Total Cross Sections and Angular Distributions of the $C^{12}(Li^6,p)O^{17}$, $C^{12}(Li^6,d)O^{16}$, and $C^{12}(Li^6,\alpha)N^{14}$ Reactions from 4.5 to 5.5 MeV†

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The Li^6+C^{12} reaction has been studied for bombarding energies in the range 4.5 to 5.5 MeV. Angular distributions and total cross sections have been obtained at 100-keV intervals using a dE/dx-E system coupled to a computer. The reaction products which have been studied are proton groups from the ground and first four excited states of O^{17}, deuterons from the ground and first four excited states of O^{16} (the 6.05–6.13-MeV doublet unresolved), and alpha particles from the ground and second excited states of N^{14}. The angular distributions of certain of the particle groups show a rather strong energy dependence. The total cross sections, however, are smoothly increasing functions of energy. There is no strong $(2J+1)$ dependency in total cross sections that would imply a statistical compound-nucleus decay. The relatively smooth variation of the angular distributions of deuterons from the excited states of O^{16} and alpha particles from the second excited state of N^{14} suggests that these proceed predominantly via a direct reaction. The ground-state groups would appear to have significant compound-nucleus contributions.

I. INTRODUCTION

In recent years the investigation of multinucleon transfer reactions has received considerable attention (cf. Ref. 1 for a survey of "deuteron" transfer reactions). In the particular case of the two-nucleon transfer reaction, Glendenning[2] has shown how the observed selectivity of this type of reaction in populating residual nuclear states arises. Because of the apparent $(\alpha+d)$ cluster structure of Li^6,[3] the (Li^6,α) and (Li^6,d) reactions should, in principle, be useful for studies of deuteron and alpha particle transfers. In this regard the Li^6+C^{12} reaction is particularly suited for this purpose because many of the states of N^{14} and O^{16} have been interpreted in terms of two and four nucleons outside a C^{12} core.[4,5] One would expect, in general, large cross sections for transitions to these states and direct-reaction features in their angular distributions.

The Li^6+C^{12} reaction has been investigated at lower energies for the incident Li^6. The $C^{12}(Li^6,\alpha)N^{14}$ reaction has been studied at energies of 1.7,[6] 3.0,[7] and 3.2–4.0 MeV,[8] while $C^{12}(Li^6,p)O^{17}$ and $C^{12}(Li^6,d)O^{16}$ have been studied at the latter two energies.[7,9] With the exception of the reactions leading to O^{16} and O^{17} at 3.2–4.0 MeV, the results obtained have been qualitatively interpreted in terms of a direct-reaction mechanism. In particular, Inglis[10] has given an interpretation of the shapes of the alpha-particle angular distributions obtained at 1.7 MeV. The results showed the ground-state group having a backward peak and the transition to the 3.95-MeV state of N^{14} exhibiting both forward and backward peaking. Honda and Horie[11] have analyzed the results at 4.0 MeV using the plane-wave Born approximation (PWBA) and both light- and heavy-particle stripping. They obtain reasonably good agreement with the data. The work of Blair and Hobbie (Ref. 9) on the protons and deuterons, however, showed an abrupt energy dependence in the angular distributions which were taken every 200 keV. This was interpreted as evidence for a significant compound nucleus contribution to the reaction mechanism.

The inverse reactions $O^{16}(d,Li^6)$ and $N^{14}(\alpha,Li^6)C^{12}$ have been studied at deuteron and alpha energies of 14.6 and 42 MeV,[12,13] respectively, corresponding to Li^6 energies of 10.8 and 35.8 MeV. These have been analyzed using the distorted-wave Born approximation (DWBA) for the pickup of an alpha and deuteron.

In the present work the Li^6+C^{12} reaction has been studied in the energy range 4.5 to 5.5 MeV at 100-keV intervals. Angular distributions have been obtained for proton groups from the 0.0-, 0.87-, 3.06-, 3.85-, and 4.55-MeV states of O^{17}, deuterons from the 0.0, (6.05–6.13), 6.92- and 7.12-MeV states of O^{16}, and alpha particles from the 0.0- and 3.95-MeV states of N^{14}. The distributions have been taken at 10-deg intervals from approximately 10 to 150 deg (center-of-mass system).

II. EXPERIMENTAL PROCEDURE

The Li^6 beam from the University of Iowa 5.5-MeV Van de Graaff was used in this experiment. A Y magnet located in the high-voltage terminal allows the use of a

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1 D. A. Bromley, *Symposium on Nuclear Spectroscopy with Direct Reactions*, edited by F. E. Throw, Argonne National Laboratory Report ANL-6848, 1964 (unpublished).
2 N. K. Glendenning, Phys. Rev. **137**, B102 (1965).
3 Y. C. Tang, K. Wildermuth, and L. Pearlstein, Phys. Rev. **123**, 548 (1961).
4 W. W. True, Phys. Rev. **130**, 1530 (1963).
5 B. Roth and K. Wildermuth, Nucl. Phys. **21**, 196 (1960).
6 Pham-Dinh-Lien and L. Marquez, Nucl. Phys. **33**, 202 (1962).
7 S. Bashkin, V. P. Hart, and W. A. Seale, Phys. Rev. **129**, 1750 (1963).
8 R. K. Hobbie and F. F. Forbes, Phys. Rev. **126**, 2137 (1962).
9 J. M. Blair and R. K. Hobbie, Phys. Rev. **128**, 2282 (1962).
10 D. R. Inglis, Phys. Rev. **126**, 1789 (1962).
11 T. Honda and H. Horie (to be published).
12 W. W. Daehnick and L. J. Denes, Phys. Rev. **136**, B1325 (1964).
13 C. D. Zafiratos, Phys. Rev. **136**, B1279 (1964).

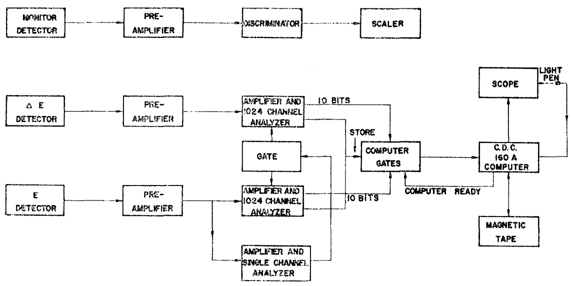


FIG. 1. Block diagram of electronics.

conventional rf ion source in addition to the lithium ion source. The absolute energy calibration of the accelerator is known to $\pm 0.2\%$ using the $Li^7(p,n)Be^7$ threshold.

The target chamber used for the present work has been described elsewhere.[14] The beam is defined at the entrance to the chamber by a pair of antiscattering apertures of diameters 2 and 2.5 mm located 15 cm from the target. A surface-barrier detector positioned at 90° lab was used to monitor the reaction and served to normalize the data.

Reaction particles were detected with a lithium-drifted silicon detector (E detector) with an acceptance angle of ± 1.3 deg. Particle identification was accomplished using a gas proportional counter.

