Sequential Reactions from Li^6 on Be^9†

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Various sequential reactions resulting from Be^9 (Li^6, α) have been studied to look for levels in B^{11} having a (Be^9+d) structure. The studies included measurement of particle-γ and particle-particle coincidences. No unusual levels were found.

INTRODUCTION

It has been suggested[1] that in some cases the mechanism of reactions induced by Li^6 and Li^7 may be understood by assuming an $(\alpha+d)$ structure for Li^6 and an $(\alpha+t)$ structure for Li^7. The small binding energies of these configurations (1.47 and 2.47 MeV, respectively) make this idea appealing. Dissociation of Li^6 at high energies has been explained[2] by assuming such a configuration. Experiments done at the University of Minnesota using Li^6 and Li^7 beams suggest a direct interaction mechanism for (Li^6,α) and (Li^7,α) reactions.[3,4]

A study of the intensities of γ rays from Li^{7*} (480 keV) and B^{10*} (720 keV), produced in the $Be^9(Li^6,2\alpha)Li^{7*}(\gamma)$ and $Be^9(Li^6,\alpha n)B^{10*}(\gamma)$ reactions, revealed that the ratio of the intensities of these γ rays remained constant over bombarding energies from 1.1 to 2.9 MeV.[5,6] Because of this it was suggested[5] that these reactions both proceed through the level at 13.16 MeV excitation in B^{11}, which was assumed to be a threshold state having a (Be^9+d) configuration. The level was presumed to be easily formed by the transfer of a deuteron from Li^6 to Be^9. We felt, however, that the results did not warrant this conclusion and that the constant ratio of γ intensities could be due simply to the large Coulomb barrier in the incident channel. The present studies were undertaken to investigate the role played by such a level and to confirm or exclude the possibility of a (Be^9+d) threshold state in B^{11}.

Many charged particle reactions result when Li^6 ions strike a Be^9 target; in each of those listed in Table I at least one α particle is emitted. The first two reactions produce the γ rays mentioned above when Li^7 and B^{10} are produced in their first excited states. Each reaction could proceed directly, or, more probably, by one of the sequential processes listed.

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[1] G. C. Morrison, in *Direct Interactions and Nuclear Reaction Mechanisms*, edited by E. Clementel and C. Villi (Gordon and Breach Science Publishers, Inc., New York, 1963), p. 878.
[2] R. Ollerhead, C. Chasman, and D. A. Bromley, Phys. Rev. **134**, B74 (1964).
[3] R. K. Hobbie, C. W. Lewis, and J. M. Blair, Phys. Rev. **124**, 1506 (1961).
[4] R. K. Hobbie and F. F. Forbes, Phys. Rev. **126**, 2137 (1962).
[5] C. Lemeille, L. Marquez, N. Saunier, and M. Coste, J. Phys. Radium **22**, 349 (1961); C. Lemeille, L. Marquez, and N. Saunier, *ibid.* **22**, 586 (1961).
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All of these reactions can take place sequentially through levels in B^{11}. The hypothesized threshold state, if it exists, should be preferentially excited in all cases. We studied reactions 1 and 2 by α-γ coincidences and 1, 3, and 4 by α-α, α-t, and α-p coincidences, respectively, without finding any evidence for such a state. The details are discussed below.

α-γ COINCIDENCE STUDIES

If reactions 1b or 2b proceed through a particular state in B^{11}, then the α particle emitted in the first step of each reaction will have a definite energy as a function of angle, given by the kinematics of the reaction $Be^9(Li^6,\alpha)B^{11*}$. In the case of reaction 1, this peak would be superposed on a continuum of α particles from the decay of B^{11}; in reaction (2b) there would be no α-particle continuum. (Alternatives 2a, 2c, and 2d would produce a continuum but no peak.) The same arguments are true if the Li^7 and B^{10} are produced in their first excited states (480 and 720 keV, respectively) rather than their ground states. Reactions 1 and 2 were studied by observing coincidences between α particles and γ rays from the de-excitation of these states.

A momentum-analyzed 3.5-MeV Li^6 beam from the Minnesota 4-MeV Van de Graaff accelerator passed through a Be^9 target at the center of a circular scattering chamber. A solid-state particle detector was mounted inside the chamber, while a 5×4.3-cm NaI(Tl) crystal,

TABLE I. Reactions of Li^6 on Be^9 which produce at least one α particle.

