Differential Cross Sections of the $Be^9(Li^6,\alpha)B^{11}$ Reaction*†

J. J. LEIGH AND J. M. BLAIR
School of Physics, University of Minnesota, Minneapolis, Minnesota
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The differential cross sections of the $Be^9(Li^6,\alpha)B^{11}$ reaction have been measured as a function of energy and angle. The α particles leaving the B^{11} in the ground state, α_0, in the first excited state, α_1, and in the second and third excited states, $\alpha_2+\alpha_3$, were observed at 10° intervals from 10° to 160° (lab system) at Li^6 energies of 3.00, 3.25, and 3.50 Mev, and at 20°, 60°, 90°, 120°, and 160° (c.m. system) at Li^6 energies of 2.00, 2.50, 3.75, and 4.00 Mev. The angular distributions of the α_0 and α_1 groups are asymmetric about 90° c.m. Relative maxima occur at both large and small angles for each of the α-particle groups, with the yields at large angles being comparable to those at small angles. In all cases the angular distribution varies slowly with bombarding energy and the yields at each angle increase monotonically with increasing energy. At 3.50 Mev the total cross sections are 0.97 ± 0.38 mb for α_0 and 0.65 ± 0.26 mb for α_1. The experimental results suggest that the reactions proceed mainly by direct-interaction mechanisms. The similarity of the angular distributions of the $Be^9(Li^6,\alpha)B^{11}$ and the $Be^9(He^3,p)B^{11}$ reactions is pointed out.

I. INTRODUCTION

INCREASING sophistication in the art of nuclear experimentation, both in the means for inducing reactions and in the techniques for detecting the results, has disclosed a vast and hopefully fertile field of investigation: the study of nuclear reactions resulting from the bombardment of light nuclei with the so-called complex nuclei ($A>5$). At present the only reactions of this kind which have been studied below 4 Mev have been induced by bombardments with Li^6 and Li^7 nuclei.[1,2]

Because of large Coulomb barriers the classical distance of closest approach in such low-energy bombardments may be several nuclear diameters. Under these circumstances compound nucleus formation should be severely inhibited. Nonnegligible cross sections are observed nevertheless, so other interaction mechanisms must be considered. Direct-interaction processes[3] such as stripping,[4] pickup,[5] and heavy-particle stripping[6] and nucleon transfer processes[7,8] may contribute significantly. Coulomb effects[9] may be large. An understanding of the relative importance of the various processes is clearly desirable.

Theoretical understanding of the mechanisms by which reactions induced by low-energy complex nuclei proceed is presently limited by the paucity of experimental data. In only a few cases have angular distributions for such reactions been obtained, and only one of these[1] has been subjected to theoretical calculations on a possible reaction mechanism.[8] With this in mind, investigations have begun at this laboratory which we hope will provide both data and stimulation for a fuller understanding of nuclear interaction mechanisms.

The present report provides differential cross sections and excitation functions for the $Be^9(Li^6,\alpha)B^{11}$ reactions going to the ground and the first excited states of B^{11} and to the second and third excited states combined. The reaction leading to the ground state has a $Q=14.35$ Mev. Bombarding energies from 2.00 to 4.00 Mev and laboratory scattering angles from 10° to 160° were studied.

II. EQUIPMENT

The Minnesota 4-Mv electrostatic generator accelerates beams of either Li^{6+} or Li^{7+} ions produced by separate, remotely selected filaments in a multifilament source. After acceleration the beam passes through a differentially pumped gas stripping cell containing argon at a pressure of $\approx 8\mu$ Hg at the midpoint of the cell. The stripping gas increases the ionization of some of the incident singly ionized lithium atoms. Following the stripping the beam is analyzed by a 90° magnet of 16-inch radius to select the component of the beam having the desired mass and ionization. The resulting beam is focused by two strong-focusing electrostatic lenses.

In the experiment reported here a Li^{6++} beam enters

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† This work was supported in part by the joint program of the U. S. Atomic Energy Commission and the Office of Naval Research.
[1] E. Norbeck, J. M. Blair, L. Pinsonneault, and R. J. Gerbracht, Phys. Rev. **116**, 1560 (1959), and references therein.
[2] Reports by E. Norbeck, by G. C. Morrison and M. N. Huberman, and by S. M. Shafroth, in Proceedings of the Second Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee, May 2–4, 1960 (unpublished).
[3] S. T. Butler, N. Austern, and C. Pearson, Phys. Rev. **112**, 1227 (1958). T. Fulton and G. Owen, Phys. Rev. **108**, 789 (1957).
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[5] H. C. Newns, Proc. Phys. Soc. (London) **A65**, 916 (1952).
[6] L. Madansky and G. E. Owen, Phys. Rev. **99**, 1608 (1955). G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957).
[7] G. Breit, in Proceedings of the Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee, May 5–7, 1958, p. 284 (unpublished). G. Breit, in Proceedings of the Second Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee, May 2–4, 1960 (unpublished).
[8] S. K. Allison, in Proceedings of the Second Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee, May 2–4, 1960 (unpublished); Phys. Rev. **119**, 1975 (1960).
[9] W. Tobocman and M. M. Kalos, Phys. Rev. **97**, 132 (1955).