The targets were self-supporting carbon foils ranging in thickness from 7.4 to 9.6 $\mu g/cm^2$. Target thicknesses were measured using the shift in energies of the $Li^7(p,n)Be^7$ threshold, and the $Be^9(p,\gamma)B^{10}$ resonance at 1.881 and 1.084 MeV, respectively. Conversion of energy loss to micrograms per centimeter^2 was made using data from Whaling.[15] Extrapolation of recent results of Allison *et al.*[16] on the stopping powers of Li^6 in N_2 results in an effective target thickness of ~ 50 keV for the beam.

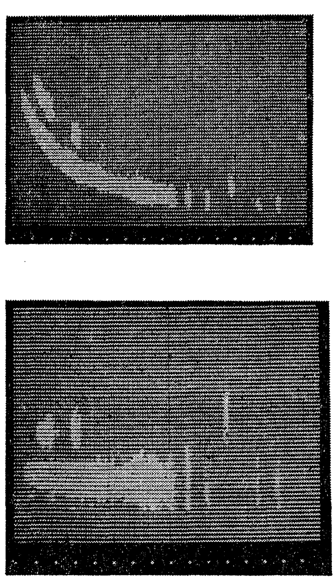


FIG. 2. Top: condensed dE/dx-versus-E display; bottom: condensed dE/dx-versus-E display after multiplication (see text).

Figure 1 shows a block diagram of the electronics used. A Control Data 160-A computer was used for two-parameter analysis of the E and ΔE signals with the computer output written in turn on magnetic tape. This system has been described in more detail elsewhere.[17] All data analysis was also performed by the computer. The data on magnetic tape were first multiplied in the form $E(\Delta E+C)$, where C is an arbitrarily chosen constant. The effect of this is shown in Fig. 2. The top picture shows a condensed dE/dx versus E display of the raw data while the bottom picture shows the same data after multiplication. The multiplication was done for convenience in further analysis of the data. The multiplied data were then scanned and marked with a light pen in the regions between protons and deuterons, etc. After this operation, a 1024-channel spectrum of each particle group could be displayed with provision for summation by the computer of the number of counts in any peak. The method of analysis has been described elsewhere in more detail.[18]

Absolute differential cross sections were obtained by normalizing the results at each energy to the average differential cross section of $d_{1,2}$ obtained from two to five runs using standard integration techniques. The effect of carbon buildup was monitored by comparing yields from different targets, one of which had been bombarded for a long period of time. An assigned relative error of $\pm 8\%$ between the results at different energies is believed to be in large part due to this effect. In addition there is an estimated error of $\pm 20\%$ in the absolute cross section scale due, for the most part, to uncertainties in target thickness and equilibrium charge of the Li ions after passing through the carbon foils.[19] Absolute measurements were made at 4.0 MeV for comparison to previous results.[8,9] The total cross sections obtained were $\sim 15\%$ lower which is within our estimated error. A probable error of 10–15% was assigned in the previous work.

III. RESULTS

a. Protons

Figure 3 shows a typical energy spectrum of the proton groups from states of O^{17}. Because of the complexity of the level structure above $\sim$7.5-MeV excitation the peaks are not well resolved in this region. [The full width at half-maximum (FWHM) peak widths ranged from 120 keV for protons to 250 keV for low-energy α particles.] The continuum which begins at

[14] K. G. Kibler, M.S. thesis, University of Iowa, 1964 (unpublished).
[15] W. Whaling, *Handbuch der Physik* (Springer-Verlag, Berlin, 1958), Vol. XXXIV.
[16] S. K. Allison, D. Auton, and R. A. Morrison, Phys. Rev. **138**, A688 (1965).
[17] R. R. Carlson and E. Norbeck, Phys. Rev. **131**, 1204 (1963).
[18] D. W. Heikkinen, University of Iowa Report, University of Iowa 65-24 (unpublished).
[19] The equilibrium charge of Li was taken from C. Zaidins, California Institute of Technology Report, 1962 (unpublished).

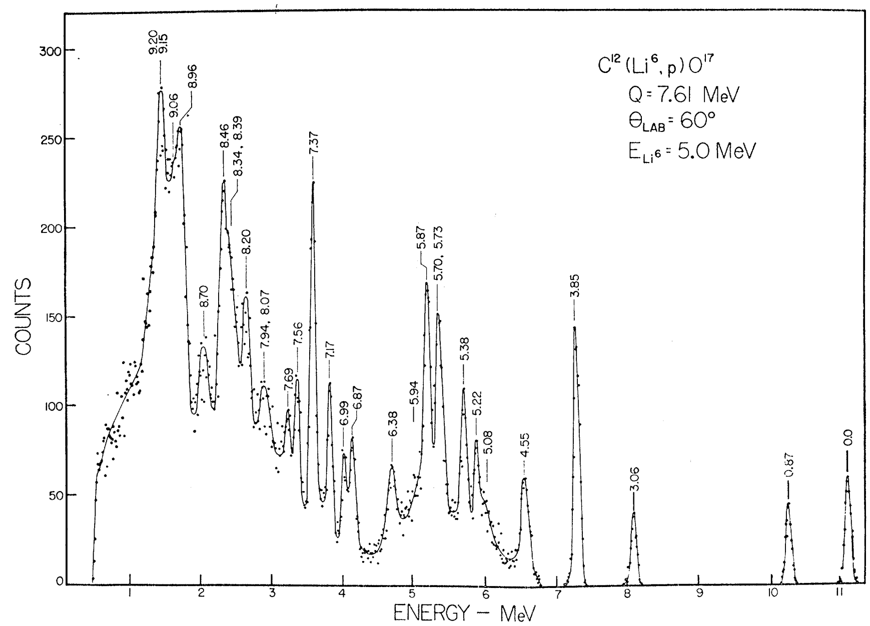


FIG. 3. Energy spectrum of protons from $C^{12}(Li^6,p)O^{17}$. Excitation energies in MeV are above each peak.

$\sim$4.5-MeV excitation can be ascribed to reactions which have as the final state $O^{16}+p+n$ or $C^{13}+He^4+p$. The Q values for these reactions are 3.45 and 1.25 MeV, respectively.

The results of excitation-curve measurements taken at 42° lab are presented in Fig. 4. As has been noted, each point has associated with it an error of $\pm 8\%$. It can be seen that a certain amount of structure is apparent, outside of errors. However, no evidence is seen for strong compound-nucleus resonances.

The angular distributions of the proton groups (p_0-p_4) are shown in Figs. 5–9. Also shown are the coefficients A_L/A_0 obtained by fitting the angular distributions to a Legendre polynomial expansion of the form

$$\frac{d\sigma}{d\Omega}=A_0\left(1+\sum_{L=1}^{L_{\max}}\frac{A_L}{A_0}P_L(\cos\theta)\right).$$

For the proton groups $L_{\max}=6$ resulted in a satisfactory fit while $L_{\max}=8$ was needed for the deuteron- and alpha-particle groups.[20] The error bars on the A_L/A_0 coefficients represent the residual fitting errors.[21] These are always larger than the statistical errors in the present work. By taking the ratio A_L/A_0 the effect of rapidly increasing penetrabilities in the incident channel can be eliminated to some extent when considering energy dependence.