Number	First stage Products	First stage Q (MeV)	Second stage Reaction	Second stage Q (MeV)
1a	$\alpha+\alpha+Li^7$	5.68		
b	$\alpha+B^{11*}$	$14.34-E_x$	$B^{11*}\rightarrow\alpha+Li^7$	$E_x-8.66$
c	Li^7+Be^8	5.59	$Be^8\rightarrow\alpha+\alpha$	0.09
2a	$\alpha+n+B^{10}$	2.89		
b	$\alpha+B^{11*}$	$14.34-E_x$	$B^{11*}\rightarrow n+B^{10}$	$E_x-11.46$
c	$B^{10}+He^5$	1.93	$He^5\rightarrow\alpha+n$	0.96
d	$n+N^{14*}$	$14.49-E_x$	$N^{14*}\rightarrow\alpha+B^{10}$	$E_x-11.61$
3a	$\alpha+t+Be^8$	3.12		
b	$\alpha+B^{11*}$	$14.34-E_x$	$B^{11}\rightarrow t+Be^8$	$E_x-11.22$
c	$t+C^{12*}$	$10.50-E_x$	$C^{12*}\rightarrow\alpha+Be^8$	$E_x-7.38$
d	Be^8+Li^{7*}	$5.58-E_x$	$Li^{7*}\rightarrow\alpha+t$	$E_x=2.46$
4a	$\alpha+p+Be^{10}$	3.11		
b	$\alpha+B^{11*}$	$14.34-E_x$	$B^{11*}\rightarrow p+Be^{10}$	$E_x-11.23$
c	$p+C^{14*}$	$15.13-E_x$	$C^{14*}\rightarrow\alpha+Be^{10}$	$E_x-12.02$
d	$Be^{10}+Li^5$	1.31	$Li^5\rightarrow\alpha+p$	1.80

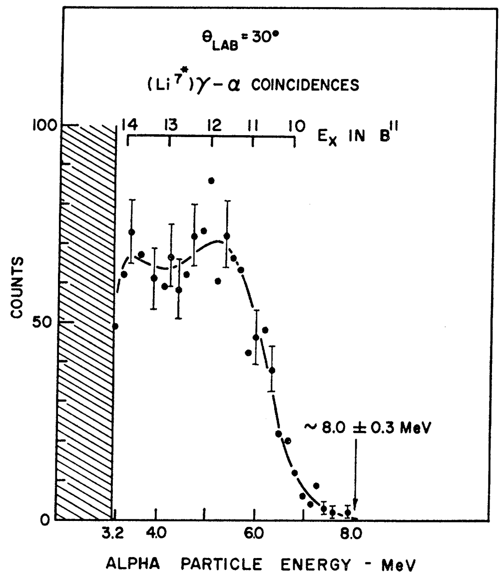

FIG. 1. The α spectrum obtained at 30° in coincidence with Li^{7*} γ rays. The low-energy cutoff is instrumental and corresponds to $E_x=14.2$ MeV in B^{11}.

mounted on the Lucite top cover of the chamber, detected the γ rays. Mylar foil shielded the semiconductor detector from the elastically scattered Li^6 ions. No particle identification was needed because of the coincidence requirements. The resolving time of the coincidence system was about 0.2 μsec. The α spectrum was recorded on an RCL 512-channel analyzer, gated by the coincidence circuit output and the desired region of the γ spectrum.

Figures 1–4 show the α spectra obtained in coincidence with the γ rays. In all cases the low-energy cutoff is

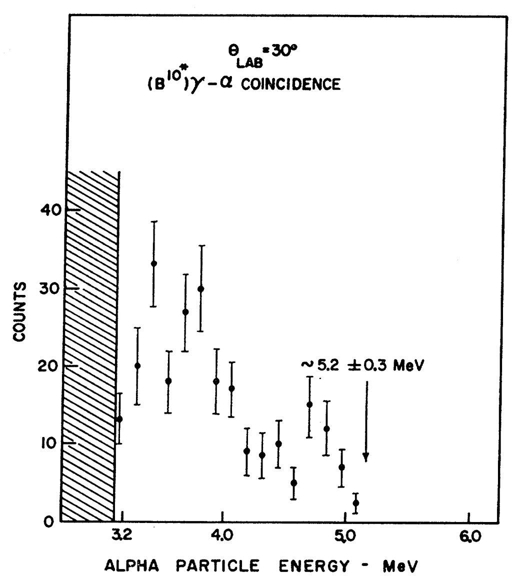

FIG. 2. The α spectrum obtained at 30° in coincidence with B^{10*} γ rays. The low-energy cutoff is instrumental and corresponds to $E_x=14.2$ MeV in B^{11}

instrumental. A peak corresponding to the 13.16-MeV level would occur at 4.2 MeV at 30°, 3.4 MeV at 50°, and 3.1 MeV at 60°. The most striking feature of all the spectra is the absence of any pronounced peaks, ruling out the copious production of the 13.16-MeV or any other level of B^{11}. Hence, the level does not seem to have the special (Be^9+d) structure suggested by Lemeille *et al.*[5] The 50° spectrum (Fig. 3) shows no prominent peaks for B^{11} excitation energies from 14 to 16 MeV. The structure of the spectra can be best explained by the participation of many or all of the available levels in B^{11}. In the case of reaction 1b, α particles are also produced in the second step. We have no estimates of the contributions of the different processes. As shown in Fig. 5, an attempt to fit the spectra with the known levels in B^{11} suggested the existence of two previously unreported levels about 350 keV wide at ~12.5 and 13.6 MeV excitations. A search of the literature[7,8] also revealed the possibility of their existence. Recently, Cusson has studied $Li^7(\alpha,\alpha)Li^7$ scattering from these levels.[9]