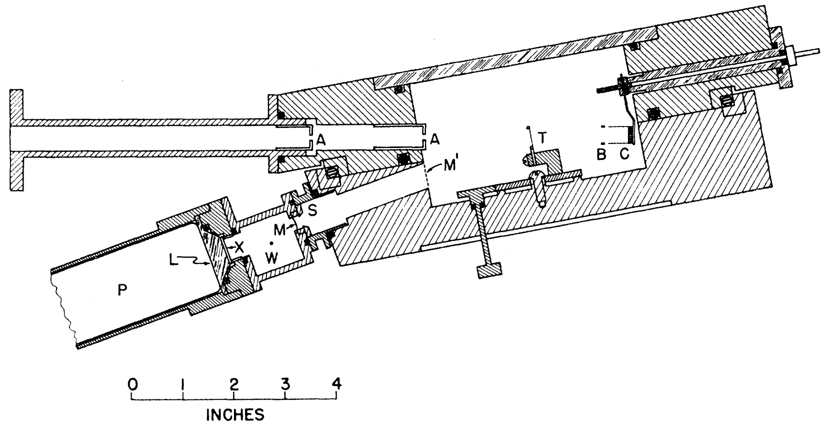

FIG. 1. Cross-sectional view of target chamber and counters. The lettered components are identified in the text.

the target chamber,[10] shown in Fig. 1, through two circular apertures A of 0.125-inch diameter. After passing through a thin beryllium target T in a rotatable mounting, the ion beam is collected in the Faraday cage C. A bias ring B at a potential of -180 volts suppresses secondary electrons arising from the target and the Faraday cage. The collected current is conducted to a current integrator which automatically terminates the bombardment period after the accumulation of a selected quantity of charge.

The differential cross section of the $Be^9(Li^6,\alpha)B^{11}$ reaction was studied by observing the α particles. To do this successfully requires a detection system which unambiguously identifies α particles of several energies in the presence of products from other reactions, particularly the (Li^6,p), (Li^6,d), (Li^6,t), and (Li^6,He^5) reactions. Each of these reactions has a positive Q value and produces charged particles of several energies corresponding to the various excitation states of the residual nuclei.

The detection system used in the present experiment incorporates a proportional counter and a scintillation counter in tandem. Figure 1 shows a cross-sectional view of the counters, mounted on the rotating lower part of the chamber, in the position corresponding to a laboratory scattering angle of 160°. Reaction products from the target T enter the proportional counter through a 0.00025-inch Mylar window M. The 0.200-inch aperture S defines the solid angle of $(1.39\pm0.04)\times10^{-3}$ steradian subtended by the counters. The proportional counter filling is ≈ 8 cm Hg of argon and 2–3 mm Hg of carbon dioxide. W is the high-voltage anode wire. Having passed through the proportional counter, the particles stop in the 1-mm thick CsI(Tl) crystal X, whose face is covered by a 0.00035-inch aluminum foil for light shielding. L and P are a Lucite light pipe and a photomultiplier tube, respectively. Not shown in Fig. 1 is a ThC–ThC′ α-particle source which can be rotated to a position in front of the counters when they are at the 90° position. This test source is used for calibration of the scintillation counter and for adjustment of the particle identification circuit described below.

The amplitude of the output pulse of a proportional counter is proportional to the amount of energy ΔE that the particle loses in the counter gas. ΔE is essentially proportional to the rate of energy loss $d\mathcal{E}/dx$. The output of the scintillation counter is a pulse whose amplitude is proportional to the remaining kinetic energy E $(=\mathcal{E}-\Delta E)$ of the particle.