It is apparent from the data that the proton groups tend to show large variations over the entire energy range with lesser variations from one energy to the next. This is more readily seen in the Legendre polynomial coefficients which exhibit some degree of structure. It should also be noted that all angular distributions for the proton groups have relative maxima both forward and backward of 90 deg.

The total cross sections for the proton groups are given in Fig. 10. Total cross sections were obtained by taking $4\pi A_0$ in the Legendre polynomial expansion. The error bars represent relative errors only. Within the errors, the cross sections are smoothly increasing functions of energy.

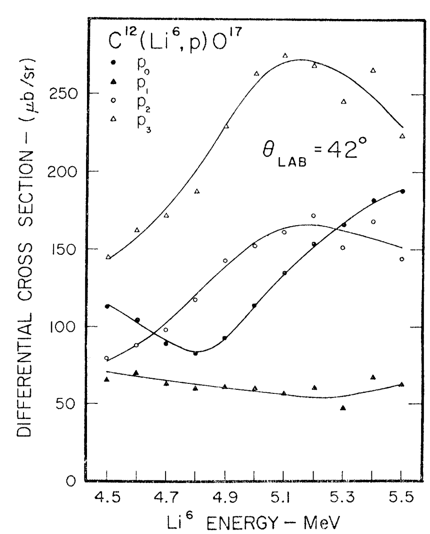


FIG. 4. Excitation curves for proton groups taken at 42° lab. Each point has a relative error of $\pm 8\%$. Cross-section scale has an error of $\pm 20\%$.

[20] The low energies of d_3 and d_4 prevented their being detected at back angles. Because of the fewer data points, satisfactory fits were not obtained for these groups.

[21] M. E. Rose, Phys. Rev. 91, 610 (1953).

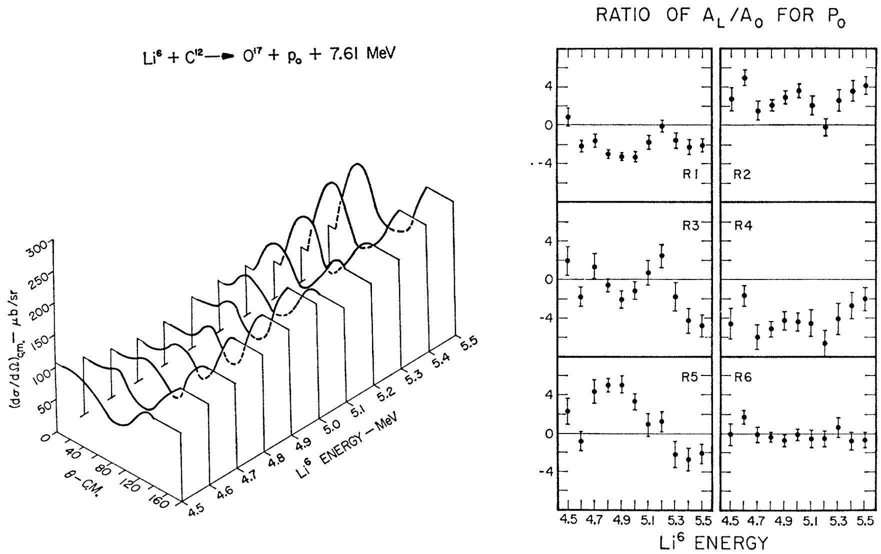


FIG. 5. Left: angular distributions of protons from $C^{12}(Li^6,p_0)O^{17}$. Right: Legendre-polynomial coefficients. The ratio A_1/A_0 is denoted by R_1, A_2/A_0 by R_2, etc.

b. Deuterons

The energy spectrum of deuteron groups from states of O^{16} is shown in Fig. 11. The excited state groups show large yields in comparison to the ground-state reaction. This is in part due to the $(2J+1)$ statistical factor for these states. As noted previously, the 6.05–6.13-MeV doublet is unresolved. However, the main contribution to this doublet is due to the 6.05-MeV (0^+) state. This is based on two observations. The first is that the width of the peak indicates a contribution due mainly to one state. Secondly, the energy calibration for the observed peak comes close to the expected position of the 6.05-MeV state alone.[22] Figure 12 shows clearly the relative yields of the two states at a more forward angle. This supports the above conclusion.

The excitation curves for the deuteron groups from Fig. 13 show a marked difference between that of the ground state and those for the excited states. As can be seen the yield curves for the excited state groups are smoothly increasing with energy.

The angular distributions in Figs. 14–16 again show a different energy dependence between the ground- and excited-state groups. The latter have a generally smooth variation with energy, whereas the ground-state group does not, particularly above 5.0-MeV bombarding energy. This is made more evident by a comparison of the Legendre polynomial coefficients for d_0 and $d_{1,2}$

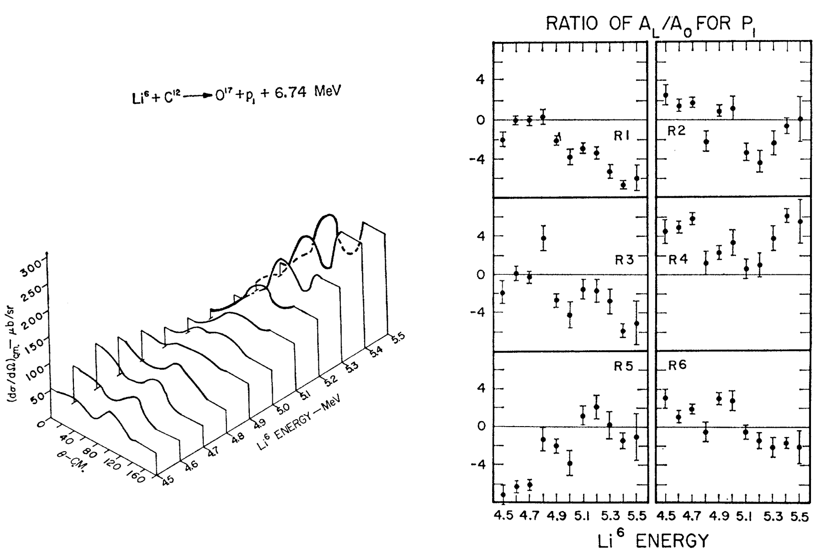


FIG. 6. Left: angular distributions of protons from $C^{12}(Li^6,p_1)O^{17}$. Right: Legendre-polynomial coefficients (see caption for Fig. 5).

[22] The energy calibration was accurate to ±50 keV.