PARTICLE-PARTICLE COINCIDENCE STUDIES

Procedure

Since, in most of the reactions listed above, at least two charged particles are emitted, it was decided to study them further by observing particle-particle

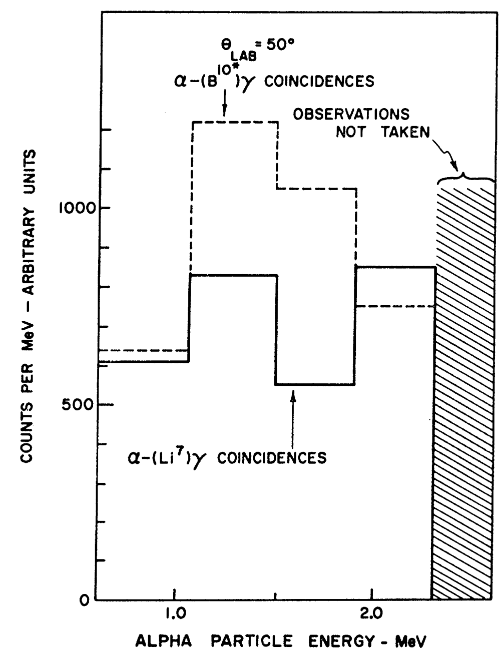

FIG. 3. Histograms of low-energy spectra at 50° in coincidence with Li^{7*} and B^{10*} γ rays. Only the low-energy portion of the coincidence spectrum was studied. The low-energy cutoff is instrumental. The range of excitation energies in B^{11} is 14–16 MeV.

[7] H. Bichsel and T. W. Bonner, Phys. Rev. **108**, 1024 (1957).
[8] R. B. Day and M. Walt, Phys. Rev. **117**, 1330 (1961).
[9] R. Y. Cusson, Nucl. Phys. **86**, 481 (1966).

coincidences. Reactions 1, 3, and 4 were studied by α-α, α-t, and α-p coincidence techniques, with special emphasis on reaction 1. In these experiments we have attempted to estimate the relative contributions of the many reaction mechanisms.

Only Li^6 ions at 3.3 MeV were used for these studies. The reaction chamber supported two solid-state detectors which could be located independently in a horizontal plane through the target. Each detector subtended a solid angle of 1.06×10^{-2} sr, and each was protected by a 0.86-mg/cm^2 Mylar foil from elastically scattered Li^6 ions as well as Li^7 produced in the reaction. A plot of the energy in one detector versus the energy in the other shows loci which depend on the Q, the bombarding energy, and the detector angles. At many pairs of angles the α-α loci are well separated from the α-p and α-t loci, as shown in Fig. 6, because of the high Q of the α-α-Li^7 reaction. To facilitate the study of α-p and α-t coincidences, a gas proportional counter to measure dE/dx was placed in front of one of the detectors, and an analog pulse multiplying circuit was used to identify protons and tritons. The need for a two-parameter analyzer to store the E_1-E_2 matrix was satisfied by using two independent multichannel analyzers, gated by a coincidence unit with 70 nsec resolving time. When a coincidence occurred, the channel numbers from the two analyzers were punched on a paper tape. Because of the very low counting rate, the punching time did not produce a dead-time problem. The ratio of true to accidental coincidences was always better than 8. A computer read the paper tape and printed the two-parameter matrix.

The α-α, α-t, and α-p spectra obtained with the detectors set at $-30°$ and $+60°$ are shown in Figs. 6–8. Usually, one detector was fixed at $\theta=-30°$ (to be designated henceforth as the θ_f or E_f detector) while the other was moved to different angles (the θ_m or E_m detector). The events on the desired locus were projected on the energy axis of the fixed detector. These projections, for different values of θ_m, are shown in Figs. 9–12.

The measurements discussed above will not detect reaction mechanism 1c. α particles produced by the breakup of Be^8 emerge in the laboratory system within a cone having the Be^8 velocity vector as its axis. The maximum cone angle is given by $\sin\theta_{max}=(B/E)^{1/2}$, where B is the breakup energy of Be^8 and E its kinetic energy in the laboratory system. Therefore, this reaction can be detected only at specially selected pairs of angles. The projected spectrum for such a case is shown in Fig. 13, where $\theta_f=41°$ and $\theta_m=56°$. When the detectors were moved to 39° and 58° (making the included angle larger than the maximum cone angle) the counting rate became comparable to the accidental rate, with counts scattered all over the E_f-E_m plane, confirming that the events obtained at 41°–56° were due to Be^8