It is known that the product $\mathcal{E}^{0.8}(d\mathcal{E}/dx)$ should depend only on the mass and the nuclear charge of the particle.[11] Figure 2 shows a block diagram of the electronic circuit used in this experiment to select only pulses due to α particles by utilizing the constancy of the above product for a particular kind of particle. After suitable amplification the E and the ΔE pulses are fed into the "log" circuits, whose outputs are proportional to the logarithms of the input pulse heights. The "add" circuit forms the sum of the logarithm of the ΔE pulse and a fraction $n<1$ of the logarithm of the E pulse, producing an output pulse whose amplitude is proportional to $\log(E^n\Delta E)$. The circuit is adjusted by varying n until the 6.05- and 8.78-Mev α particles from the ThC–ThC′ source produce the same "add" output. (When carefully adjusted for selection of α-particle pulses, n is found to be approximately $\frac{1}{3}$ rather than 0.8.) The discriminator following the "add" circuit rejects pulses whose amplitude is less than that corresponding to α particles. An additional discriminator is used to select only E pulses larger than a minimum size, thus eliminating pulses due to He^5 nuclei from the relatively low Q (1.94 Mev) reaction $Be^9(Li^6,He^5)B^{10}$. Coupled with the other discriminator and the coincidence circuit, the E discriminator also reduces the background counting rate to essentially zero by preventing large ΔE pulses, resulting from particles stopping in the proportional counter, from opening the gate. Thus, finally, when the occurrence of a coincidence establishes the presence of an α-particle E pulse of sufficient amplitude, the gate

[10] The basic chamber has been described previously. H. D. Holmgren *et al.*, Phys. Rev. **95**, 1544 (1954).

[11] K. B. Mather and P. Swan, *Nuclear Scattering* (Cambridge University Press, New York, 1958), p. 99.

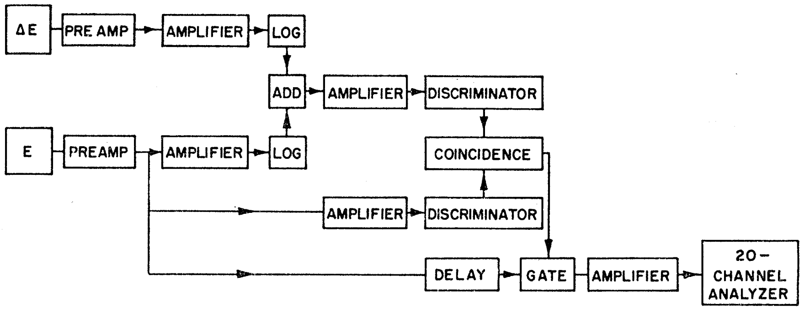

FIG. 2. Block diagram of particle identification and energy-analyzing circuit.

circuit[12] passes the E pulse to an amplifier and the resulting pulse is sorted in a 20-channel pulse-height analyzer. A typical pulse-height spectrum of α particles from the $Be^9(Li^6,\alpha)B^{11}$ reaction obtained with this system is shown in Fig. 3. The peaks labelled α_0, α_1, and $\alpha_2+\alpha_3$ are due to the α particles leaving the B^{11} in the ground state, the first excited state (2.13 Mev), and the second and third excited states (4.46 and 5.03 Mev), respectively. The separate contributions from α_2 and α_3 cannot be resolved with the present scintillation counter. Figure 3 also shows a calibration peak due to the 8.78-Mev α particles from ThC′.

III. PROCEDURE

Thin beryllium targets without backing were prepared by evaporating beryllium onto soaped glass slides.[13] The resulting beryllium foil is floated off the slide in water and picked up on a wire target frame. Four targets were used in this experiment, ranging in thickness from 116±23 kev to 256±36 kev for Li^7 ions incident at 3.25 Mev. The yields from the various targets were normalized to that of one of them by comparing the yields at the laboratory scattering angle of 90° and the laboratory bombarding energy of 3.25 Mev.

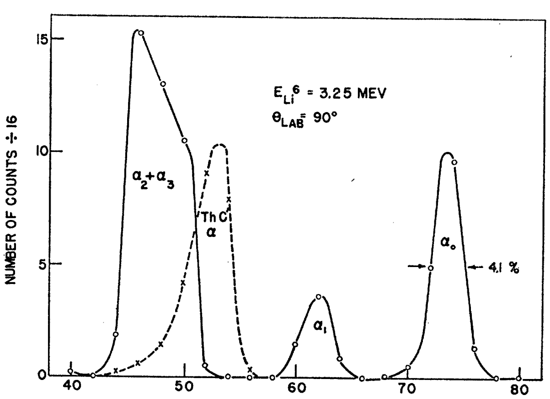

FIG. 3. Typical pulse-height spectrum of the four highest energy α-particle groups from the $Be^9(Li^6,\alpha)B^{11}$ reaction. The broken curve is a superimposed calibration peak due to the 8.8-Mev α particles from ThC′.

[12] Fred F. Forbes (to be published).
[13] G. Dearnaley, Rev. Sci. Instr. **31**, 197 (1960).