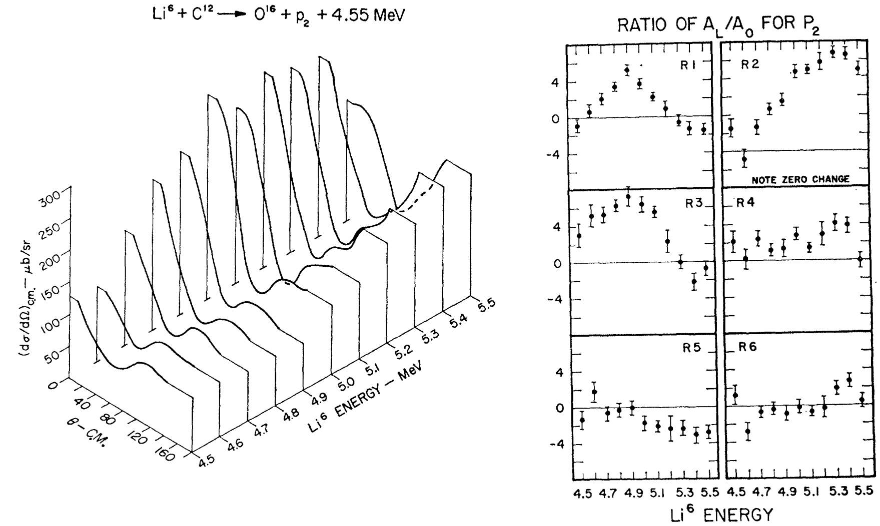


FIG. 7. Left: angular distributions of protons from $C^{12}(Li^6,p_2)O^{17}$. Right: Legendre-polynomial coefficients (see caption for Fig. 5).

from Figs. 14 and 15. The character of the d_0 angular distribution changes from more forward peaked at energies <5.0 MeV to backward peaked at the higher energies.

The total cross sections of the deuteron groups in Fig. 17 again show the large yield of the excited-state groups in comparison to the ground-state transition.[23] It should also be noticed that despite the fact that the d_0 angular distribution had a rather strong energy dependence, the total cross section shows no evidence of this in terms of resonance structure.

c. Alpha Particles

An energy spectrum of alpha particles from states of N^{14} is presented in Fig. 18. There is weak population of the 2.31-MeV ($T=1$) state in contrast to lower energies where the yield is larger. A discussion of the cross section for this state as a function of energy has been presented elsewhere.[24] As previously noted, the inherently poorer energy resolution for alpha particles precluded any quantitative measurements on individual levels above 3.95-MeV excitation.

Figure 19 shows the yield-curve measurements for

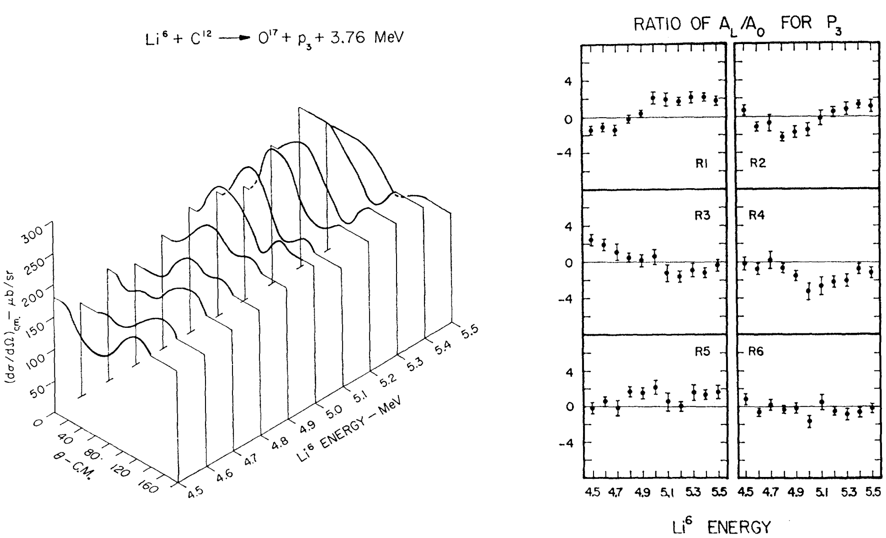


FIG. 8. Left: Angular distributions of protons from $C^{12}(Li^6,p_3)O^{17}$. Right: Legendre-polynomial coefficients (see caption for Fig. 5).

[23] The total cross sections for the d_3 and d_4 groups were obtained by an area integration. This was normalized to 180 deg by adding an amount equal to the average differential cross section integrated over the nonobserved angles.

[24] R. R. Carlson and D. W. Heikkinen, Phys. Letters (to be published).

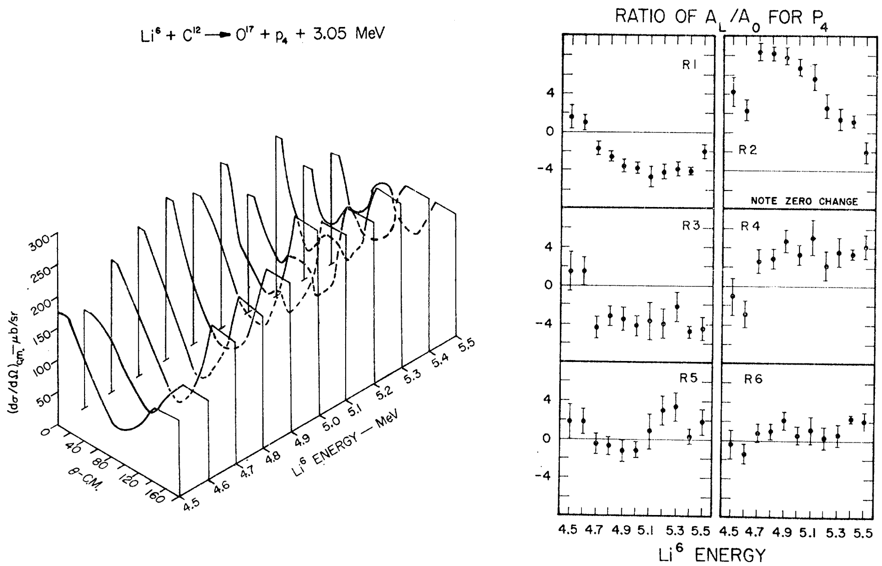


FIG. 9. Left: Angular distributions of protons from $C^{12}(Li^6,p_4)O^{17}$. Right: Legendre-polynomial coefficients (see caption for Fig. 5).

alpha particles. The α_0 curve shows somewhat more structure than that for α_2.

The angular distributions of the two alpha-particle groups are shown in Figs. 20 and 21. As was the case for the deuterons the ground-state group shows considerably more energy variation than does the α_2 group. This can also be noticed in the Legendre polynomial coefficients which show much less energy dependence for the α_2 coefficients.

Total cross sections are given in Fig. 22. It is interesting to note that even though the spin and parities of both states are the same (1^+), the cross section for α_2 is a factor of ~ 2 larger over the entire energy range. The energy dependence of the α_0 cross section shows some evidence of structure but not outside the relative errors. This hint of structure is due in part to the fact that equally good fits to the data were not obtained at all energies.

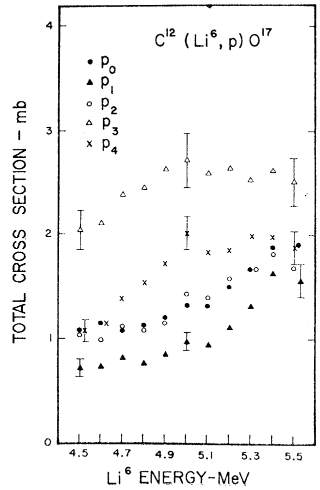


FIG. 10. Total cross sections for the proton groups. Relative errors are shown by typical error bars. Cross-section scale has an error of ±20%.

d. Summary of Results

We can briefly summarize the general features of the results. Large cross sections are observed for transitions to the excited states of O^{16} and N^{14} relative to the ground state groups. Reactions which have the smallest cross sections tend to show the most energy dependence in their angular distributions. Essentially all particle groups have total cross sections which increase smoothly with energy.