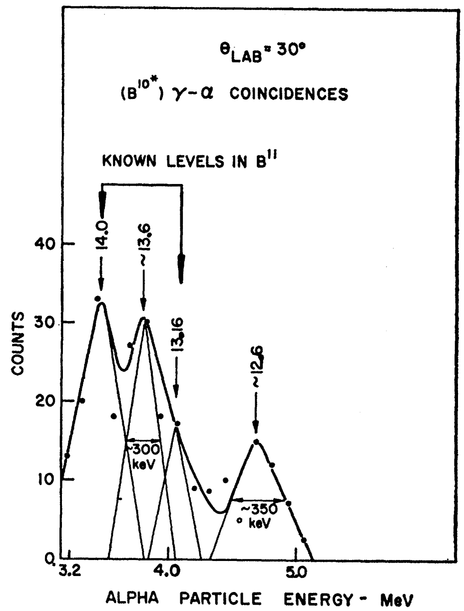

FIG. 5. The spectrum in Fig. 2 fit with peaks corresponding to the various excited states in B^{11}.

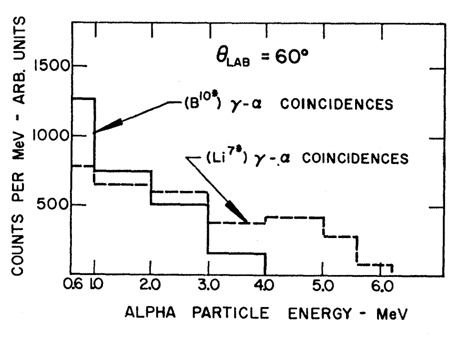

FIG. 4. A histogram of the α spectrum obtained at 60° in coincidence with B^{10*} and Li^{7*} γ rays. The low-energy cutoff is instrumental and corresponds to $E_x=15.76$ MeV in B^{11}.

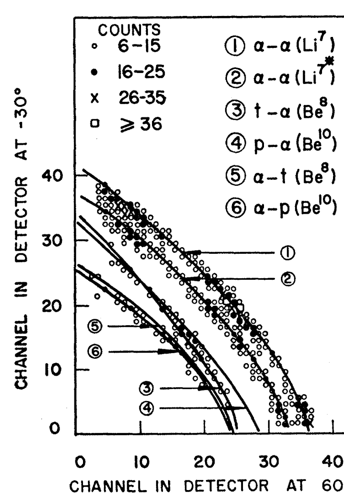

FIG. 6. Loci obtained with detectors at 30° on one side of the beam and 60° on the other. No particle identification was used; the various loci are indicated in the figure.

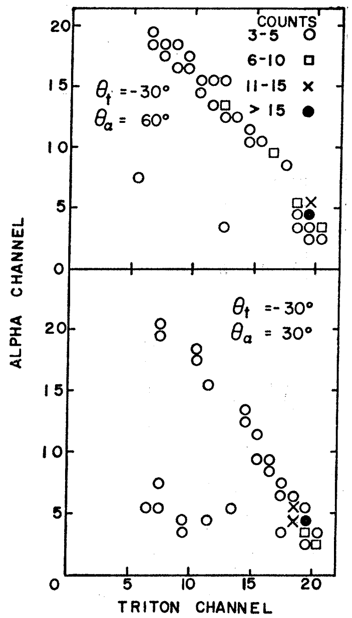

FIG. 7. Loci for t-α coincidences, obtained with a particle identification system.

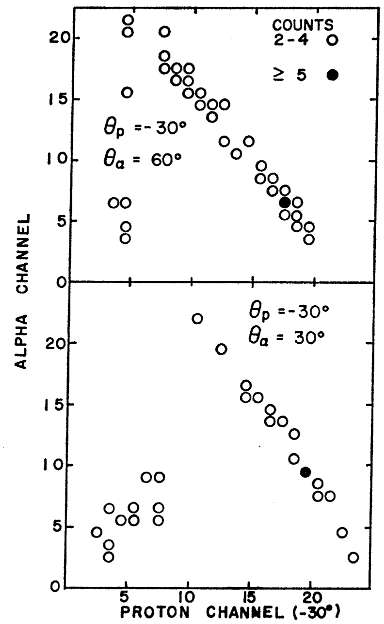

FIG. 8. Loci for p-α coincidences obtained with a particle identification system.

breakup. Because of the extremely low counting rate, observations were not made at any other pairs of angles.