Calibration of the electrostatic generator energy scale is accomplished by determining the inflection point in the thick target yield of γ rays from the $H^1(Li^7,\gamma)Be^8$ reaction, the hydrogen being provided by an ice target which can be mounted in place of the counters at the 0° position. The inflection point is taken to occur at the Li^7 energy of 3.072 Mev, based on the resonance energy[14] $E_p=0.4412$ Mev for the reaction $Li^7(p,\gamma)Be^8$. Target thicknesses can be determined by doing the calibration procedure with a beryllium target ahead of the ice target, observing the increase in bombarding energy required to produce the inflection point. By comparing the relative γ-ray yields per unit charge of collected beam at the respective inflection points with and without the beryllium target, the equilibrium charge attained by the Li^7 ions in passing through the target can be ascertained at the calibration energy. Because of the limited resolution of the γ-ray detector and the background of γ rays caused by reactions in the beryllium target, this equilibrium charge determination is not precise. Of the two determinations of equilibrium charge which we have made in this way one gave 2.68 electrons in excellent agreement with published results[15] but the other gave only 2.18 electrons.

In determining the angular distributions of the α particles from the $Be^9(Li^6,\alpha)B^{11}$ reaction, the high voltage on the scintillation counter and the channel width and threshold level of the 20-channel analyzer were adjusted to enable the three groups α_0, α_1, and $\alpha_2+\alpha_3$ to be observed simultaneously while eliminating most of the large quantity of lower energy unresolved α-particle groups. At the laboratory bombarding energies of 3.00, 3.25, and 3.50 Mev, the yields were measured at 10° intervals from 10° to 160° in the laboratory system. Three to ten runs were made at each angle. At 2.00, 2.50, 3.75, and 4.00 Mev the yields were measured at the laboratory angles corresponding to the center-of-mass angles 20°, 60°, 90°, 120°, and 160° for the α_0 group. For these latter energies at least three runs were made at each angle with the exception

[14] F. Bumiller, H. H. Staub, and H. E. Weaver, Helv. Phys. Acta **29**, 83 (1956). H. H. Staub, Suppl. Nuovo cimento **6**, 306 (1957).
[15] Ia. A. Teplova *et al.*, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 974 (1955) [translation: Soviet Phys.—JETP **5**, 797 (1957)].

of 2.00 Mev where the small yield dictated only one run at each angle. For a given energy the yields at all the angles observed were measured with the same target and with the same total collected beam.

When measuring yields at scattering angles less than 90°, it was found necessary to insert an additional 0.00025-inch Mylar foil at M' in Fig. 1 to prevent pulses due to Li^6 scattered by the target from jamming the electronic circuits.

The target normal was always maintained at an angle of $45.9° \pm 0.4°$ with respect to the beam, lying in the first quadrant for scattering angles less than 90° and in the fourth quadrant for angles greater than 90° at 3.00, 3.25, and 3.50 Mev but in the fourth quadrant only for the 120° angle at 2.00, 2.50, 3.75, and 4.00 Mev. Both target orientations were used at 90° at the energy of the angular distribution and/or at the 3.25 Mev target thickness normalization energy. A difference in the yields for the two orientations was observed. This difference is probably due to target wrinkles but could also be due to the most intense portion of the beam failing to be parallel to the geometrical beam axis. We have assumed that the effect is permanent enough to allow the yields taken with the target normal in the fourth quadrant to be multiplied by the ratio of the yields at 90° for the two target orientations. These ratios are: 1.15 at 4.00, 3.75, and 2.00 Mev; 0.89 at 2.50 and 3.00 Mev; 1.12 at 3.50 Mev; and 1.09 at 3.25 Mev. The ratios may be in error by as much as 15% but this possible error has not been incorporated in the errors associated with the points in the figures which follow.

IV. RESULTS

The principle results of the experiment are presented in Figs. 4–6 showing the angular distributions of α particles from the $Be^9(Li^6,\alpha)B^{11}$ reaction and in Figs. 7–9 showing the excitation functions at five selected center-of-mass angles. The experimental points in Figs. 4–6, and at the energies 2.00, 2.50, 3.75, and 4.00 Mev in Figs. 7–9, are the averages of the several runs at the corresponding energies and scattering angles. The error bars associated with these points are either the root-mean-square deviation from the average or the square root of the total yield of the several runs divided by the number of runs, whichever is larger. The former type of error bar is preponderant. The points at 3.00, 3.25, and 3.50 Mev in Figs. 7–9 were interpolated, with estimated errors, from the curves in Figs. 4–6. The curves drawn through the points were fitted only by eye, and may be considered qualitative at 2.00, 2.50, 3.75, and 4.00 Mev in Figs. 4–6 because of the small number of measured points.

One unit of relative yield has the same meaning in all the figures, and is proportional to the yield per unit of collected beam charge, normalized to a particular target thickness.