In the next section a qualitative interpretation of these results will be given.

IV. DISCUSSION

The observation of a rather strong energy dependence in the angular distributions of certain of the particle groups is suggestive of compound nucleus contributions to the reaction mechanism. However, the lack of correlated resonance structure in the excitation curves or total cross sections indicates the reaction is not proceeding via strong isolated resonances in the compound nucleus F^{18}.

The excitation of F^{18} reached in this reaction is $\sim$16.5 MeV. From the results of Ericson[25] we can make an estimate of the partial level width for neutron emission, Γ_n, for this excitation. The estimate arrived at is $\Gamma_n \sim 50$ keV. Because proton, deuteron and alpha exit channels are open we make the assumption that the total level width Γ is about $2\Gamma_n$ or $\Gamma \sim 100$ keV. From Lang[26] we can obtain an approximate value for the level spacing D. Combining this with the above value for Γ we obtain $\Gamma/D=2$ for $J=0$, 5 for $J=1$ and 2,

[25] T. Ericson, *Advances in Physics*, edited by N. F. Mott (Taylor & Francis, Ltd., London, 1960), Vol. 9, p. 425; Ann. Phys. (N. Y.) **23**, 390 (1963).

[26] D. Lang, Nucl. Phys. **26**, 434 (1961).

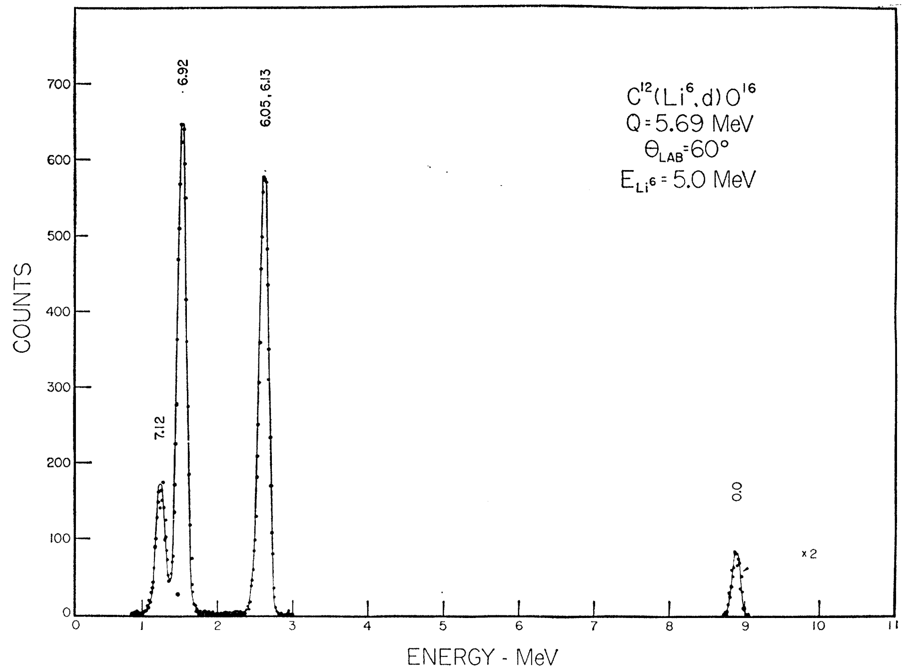


FIG. 11. Energy spectrum of deuterons from $C^{12}(Li^6,d)O^{16}$. Excitation energies in MeV are above each peak.

4 for $J=3$, and 0.6 for $J=4$. These obviously are crude approximations because we have ignored the spin dependence of level widths in addition to the above assumption. The only implication to be drawn is that we are in the region of overlapping levels where the theory of Ericson might be applicable.[27] On this basis fluctuations in both differential and total cross sections might be expected. However, it is well known[25] that orbital angular momentum and nonzero spins damp the fluctuations. An approximate expression from Ericson for the size of fluctuations in differential cross sections with spin i, I, i', I' for the particles in entrance and exit channels is given by

$$R=2/(2i+1)(2I+1)(2i'+1)(2I'+1)$$

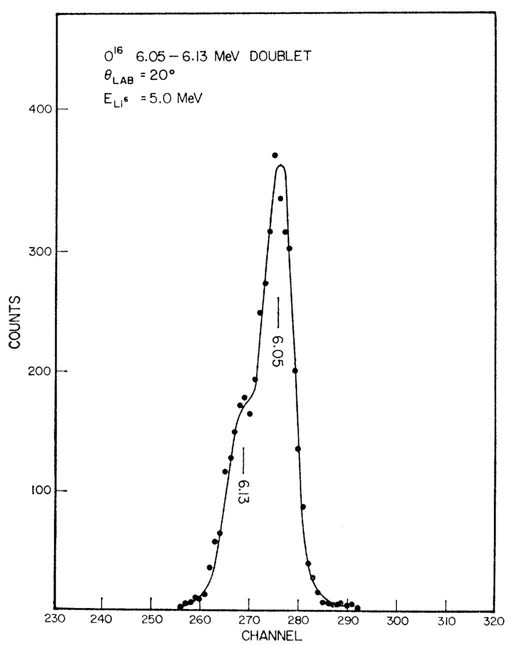


FIG. 12. Spectrum of deuterons from the 6.05–6.13-MeV doublet in O^{16} with $E_{Li^6}=5.0$ MeV and $\theta_{lab}=20°$.

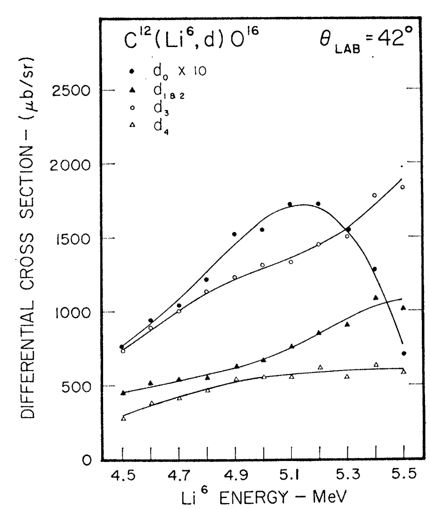


FIG. 13. Excitation curves for deuteron groups taken at 42° lab (see caption for Fig. 4).

[27] In addition to Ref. 25, see also E. Almquist, J. A. Keuhner, D. McPherson, and E. W. Vogt, Phys. Rev. 136, B84 (1964); E. W. Vogt, D. McPherson, J. A. Keuhner, and E. Almquist, *ibid.* 136, B99 (1964).

