=13$ cm) corresponds to an excitation of 3.03 ± 0.03 Mev in Be^9; the uncertainty here arises from the inability to locate the peak to any better accuracy. The other two peaks at $d=21$ and $d=9$ cm arise from protons inelastically scattered, exciting the 3.09- and 3.68-Mev levels in C^{13}. In addition, a few high points are seen at $d=6$ cm, the location expected for a peak from the 3.86-Mev C^{13} level. The plate taken at 40 degrees did not cover this region.

While there is no doubt of the existence of the broad peak, its width cannot be stated with accuracy because the momentum analysis does not extend to low enough momenta to locate the level of the continuum on which the peak is superimposed. This uncertainty makes it impossible to measure the true shape of the peak from the present data. Nevertheless, these results show that the width, ΔQ, of the level as seen under these circumstances cannot be less than 280 kev. On the 40-degree exposure, the background from slit-edge scattering was sufficiently high that no better measurement of the width was afforded.

The strong elastic peak at mass 14 raises the question of whether any inelastic scattering from nitrogen might be observed. The positions expected for peaks corresponding to the 2.31- and 3.95-Mev levels are indicated by arrows in Fig. 1. The computed position for the 2.31-Mev state is a distance of 6.5 mm to the right of, that is, 22 kev higher than, the observed edge; this separation represents over twice the error expected in the computed location. No evidence for inelastic scattering to this level is observed.

No inelastic peaks are expected from C^{12} or O^{16} in the region studied. The elastic peaks for all the contaminants other than carbon, nitrogen, and oxygen are sufficiently small so that no measurable inelastic yield is expected from them.

B. $B^{11}(d,\alpha)Be^9$

In order to study the beryllium levels further, magnetic analyses of the alpha particles emitted from a thin film of boron under deuteron bombardment were obtained. The result of a bombardment at a deuteron energy of 7.01 Mev is shown in Fig. 2.

By means of exposures at bombarding energies between 5.0 and 7.3 Mev at angles of 60 and 90 degrees to the incident beam, it was possible to ascertain that the peak at $d=35$ cm was caused by alpha particles from the $O^{16}(d,\alpha)N^{14}$ reaction ground-state group. The peak at $d=58$ cm shifted in a manner consistent only with the $B^{10}(d,t)$ reaction leading to the ground state of B^9. Since B^{10} is 19% abundant in natural boron, the group is not unexpected. The track length expected for tritons at this momentum is quite close to that expected for alpha particles, and no distinction was made in counting them. In the interest of increasing the intensity, this experiment was performed under relatively low-resolution conditions; furthermore, observations were taken with the target in such a position that the emitted alphas passed through the target, tending to displace the positions of the peaks by an amount corresponding to the target thickness. Because of these factors, the energy measurements in this experiment were not of the highest precision. The ground-state Q value of the $B^{10}(d,t)B^9$ reaction is measured as -2.187 ± 0.010 Mev. A calculation using the masses of Li *et al.*[13] predicts a value of -2.176 Mev.

The peaks at $d=69$ cm and $d=46$ cm and the broad group at $d=41$ cm all shift with energy and angle as expected for groups associated with states in Be^9. The Q value measured on two observations of the ground state is 8.015 ± 0.010 Mev. Four measurements of the separation between the ground state and the sharp excited state yield an excitation energy of 2.424 ±0.005 Mev in Be^9, in good agreement with the results of Sec. A, as well as those of reference 7. The peak of the broad group is located at 3.05 ± 0.03 Mev excitation, the uncertainty arising from the difficulty of locating the peak to any better accuracy. In Fig. 2, this peak shows a low-energy side somewhat more ragged than expected from the statistical accuracy alone. As a result, the nominal 325-kev difference in the alpha-particle energies at the half-maximum points must be assigned a large error of ±90 kev. Thus, the width ΔQ of the state derived from this measurement is 425 ± 120 kev. However, another observation at 6.5 Mev and 90 degrees yields $\Delta Q=250\pm50$ kev. The reason for this discrepancy is not known. It might of course be caused by the presence of an unexpected contaminant peak at about 39 cm distance in Fig. 2.