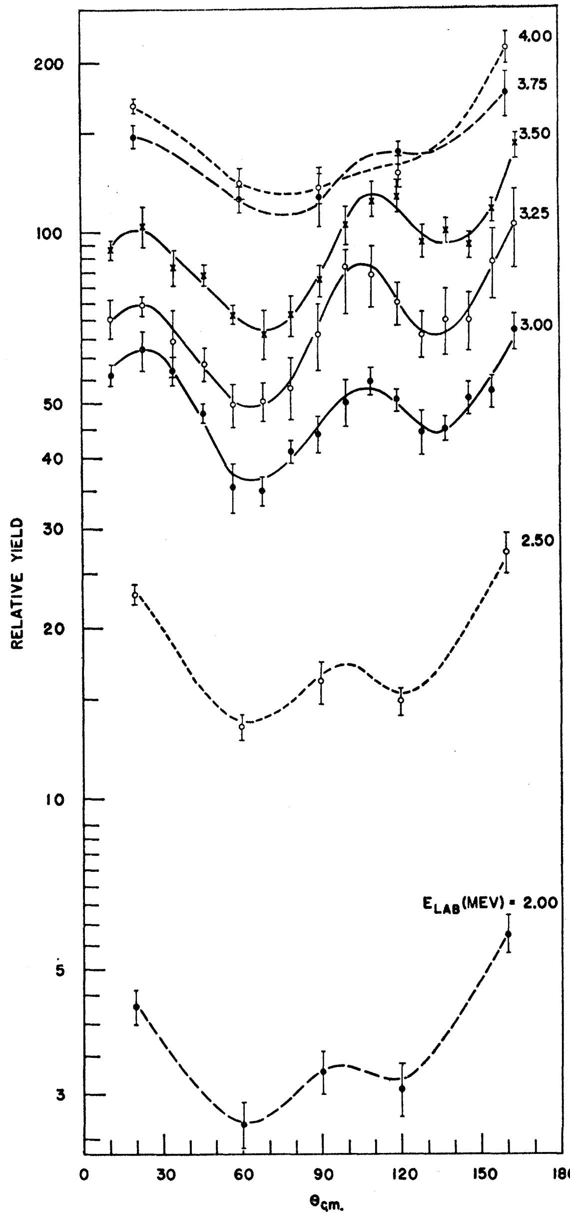

FIG. 4. Angular distributions of α particles leading to the ground state of B^{11}.

If $\bar{z}$ is the average (i.e., equilibrium) charge, in units of the charge of an electron, of the lithium ions leaving the beryllium target, then one unit of relative yield is equal to a differential cross section $S=(3\pm1)\bar{z}\times10^{-4}$ mb/sr. The principle uncertainties involved in determining S are: 16% in the measured energy thickness of the normalizing target, 10% in the stopping power of beryllium for lithium ions, and 6% in the normalization factors relating the various targets to the normalizing target. The equilibrium charge $\bar{z}$ may be interpolated from the curve given in reference 15, using the appropriate velocities for the Li^6 ions. Approximate values