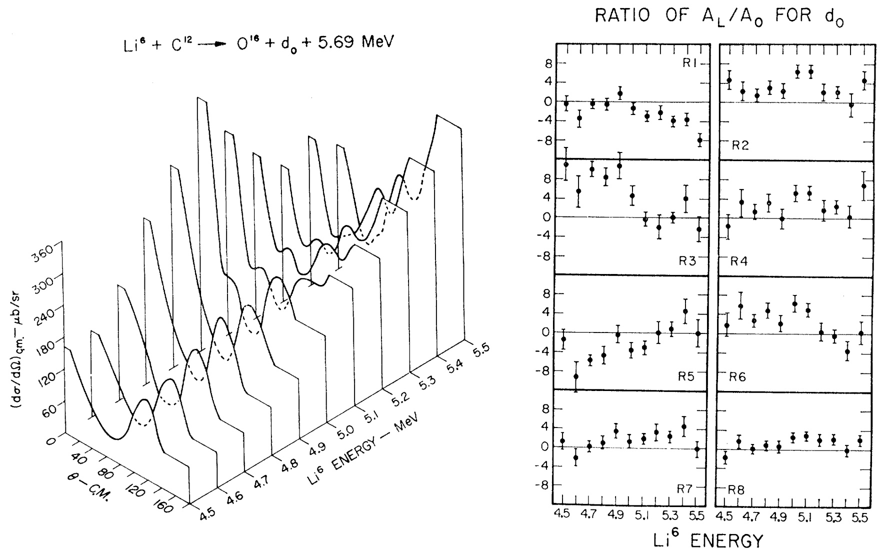


FIG. 14. Left: Angular distributions of deuterons from $C^{12}(Li^6,d_0)O^{16}$. Right: Legendre-polynomial coefficients (see caption for Fig. 5).

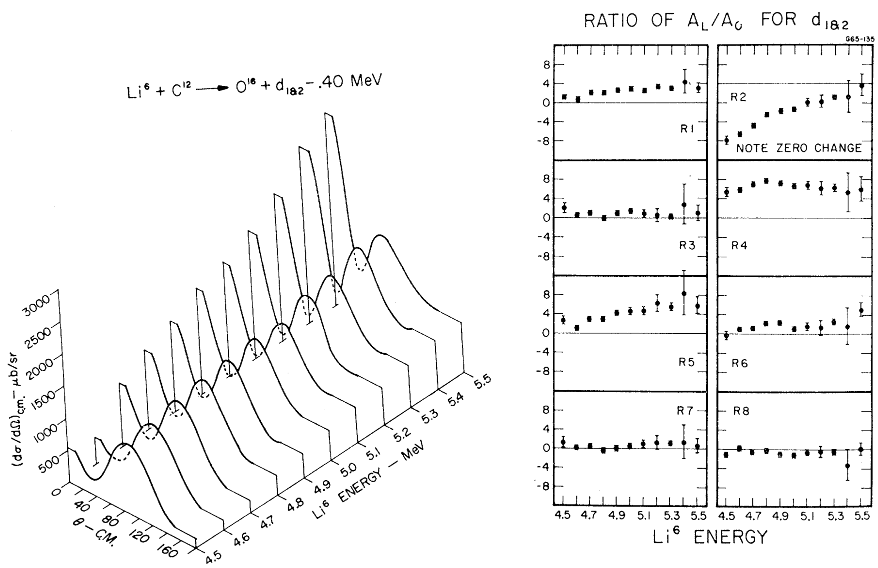


FIG. 15. Left: Angular distributions of deuterons from the 6.05–6.13-MeV doublet in O^{16}. Right: Legendre-polynomial coefficients (see caption for Fig. 5).

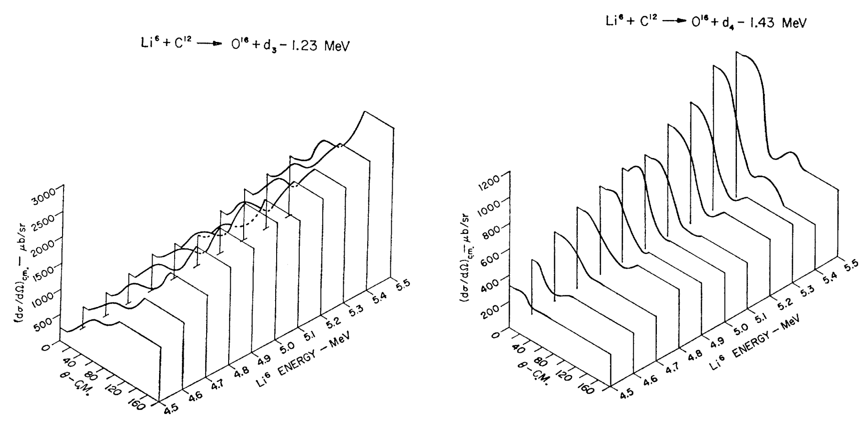


FIG. 16. Left: Angular distributions of deuterons from $C^{12}(Li^6,d_3)O^{16}$. Right: Angular distributions of deuterons from $C^{12}(Li^6,d_4)O^{16}$.

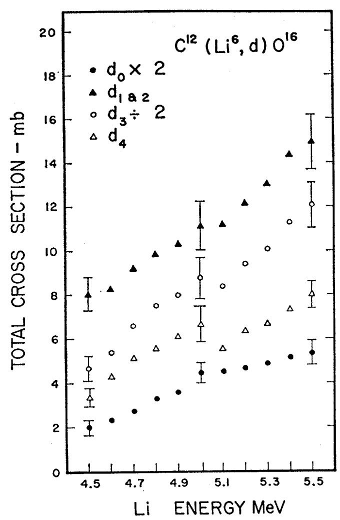


FIG. 17. Total cross sections for deuteron groups (see Ref. 23 and caption for Fig. 10).

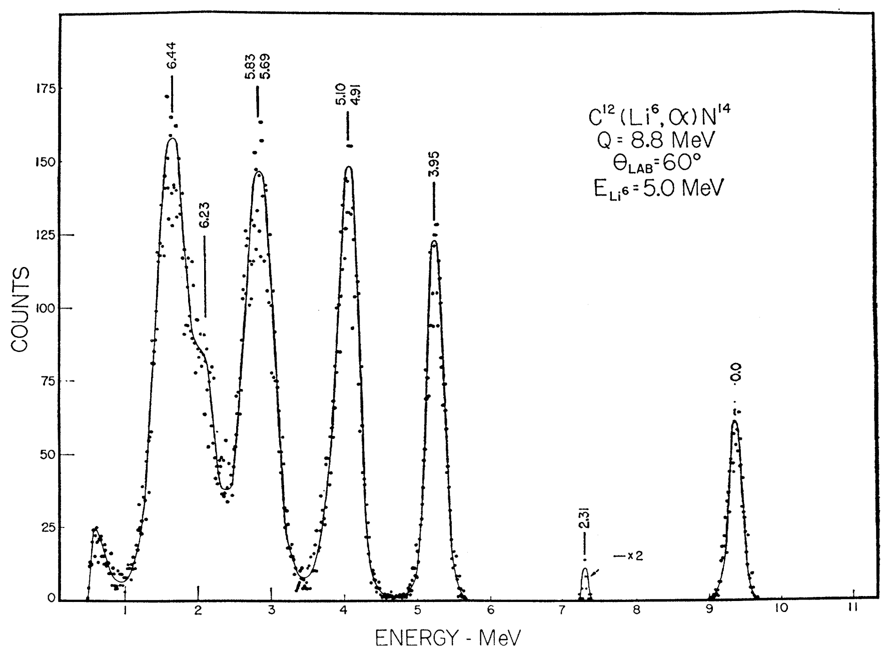
compared to $R=1$ for all spins 0. Thus, for the most favorable case (e.g., the d_0 and α_0 transitions) the fluctuations are damped by a factor of 4.5. The total cross sections are expected to show lesser variations. In addition the energy increments and energy resolution (~70 and 35 keV in the c.m. system) are larger than that usually employed in fluctuation studies.