DISCUSSION

If a direct three-body breakup (reaction 1a) with constant matrix element were responsible for the reaction, a yield varying smoothly with energy would be expected for curves such as those shown in Figs. 9 and 10; however, many peaks are seen in these spectra. The minima between the peaks indicate that direct breakup contributes less than 5% to the total cross section. Some peaks, whose energies in the fixed detector are independent of θ_m, are due to α particles produced in the first stage, $Be^9(Li^6,\alpha)B^{11*}$, while those with varying energies are due to the breakup of B^{11*} into $\alpha+Li^7$. The set of curves labeled A_n in Fig. 9 gives the expected energies of first-emitted α particles corresponding to the known excited states in B^{11}, while the set B_n shows the energies of α particles emitted in the second stage. In favorable cases, one could compare the peak locations with these curves to determine whether a given peak is due to an α particle emitted in the first or second stage of the reaction.[10,11] Of course, depending on the angles and the excited levels in B^{11}, these peaks may overlap, and one cannot then determine the order of emission. The identification in such cases is further complicated

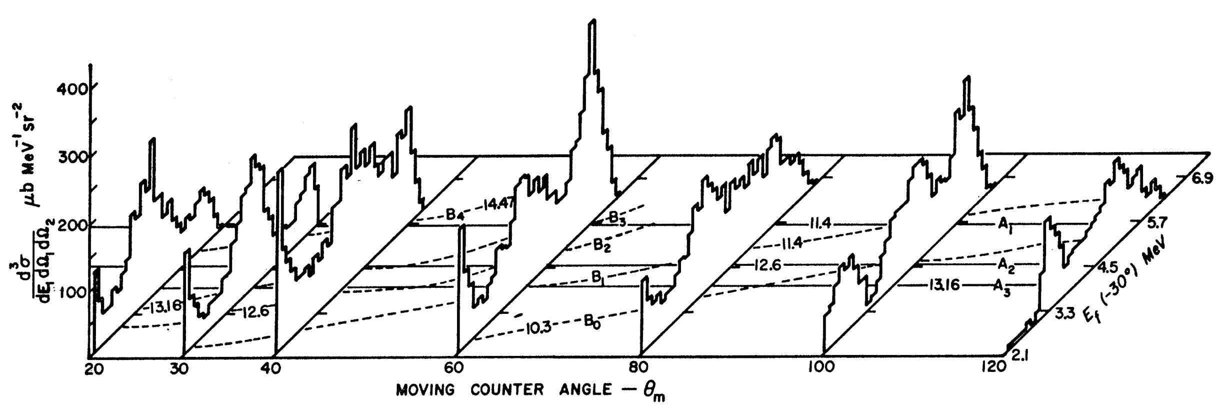

FIG. 9. Loci of α-α coincidences for which the Li^7 is in its ground state are projected on the energy axis of the fixed detector. Curves labeled A_i and B_i are explained in the text.

[10] G. C. Phillips, Rev. Mod. Phys. 36, 1085 (1964); 37, 409 (1965).
[11] P. F. Donovan, J. V. Kane, C. Zupancic, C. P. Baker, and J. F. Mollenauer, Phys. Rev. 135, B61 (1964).

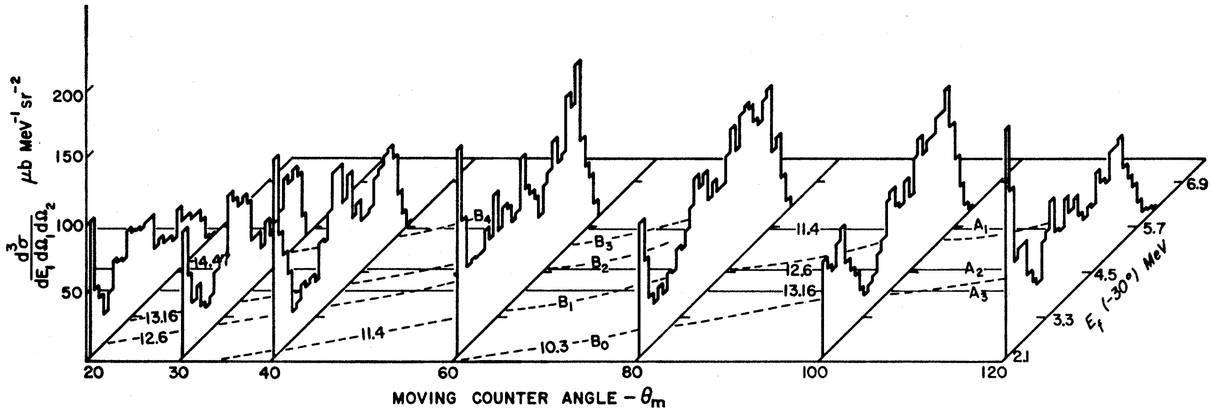

FIG. 10. This plot is similar to Fig. 9. In this case the Li[7] is left in its 480-keV first excited state.

by constructive or destructive interference.[10] Moreover, there is a broadening of any peak due to the finite solid angles and the width of the intermediate state. In our case, for $\theta_f=30°=\theta_m$, the peak at 4.05 MeV could be due to either α_1 or α_2 from the 250-keV wide, 13.16-MeV level in B[11]. Although pronounced, this peak is very broad (~1 MeV). Through such studies of the spectra in Fig. 9, we conclude that B[11] levels at 10.3, 11.4, ~12.6, and 13.16 MeV all participate in the reaction, and we cannot exclude the participation of additional levels.