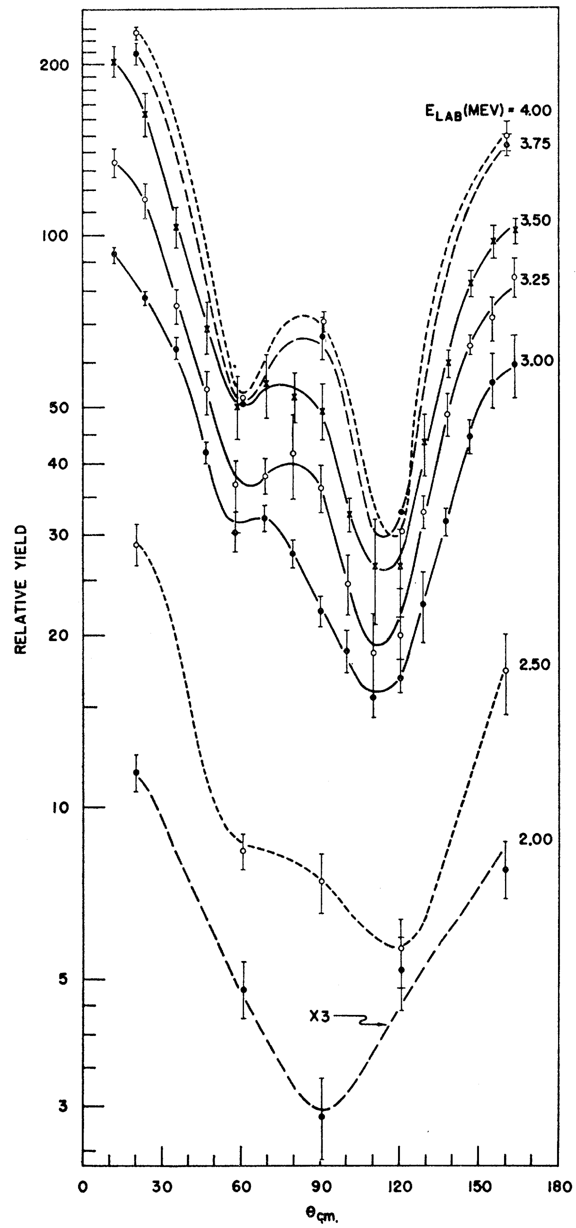

FIG. 5. Angular distributions of α particles leading to the first excited state of B^{11}. The error bars for the yields near 60° and 120° at bombarding energies of 4.00 and 3.75 Mev, which were omitted for clarity, can be obtained from Fig. 8.

of $\bar{z}$ thus obtained are 2.50, 2.63, 2.71, 2.73, 2.76, 2.78 and 2.80 at the energies 2.00, 2.50, 3.00, 3.25, 3.50, 3.75, and 4.00 Mev, respectively.

Total cross sections were obtained from the 3.00, 3.25, and 3.50 Mev angular distributions by mechanical integration of the angular distributions plotted against the cosine of the center-of-mass scattering angle. The results, using the values of S and $\bar{z}$ given above, are shown in Table I. The uncertainty in these total cross sections is ±40%.

V. DISCUSSION OF RESULTS

Several features of the results presented in Figs. 4–9 may be pointed out. All the angular distributions show a peaking of the yield in the forward directions, although the α_0 yield begins to decrease as the angle becomes less than about 15°. The α_0 yield is also markedly peaked in the backward direction at all the energies measured. The degree of backward peaking in the α_1 and the $\alpha_2+\alpha_3$ yields increases with energy, the backward yield becoming nearly as great as the forward yield near 4.00 Mev. The angular distributions are distinctly asymmetric about 90° with the exception of

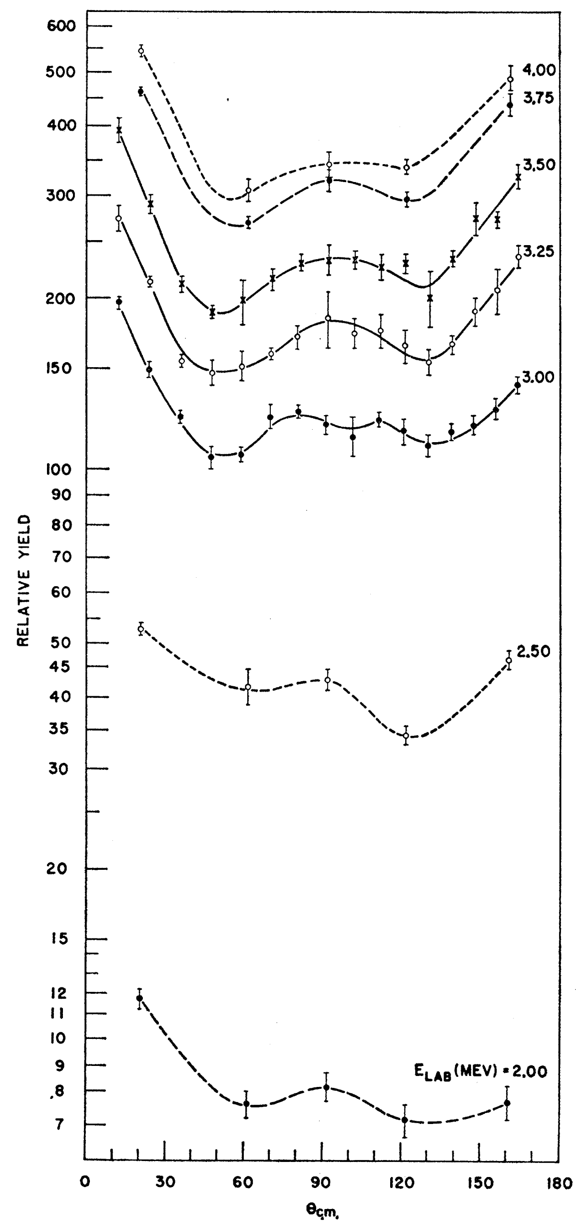

FIG. 6. Sums of angular distributions of α particles leading to the second and the third excited states of B^{11}.

the $\alpha_2+\alpha_3$ distribution. (The latter of course should not be invoked in symmetry considerations since it is the sum of yields of reactions leading to different states of the residual nucleus.) On the other hand, the rates of change with energy of the excitation functions do appear to be symmetric about 90°. The latter feature is particularly apparent when comparing the 20° and 160° excitation functions for α_1 with the 60° and 120° curves, as shown in Fig. 8.