There are some simple consequences of the statistical model which can be tested by the present data. The first is that in averaging over an energy interval ΔE greater than Γ the angular distributions are expected to be symmetric about 90 deg. In Table I the energy-averaged Legendre-polynomial coefficients are presented. As mentioned previously, the ratio A_L/A_0 tends to weight each angular distribution equally by negating the effect of increasing penetrabilities. From Table I it can be seen that with the exception of the d_0 group the even L coefficients are indeed the largest. However, the odd-L coefficients are not all zero as would be expected for a purely statistical reaction. This is not unexpected because the angular distributions of certain groups do show a smooth variation with energy as expected on the basis of a direct reaction.

Another test of the statistical model can be made in considering relative total cross sections to a specific residual nucleus. Under certain conditions set forth by McDonald,[28] relative cross sections are proportional to $(2J_f+1)$, where J_f is the spin of the residual nuclear state.[29] In Table II the average cross sections and the same divided by $(2J_f+1)$ are presented. While there is some tendency for a proportionality to $(2J_f+1)$, the deviations are large. In particular, the spin-averaged cross sections are generally larger for excited states in comparison to ground states. Corrections for barrier penetrabilities in the outgoing channel would increase the discrepancy.

The cross sections for the deuterons from the excited states of O^{16} support the evidence for rotational bands with large alpha widths obtained from the $C^{12}(\alpha,\alpha)C^{12}$ reaction.[30] In addition, Kelson[31] has given an interpreta-

FIG. 18. Energy spectrum of alpha particles from $C^{12}(Li^6,\alpha)N^{14}$. Excitation energies in MeV are above each peak.



[28] N. McDonald, Nucl. Phys. **33**, 110 (1962).

[29] In this regard, the Li+B reactions show a strong dependency on $(2J_f+1)$. See R. R. Carlson and R. L. McGrath, Phys. Rev. Letters **15**, 173 (1965).

[30] E. Carter, G. Mitchell, and R. Davis, Phys. Rev. **133**, B1421 (1964).

[31] I. Kelson, Phys. Letters **16**, 143 (1965).

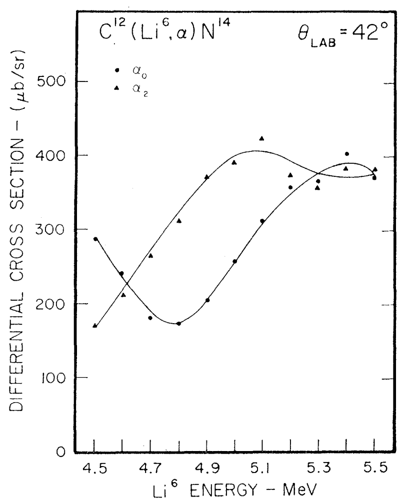


FIG. 19. Excitation curves for alpha particles taken at 42° lab (see caption for Fig. 4).

tion of the level structure of O^{16} in terms of single-particle excitations and rotational bands. The levels at 6.13 and 7.12 MeV are found to be single-particle excitations. It is noticed that these states have cross sections which are smaller in comparison to the other excited state groups. These would not be expected to have large cross sections in reactions involving the transfer of an alpha particle.

As has been mentioned, the cross sections for the alpha particle groups differ by a factor of 2. On the basis of a direct reaction it would be expected that (Li^6,α) and (α,d) reactions might exhibit similar characteristics. This is because the transferred pair of nucleons are in the same configuration ($S=1$, $T=0$). A comparison of the results of Pehl *et al.*[31] on the $C^{12}(\alpha,d)N^{14}$ reaction with the present work shows entirely different results for relative cross sections. They find the ground-state yield a factor of 3 larger than that of the 3.95-MeV level which is in agreement with the $(p_{1/2})^2$ and $(p_{3/2})^{-1}(p_{1/2})^{-1}$ configurations proposed for ground and second excited states.[4] However, we find essentially the opposite for the relative cross sections.

Large momentum transfers in a direct reaction usually lead to a reduction of the cross section (see Ref. 1). The momentum transfers here are $L\sim 5$ and 4 at forward angles for the ground and second excited states. However, the angular momentum mismatch is greater

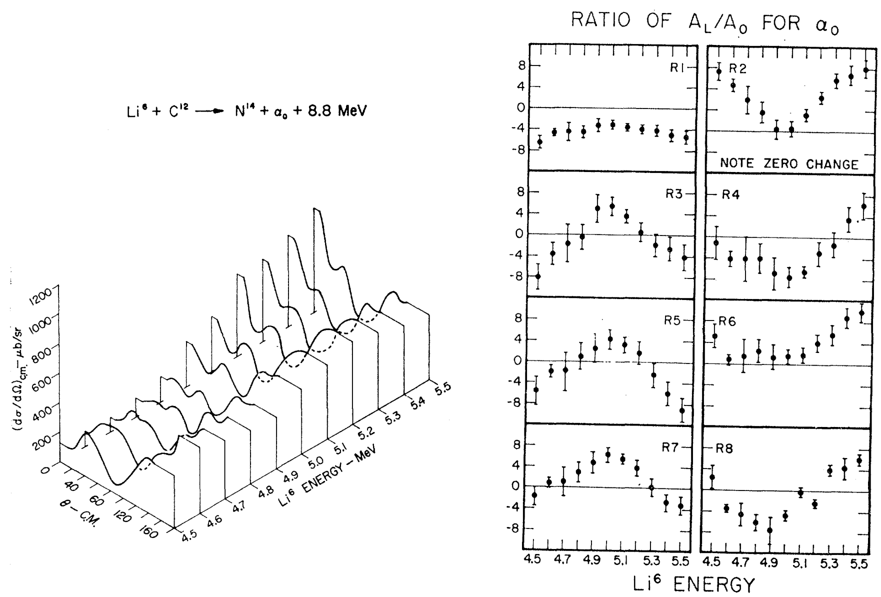


FIG. 20. Left: Angular distributions of alpha particles from $C^{12}(Li^6,\alpha_0)N^{14}$. Right: Legendre-polynomial coefficients (see caption for Fig. 5).

TABLE I. Energy-averaged Legendre-polynomial coefficients A_L/A_0.