Considering the case in which Li[7] is left in its 480-keV first excited state, shown in Fig. 10, we again find many peaks that cannot be explained by the phase-space distribution. It is seen that the same B[11] levels as in the previous case can give rise to the structure in these spectra. The presence of other bumps in the spectra may be due to other levels, such as those at 14.0 and 14.4 MeV.

These conclusions were verified by the following approximate method. We summed all the spectra for different θ_m. Any peaks due to second-emitted α particles moved with θ_m and were smoothed out, while peaks due to first-emitted α particles were enhanced. We found, as shown in Fig. 14, that peaks corresponding to the levels mentioned above remained. A similar sum was made assuming that all the α particles are emitted in the second stage and combining counts for different θ_m which corresponded to the same excitation energy in B[11]. The preceding conclusions were again confirmed.

To study mechanism 1c (Be[8] breakup), we found from kinematic considerations that there could be contributions to the spectra for $\theta_m \leqslant 60°$ from the 2.9-MeV level in Be[8]. If this level and the ground state of Be[8] were the main contributors to these reactions, then there should be a pronounced reduction in the intensity of the spectra for $\theta_m \geqslant 60°$; this is not observed. Also, there are peaks in the spectra for θ_m both larger and smaller than 60°. All this suggests that the contribution of the 2.9-MeV level is very small. From the spectrum shown in Fig. 13, we find that the Be[8] ground state does take part in this reaction. The total cross section for this process is shown later to be 5 mb. It is not possible to estimate the contribution of the 2.9-MeV level breakup, but it is less than a few percent of all other processes.

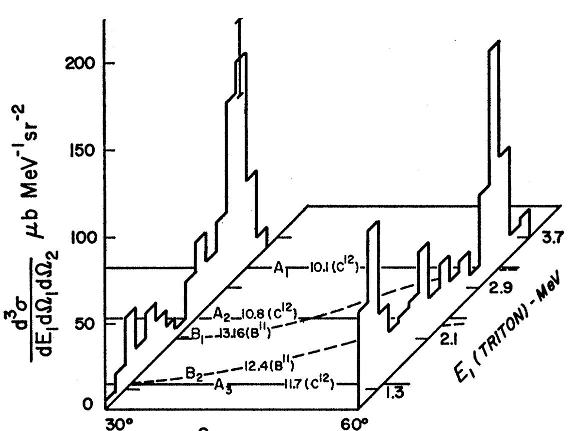

FIG. 11. The events on the t-α coincidence loci of Fig. 7 projected on the triton-energy axis.

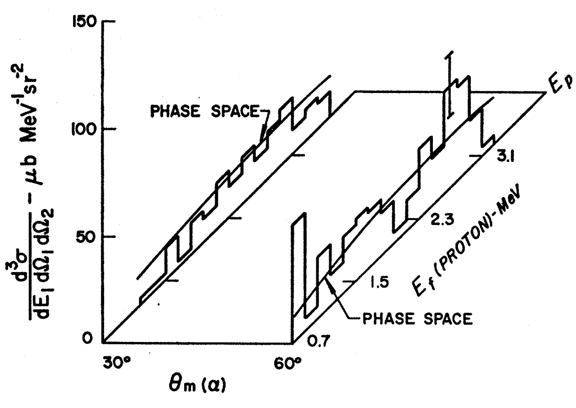

FIG. 12. The events on the p-α coincidence loci of Fig. 8, projected on the proton-energy axis. The curves labeled phase space are discussed in the text.

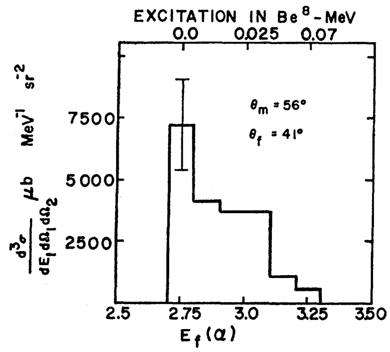

FIG. 13. The projection of the events from the $\alpha(41°)$–$\alpha(56°)$ locus onto the $E(41°)$ axis. The experimental low-energy cutoff is near 2.3 MeV. The lack of events for $2.3<E<2.75$ MeV and $E>3.3$ MeV is a genuine feature of this observation.

Total cross sections σ for the two processes 1b and 1c are estimated in the following manner. Integration of $(d^3\sigma/dE_1d\Omega_1d\Omega_2)$ over the observed energies gives $(d^2\sigma/d\Omega_1d\Omega_2)'$ for the observed energy interval. Since instrumental cutoff restricts both ends of the kinematic locus, this energy interval does not include all the particles which are emitted. Therefore, the cross section is denoted by a prime. For the B^{11} case, this is numerically integrated over $d\Omega_2$ using the data obtained at the seven lab angles and extrapolated to 0° and 180°, to obtain $(d\sigma/d\Omega_1)_L'$. Multiplying this by 4π, we get σ'. The product of σ' and the ratio of the allowed-to-observed energy ranges provides an estimate of the extrapolated total cross section σ. For the Be^8 ground-state breakup, it should be noted that if one of the α particles is detected in Ω its companion is confined to a solid angle $4\Omega_c$, where Ω_c is the solid angle of the breakup cone. The effective solid angle is[12] $\Omega_e=\Omega^2/4\Omega_c$. Neglecting the dependence of Ω_c on angle and the higher density of α particles near the cone edge, we obtain an estimate $(d\sigma/d\Omega)_L'$ which then is multiplied by 4π to give σ'. This estimate of σ' is not very accurate because of the approximation used. Table II gives the values of σ for both processes.