A continuous background of alpha particles might be expected from the $B^{10}(d,\alpha)Be^8$ reaction. The Be^9 ground-state group is at a position corresponding to about 9-Mev excitation in Be^8. Little is known of the alpha spectrum from B^{10} in this region; it may cause the background below the Be^9 ground-state peak, as well as the large rise below the $O^{16}(d,\alpha)N^{14}$ peak. However, the step in the yield observed at $d=53$ cm on Fig. 2 shifts, when bombarding energy and angle are varied, in such a way that it must be assigned to Be^9. Unfortunately, the exposures taken inadvertently place this edge near a junction of the 10-inch plates, which were obscured for a few millimeters near their edges. Therefore, measurements of this edge were obtained by extrapolating the slope, in itself fairly poorly defined, until it intersected a straight line drawn through the background. In this manner, an excitation of 1.669 ± 0.010 Mev was obtained, in agreement with results of Sec. A and the (γ,n) threshold of references 9 and 10, but with lower accuracy.

[13] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).

III. DISCUSSION

The present results confirm the conclusion of Lee and Inglis[1] that a state at 3.04 Mev in Be^9 is produced in the $B^{11}(d,\alpha)$ reaction. As these authors have suggested, the previous high-resolution work of Van Patter *et al.*,[6] using a 180-degree spectrograph which viewed only a small portion of the spectrum at any one exposure, appears to have missed this broad state of relatively low yield at the peak. In Fig. 2, the peak yield of the 2.43-Mev level is 10 times that of the 3.04-Mev level. This state is also observed with inelastic protons from Be^9, although it was not reported in earlier work.[8] However, it appears possible that peaks g and j of Fig. 1 in reference 8, interpreted there as deuterons from the $Be^9(p,d)Be^8$ reaction, may have actually been protons.[14] If this is the situation, these two peaks correspond to excitations of 1.8 and 3.1 Mev in Be^9. Since recent experiments do not support the existence of levels in Be^8 at 4.0 and 5.1 Mev, the reinterpretation seems reasonable. From the present observations, the width of the 3.04-Mev state is at least 280 kev.

The edge of the continuous distribution lies at the energy that would be expected for the threshold of the three-body reaction. It therefore appears that it may be incorrect to interpret the rise as evidence for a level. Perhaps the question is best answered by attempting to compute the expected shape by the method outlined by Watson[15] and applied to this particular problem by Rasmussen *et al.*[3]

These authors have pointed out that, for given assumptions regarding the interaction between Be^8 and the neutron, one can compute the relative number of, say, alpha particles per unit momentum interval dN/dp, in terms of the alpha-particle momentum p and the momentum of the neutron relative to the Be^8 nucleus q. For the $B^{11}(d,\alpha n)Be^8$ reaction, conservation of energy and momentum give

$$\frac{q^2}{2\mu}=W-\frac{(M+M_8+M_n)p^2}{(M_8+M_n)2M}, \qquad (1)$$

where M_n = neutron mass, M_8 = mass of Be^8,

$$\mu=M_nM_8/(M_n+M_8),$$

[14] R. Bender (private communication).

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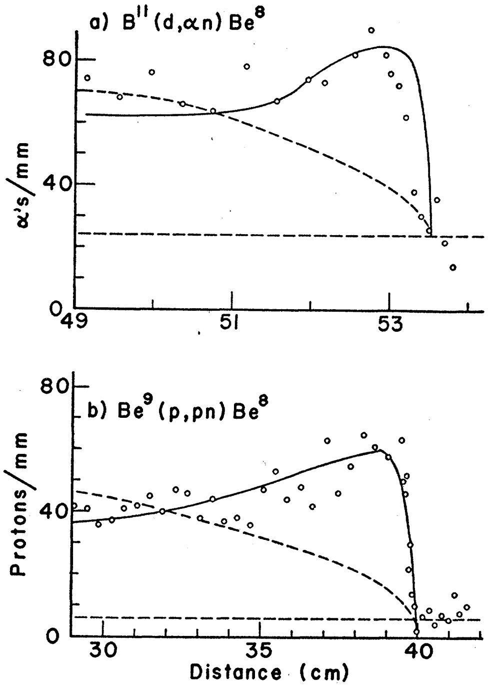