Particle group	A_1/A_0	A_2/A_0	A_3/A_0	A_4/A_0	A_5/A_0	A_6/A_0	A_7/A_0	A_8/A_0
p_0	−1.9 ±0.6	2.7 ±0.9	−0.96±1.1	−4.2±1.2	1.3 ±1.1	0.03±0.08		
p_1	−2.9 +0.6	−0.32±1.0	−2.0 +1.1	3.5±1.1	−2.4 ±1.1	0.31±0.85		
p_2	1.3 ±0.5	6.6 ±0.6	3.5 ±0.9	2.0±0.9	−1.5 ±0.8	0.07±0.7		
p_3	0.67±0.4	−0.46±0.6	0.12±0.7	01.4±0.7	0.98±0.7	−0.35±0.5		
p_4	−2.5 ±0.7	8.2 ±0.9	−2.9 ±1.1	2.5±1.1	0.84±1.2	0.76±1.0		
d_0	−2.2 ±1.0	3.0 ±1.6	5.0 ±2.3	2.6±2.0	−2.0 ±2.0	2.4 ±1.8	1.7±1.5	1.1 ±0.9
$d_{1,2}$	2.8 ±0.6	−5.5 ±0.8	1.1 ±1.0	6.6±1.0	4.7 ±1.1	1.9 ±0.9	0.8±0.9	−0.53±0.8
α_0	−4.4 ±1.0	6.7 ±1.5	−0.59±2.1	2.4±2.4	−1.4 ±2.2	4.0 ±1.8	1.6±1.6	−0.64±1.1
α_2	5.0 ±1.5	11.3 ±1.3	3.3 ±2.3	14.7±1.8	5.3 ±2.2	2.6 ±1.9	2.1±1.5	−2.0±1.4

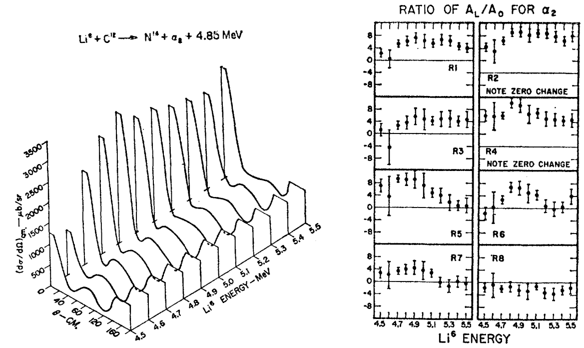


FIG. 21. Left: Angular distributions of alpha particles from $C^{12}(Li^6,\alpha_2)N^{14}$. Right: Legendre-polynomial coefficients (see caption for Fig. 5).

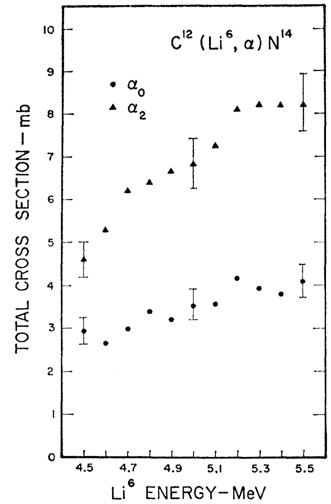


FIG. 22. Total cross sections for the alpha-particle groups (see caption for Fig. 10).

for the second excited state based on ^3S configuration[10] for this level, compared to ^3D for the ground state. Thus it would be expected the reaction to the 3.95-MeV level would be inhibited, which is not the case.

A possible explanation can be found in the results of Glendenning.[2] He finds the cross section depends on a "structure factor" G, which contains, besides the usual reduced width dependence, a dependence on the overlap of the motion of the transferred nucleons in the projectile and residual nucleus. In a classical picture the two nucleons in Li^6 have their spins aligned and their angular momentum vectors opposed to form a ^3S. The same picture has their angular momentum vectors aligned in the ground state of N^{14}. The relative motion is different in the initial and final state implying an inhibition of the ground-state reaction. The same arguments lead to an expected large cross section for the ^3S state of N^{14}. While this is an extremely simplified interpretation it has some consequences which can readily be tested. If the relative motion of the two nucleons is indeed the determining factor in (Li^6,α) reactions, then the "giant yield" states[32] observed in other two-nucleon transfer reactions on C^{12} and O^{16} would not show large relative cross sections. These 5^+ states have configurations $(d_{5/2})^2$ which, using the simple classical picture, means aligned angular momentum vectors and the consequences stated above.

Higher bombarding energies would be required for the observation of the alpha particles from the giant yield state in N^{14} at 9.0-MeV excitation.

TABLE II. Average cross sections.

Particle group	J^{π} [a]	Average[b] cross section (mb)	Spin-averaged[c] cross section (mb)
p_0	$\frac{5}{2}^+$	1.4	0.23
p_1	$\frac{1}{2}^+$	1.1	0.55
p_0	$\frac{1}{2}^-$	1.4	0.7
p_3	$\frac{5}{2}^-$	2.5	0.42
p_4	$\frac{3}{2}^-$	1.7	0.43
d_0	0^+	2.0	2.0
d_1	0^+	5.6[d]	5.6[d]
d_2	3^-	5.6[d]	0.8[d]
d_3	2^+	17.0	3.4
d_4	1^+	6.0	2.0
α_0	1^+	3.5	1.2
α_2	1^+	7.0	2.3

[a] Spins and parities of residual nuclear states.
[b] The cross section obtained by simply averaging the values obtained at each energy.
[c] The average cross section divided by $(2J+1)$.
[d] These values assume equal contributions to the 6.05–6.13-MeV doublet. However, the main contribution comes from the 0^+–6.05-MeV state (see text).

V. CONCLUSION

The results obtained show evidence for both compound-nucleus and direct-reaction mechanisms. The particle groups which show evidence for compound nucleus contributions are those which are favored by barrier penetrabilities in the exit channels. Those which are not show smoothly varying angular distributions characteristic of a direct reaction. The cross sections for the deuteron groups from excited states of O^{16} are in agreement with the predicted structure of these states. In the case of (Li^6,α) reactions it is suggested that the relative motion of the transferred nucleons can be a large factor in determining relative cross sections.

[32] R. H. Pehl, E. Rivet, J. Cerny, and B. G. Harvey, Phys. Rev. 137, B114 (1965).

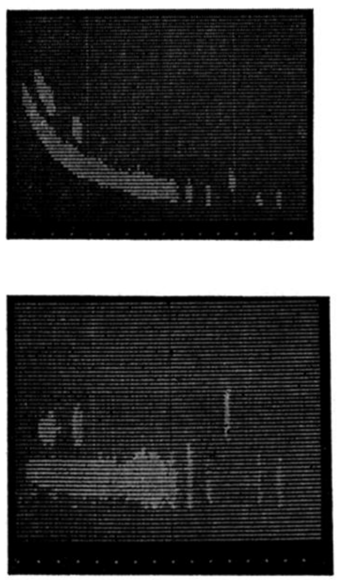


FIG. 2. Top: condensed dE/dx-versus-E display; bottom: condensed dE/dx-versus-E display after multiplication (see text).