Reaction 3 can produce up to four final particles. If all four were produced at one time, the three-particle α-t locus would be only a boundary for a region of α-t coincidence events. A well-defined E_f-E_m locus was observed (Fig. 7); hence, this is considered to be a three-particle reaction. The data shown in Fig. 11 cannot be fitted by a phase-space distribution. States at ~12.4 and 13.16 MeV in B^{11} or at ~10.1, 10.8, and ~11.7 MeV in C^{12} could be responsible for this reaction. Not shown are the $\alpha(-30°)$-$t(\theta_m)$ and $t(-30°)$-$\alpha(\theta_m)$ loci obtained as a by-product from some observations on the α-α-Li^7 reaction (see Fig. 6).[13] These confirm the excitation of a 2-MeV wide level in C^{12} at 10.1 MeV.

TABLE II. Estimated total cross sections for reactions 1b and 1c. Primes denote quantities which include only the observed energy range. Errors are due to statistics only.

Process	$(d^2\sigma/d\Omega_1d\Omega_2)_L'$	$(d\sigma/d\Omega_1)_L'$	σ'	σ
1b	450±5 μb at 40°	4.0±0.06 mb at 30°	50±0.7 mb	90±1
1c	1900±320 μb at 41°	450±70 μb at 41°	5.1±0.8 mb	

It may be pointed out that the breakup of Li^7 (case 3d) does not fit the data at both the angles simultaneously. An experiment similar to the one employed to study the Be^8 breakup would have to be used to detect the α-t breakup of Li^7. Table III gives $(d^2\sigma/d\Omega_1d\Omega_2)_L$ values for $\alpha(\theta_m)=30°$ and 60°.

In the α-p reaction (reaction 4), the spectrum at 30° can be fitted well by a phase-space distribution, although the total number of events is small and hence the statistical uncertainties are large. However, there are peaks in the spectrum for $\alpha(\theta_m)=60°$ (Fig. 12), indicating that the direct breakup mechanism is not sufficient to explain the reaction. Figure 15 shows the spectra of Fig. 12 divided by the phase-space factors. The peaks in the $\alpha(\theta_m)=60°$ spectrum are seen for proton energies of 1.6 and 2.7 MeV. These peaks correspond to the following excitation energies in the several possible intermediate nuclei: 16.0 and 15.0 MeV in C^{14}; 12.1 and 13.1 MeV in B^{11}, or 0.25 and 1.0 MeV in Li^5 (which is, of course, not consistent with our knowledge of Li^5). If these levels really participated in the reaction, then there should be peaks in the $\alpha(\theta_m)=30°$ spectrum at these values of E_p: the same as at 60° for C^{14} or 1.1 and 2.1 MeV for B^{11}. But for $\alpha(\theta_m)=30°$, we see only weak bumps at $E_p\sim2.2$ and 3.0 MeV, indicating that the 13.16-MeV level in B^{11} may participate in the reaction.

Insufficient data were taken for these last reactions to perform an integration over the angles. To compare the various reaction yields, the values of $(d^2\sigma/d\Omega_1d\Omega_2)_L'$ and $(d^2\sigma/d\Omega_1d\Omega_2)_L$ for $\alpha(\theta_m)=30°$ and 60° are given for

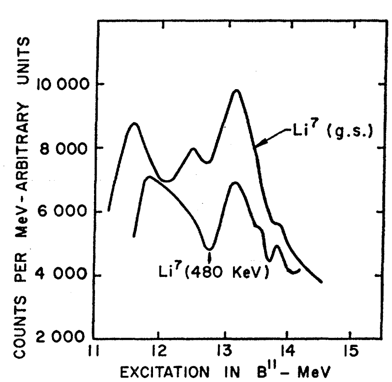

FIG. 14. Events shown in Figs. 9 and 10, all assumed to be the first-emitted α particles, are summed for all θ_m and shown as a function of excitation energy in B^{11}. Those peaks which are due to first-emitted particles are expected to be enhanced.

[12] R. E. Brown, J. S. Blair, D. Bodansky, N. Cue, and C. D. Kavaloski, Phys. Rev. **138**, B1394 (1965).

[13] R. Jambunathan, Ph.D. thesis, University of Minnesota, 1967 (unpublished).

TABLE III. "Differential" cross sections for the various processes when the α particle is emitted at 30° in the laboratory system. Errors are statistical. There may be a 15% error due to target thickness and solid angles.