Although we have not yet attempted to fit any theoretical interaction model to the experimental results, some comments on their possible interpretation will be made.

The forward and backward peaking and the asymmetry of the angular distributions about 90° suggest that the $Be^9(Li^6,\alpha)B^{11}$ reaction proceeds by direct or surface interaction processes. Since the Li^6 nucleus may be viewed as an α-particle "core" to which a deuteron is coupled relatively loosely, it would not seem unreasonable to expect that the Be^9 strips the deuteron from the incoming Li^6 to leave an outgoing α particle, in a manner analogous to (d,p) and (d,n) stripping reactions. A theory of two-nucleon stripping, such as might occur in the (Li^6,α) reactions, has been given by el Nadi.[16] Forward peaking is predicted by this theory just as it is in the usual single-nucleon stripping theories.[4] Moreover, considering the Be^9 target nucleus to be a neutron coupled to a core composed of two α particles,

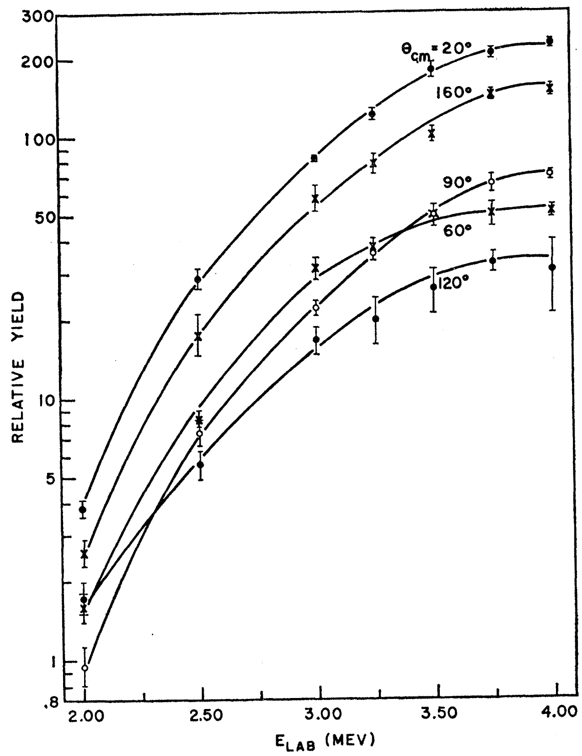

FIG. 8. Excitation functions for $Be^9(Li^6,\alpha)B^{11}$ reactions leading to the first excited state of B^{11}.

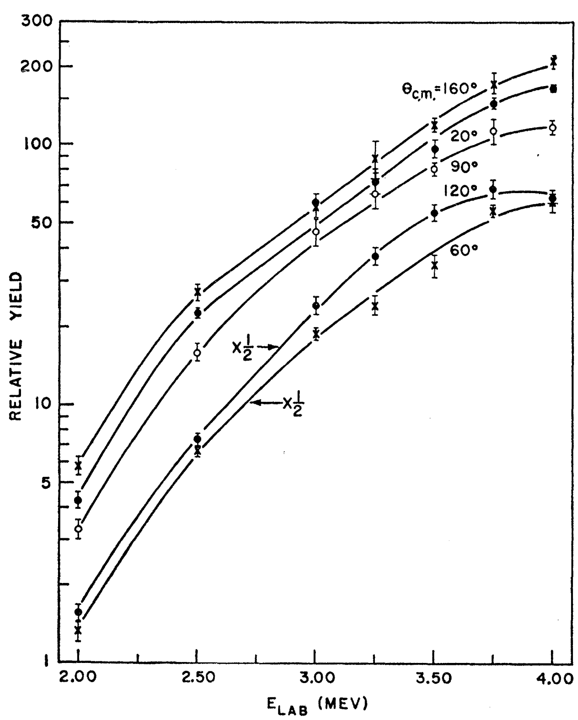

FIG. 7. Excitation functions for $Be^9(Li^6,\alpha)B^{11}$ reactions leading to the ground state of B^{11}.