FIG. 3. Expected distributions from three-particle reactions. The circles are data replotted from Figs. 1 and 2 in terms of particles per 1-mm strip across the exposed zone of photographic plate *versus* distance along the plate. The horizontal dashed lines indicate the level of the instrumental background. The dashed curves are the distributions expected for no interaction between the neutron and Be^8. The solid curves graph the distributions in the case of an s-wave potential scattering of the neutron by Be^8, of strength measured by a scattering length of 2×10^{-12} cm.

M = alpha-particle mass, and W = energy available for breakup of the compound nucleus.

In Fig. 3(a), a portion of the alpha-particle data shown in Fig. 2 has been replotted as the number of alphas per 1-mm strip *versus* distance. In Fig. 3(b), a similar treatment has been applied to part of the proton data from the upper part of Fig. 1. For this reaction, q is also given by Eq. (1) if the proton mass and momentum are substituted for M and p, respectively.

The alpha-particle (or proton) momentum distribution in the case of no interaction between alpha (or proton), neutron, and Be^8 is given by $dN/dp \sim p^2q$. This expression, transformed into the laboratory system and written in terms of the number of particles per unit distance on the photographic plate, yields the dashed curves in Fig. 3. (In the figure, the data have not been corrected for the solid-angle transformation from center-of-mass to laboratory system nor for the variation in solid angle with the position on the plate. This variation is essentially linear, the solid angle at 29 cm being approximately 8% greater than that at 40 cm.) This expression clearly does not fit either set of data.

If one assumes that there is no interaction between the alpha particle (or proton) and the other particles, but an s-wave potential scattering of the neutron by Be^8 characterized by a scattering length $a=\hbar/\alpha$, the distribution is expected to follow $dN/dp \sim p^2q/(\alpha^2+q^2)$. This expression is represented by the solid curves in Fig. 3, drawn for $a=2\times10^{-12}$ cm. This value of a gives a reasonable fit for the (p,pn) data, but is somewhat too large for the $(d,\alpha n)$ data. Furthermore, it is larger than the value of 1.3×10^{-12} cm which fits the (d,dn) data,[3] and which represents a reasonable size for the scattering length of Be^8. This suggests that the simple interaction chosen is insufficient. More complicated interactions are possible, but it seems unprofitable to introduce more parameters until more data pertinent to this problem are available. Therefore, in agreement with the conclusions of the authors of references 2 and 3, it is felt that, although a 1.8-Mev state in Be^9 is unlikely, it cannot be ruled out until a detailed fit of all the data can be obtained.

Recently, Kurath has published the result of intermediate coupling calculations in the $1p$ shell.[16] If, as seems most likely, there is no state of Be^9 at 1.8 Mev, then the Be^9 level positions are well fitted with a choice of the coupling parameter similar to that which applies to nearby nuclei. This conclusion would be strengthened if the 3.04-Mev state were assigned a spin of $\frac{1}{2}$ and negative parity. If this level decays primarily by neutron emission to the ground state of Be^8, its reduced width can be computed simply[17] for various values of the orbital angular momentum of the emitted neutron, l. The Wigner sum rule[18] places an upper limit to the reduced width. For an interaction radius of 3×10^{-13} cm, these considerations limit l to 1, and thereby the spin of the 3.04-Mev level to $\leq\frac{3}{2}$. However, since the level width of 280 kev used in this calculation is only a lower limit, a better measurement might limit the l to 0 and the spin and parity to $\frac{1}{2}^+$.

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