Reaction (See Table I)	θ_m	Observed E_{max} (MeV)	Observed E_{min} (MeV)	$(d^2\sigma/d\Omega_1 d\Omega_2)_L'$	$(d^2\sigma/d\Omega_1 d\Omega_2)_L$
1 (Li^7)	30° (α)	6.0	2.2	280±3 μb	590±6 μb
	60° (α)	6.5	2.2	495±5 μb	950±9 μb
1 (Li^{7*})	30° (α)	5.4	2.2	145±1.5 μb	320±3 μb
	60° (α)	6.0	2.2	270±3 μb	510±6 μb
3	30° (t)	3.6	0.9	85±8 μb	180±20 μb
	60° (t)	3.7	0.9	115±8 μb	240±20 μb
4	30° (p)	3.6	1.1	36±5 μb	85±12 μb
	60° (p)	3.2	0.7	68±7 μb	160±17 μb

each case in Table III. The extrapolated values are the observed values multiplied by $\Delta E_{\text{allowed}}/\Delta E_{\text{observed}}$, when $\Delta E_{\text{allowed}}$ is the total energy range kinematically accessible to the reaction.

The $Li^6+Be^9 \rightarrow \alpha+\alpha+Li^7$ reaction has been recently studied at 3.3 MeV at the University of Chicago.[14] By observing the Li^7 and α continuum spectra, they conclude that the direct breakup contribution is not large, Be^8 does not participate in the reactions, many levels in B^{11} contribute, $\sigma(Li^7)=25\pm7.7$ mb, and $\sigma(\alpha)\simeq104$ mb for the continuum α particles. From our experiments we conclude that the direct breakup contribution is small (<5%), the Be^8 ground state does form and contributes 5–10%, many levels in B^{11} participate in these reactions, and the cross sections $\sigma'(\alpha)$ leading to Li^7 and Li^{7*} are 50 and 25 mb ($\sigma\simeq90$ and 45 mb), respectively. A crude estimate of $\sigma'(\alpha)$ leading to the production of t and p is about 20 mb ($\sigma\simeq45$ mb). Therefore, $\sigma'(\alpha)$ excluding the α-n reaction is about 95±15 mb [$\sigma(\alpha)=180\pm30$]. These estimates do not differ very much from the Chicago estimates. It should be remembered that our σ' values are calculated in a very approximate way and that the σ are upper limits. It may be worth pointing out that the $Be^9(Li^7,2\alpha)Li^8$ reaction does proceed through the Be^8 ground-state breakup, in which $\sigma(Li^8)$ is about 50 mb, suggesting $\sigma(\alpha)\simeq100$ mb.[15,16]

CONCLUSIONS

The results of these experiments indicate that the 2α reactions go mainly through a sequential process, forming B^{11} as the intermediate nucleus; the direct breakup mechanism contributes very little. The many wide and overlapping levels in B^{11}, the kinematic broadening of the peaks corresponding to these levels, the experimental limitations, and the nonzero spins of the various nuclei involved make it very difficult to make any quantitative calculations. The 13.16-MeV level, though it contributes to these reactions, is by no means predominant, and there seems to be no reason to assume any special cluster structure for this level. We find that among the many kinematically accessible levels in B^{11}, the ones at 10.3, 11.4, 12.6, 13.16, and 13.5 MeV excitation contribute a major share. We find evidence in our α-γ study for the existence of two new levels in B^{11} at 12.6 and 13.5 MeV. The inclusion of the 12.6-MeV level helps greatly to explain the α-α coincidence data, while invoking the 13.5-MeV level neither hinders nor helps the analysis of the α-α data.

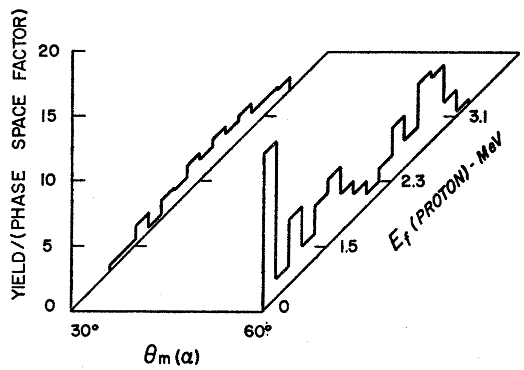

FIG. 15. The data shown in Fig. 12 have been divided by the phase-space factor.

The results for the t-α coincidences suggest that the 12.6- and 13.16-MeV levels in B^{11} may participate in the reaction. Also, there is a suggestion of the production of the 10.1-MeV level in C^{12}. The contribution of a direct breakup process is very small.

In the p-α reaction, there may be appreciable contributions from a direct breakup, but it is not the only mechanism involved. The scanty data do not warrant any stronger conclusions. The fruitfulness of this type of experiment, when the intermediate nucleus has many levels, is quite limited.

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