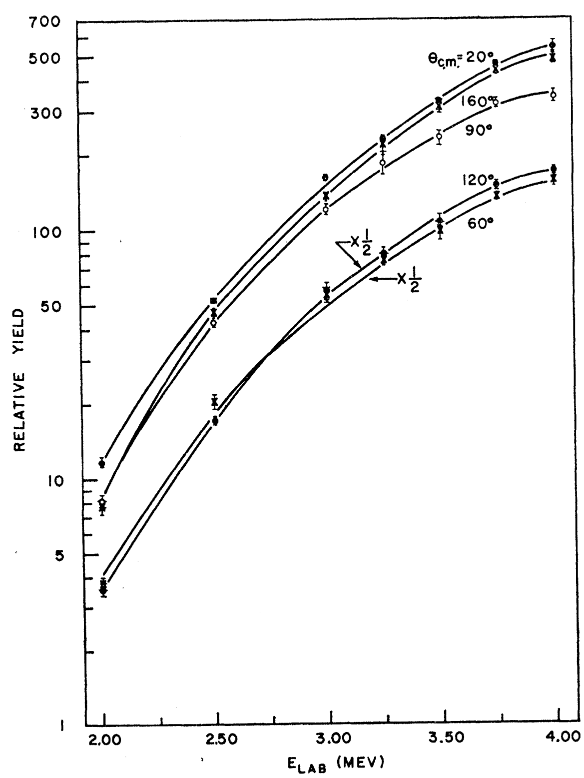

FIG. 9. Sums of excitation functions for $Be^9(Li^6,\alpha)B^{11}$ reactions leading to the second and the third excited states of B^{11}.

[16] M. el Nadi, Phys. Rev. **119**, 242 (1960).

TABLE I. Total cross sections in millibarns of the $Be^9(Li^6,\alpha)B^{11}$ reactions at three laboratory bombarding energies. The notation for the α-particle groups follows the text.

E (Mev)	α_0	α_1	$\alpha_2+\alpha_3$
3.00	0.49	0.35	1.24
3.25	0.70	0.49	1.79
3.50	0.97	0.65	2.43

it may be possible for an outgoing α particle to have come from the Be^9. This process of "heavy-particle stripping," introduced by Madansky and Owen,[6] predicts a backward peaking which tends to increase with increasing energy until the bombarding energy reaches the Coulomb barrier height. Single-nucleon stripping and the heavy-particle stripping have been combined, with interference between the two mechanisms playing a significant part in the resulting angular distributions.[17] It may be possible to similarly extend the two-nucleon stripping theory to include the heavy-particle stripping process.

It is difficult to reconcile the compound nucleus model with the results of the present experiment. If the height of the Coulomb barrier is $V=Z_1Z_2e^2/R$, where $R=r_0(A_1^{\frac{1}{3}}+A_2^{\frac{1}{3}})$, then the largest bombarding energy used in this work (4.00 Mev) is less than the Coulomb barrier unless r_0 is larger than 1.85×10^{-13} cm. Since determinations of nuclear radii do not require such large values of r_0, it seems that compound nucleus formation contributes little to the reaction cross section. If the N^{15} compound nucleus were formed, it would be highly excited (27.4 Mev if the laboratory energy of the incident Li^6 were 3.25 Mev). At such high excitations the statistical model should apply, resulting in angular distributions symmetric about 90°.[18] Finally, since the shape of the angular distributions changes only slowly with energy in the range from 2.00 to 4.00 Mev and the excitation functions are monotonic and relatively smooth, there appears to be no resonance in the total cross section. Such behavior would not be expected if the compound nucleus model applies. The observed angular distributions may, of course, be due to a small compound nucleus contribution superimposed on a direct interaction contribution. Coulomb effects may alter the simplified interaction models considerably.

To conclude, we would like to point out the marked similarity between the angular distributions of the $Be^9(Li^6,\alpha)B^{11}$ reaction at bombarding energies of 3 to 4 Mev and those of the $Be^9(He^3,p)B^{11}$ reaction at the He^3 bombarding energy of 4.50 Mev.[19] (The latter reaction has also been studied at other energies.[20]) Both reactions may be viewed as the stripping of a deuteron from the incident nucleus by the Be^9 target to form B^{11} and a light particle. The angular distributions of the α_0 and p_0 groups from the respective reactions have almost identical shapes, with maxima and minima occurring at the same center-of-mass angles. The p_1 and p_2+p_3 distributions have the same general shape as the α_1 and the $\alpha_2+\alpha_3$ distributions, respectively, but are pushed more towards the forward angles. The total cross sections of the (Li^6,α) reactions at 3.50 Mev are about 8.6% of the corresponding cross sections for the (He^3,p) reactions at 4.50 Mev when the B^{11} is left in its ground or first excited state. These similarities are at present rather surprising since the incident and outgoing particles are so different and because the He^3 is incident at an energy approximately 1 Mev above the Coulomb barrier while the Li^6 is incident at an energy approximately 1 Mev below the Coulomb barrier.

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[17] G. E. Owen, L. Madansky, and S. Edwards, Jr., Phys. Rev. **113**, 1575 (1959).

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