Differential Cross Sections for the Reactions $C^{12}(Li^6,p)O^{17}$ and $C^{12}(Li^6,d)O^{16}$ from 3.4 to 4.0 MeV*†

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Absolute differential cross sections are presented for the reactions $C^{12}(Li^6,p)O^{17}$ (ground state and first three excited states) and $C^{12}(Li^6,d)O^{16}$ (ground state), for laboratory energies from 3.4 to 4.0 MeV. Total cross sections are about 1 mb at 4.0 MeV. Fluctuations in the angular distributions and total cross sections suggest that the reactions proceed via the compound nucleus F^{18} which is excited to the region of overlapping levels. This is in contrast to the predominantly direct character of the previously studied reaction $C^{12}(Li^6,\alpha)N^{14}$.

INTRODUCTION

PREVIOUS studies in this laboratory of the charged particles from nuclear reactions induced by lithium ions have been limited to alpha particles by the thin sensitive region of the junction detectors employed. Alpha-particle differential cross sections[1] have shown features of direct interactions, e.g., the transfer of a deuteron cluster from Li^6 to the target nucleus in the reaction $C^{12}(Li^6,\alpha)N^{14}$. It seemed interesting to study the reaction mechanism when a more complex rearrangement of nucleons is involved. The availability of lithium-drifted junction detectors[2] has made it possible to extend our measurements to the reactions $C^{12}(Li^6,p)O^{17}+7.61$ MeV and $C^{12}(Li^6,d)O^{16}+5.69$ MeV. We were unable to detect the reaction $C^{12}(Li^6,He^3)N^{15}-0.94$ MeV, because of the low energy of the emerging He^3 ions. Other reactions producing charged particles are not energetically possible with our 4.1-MeV maximum beam energy.

APPARATUS AND PROCEDURE

The accelerator, target chamber, and target were the same as used previously.[1,3,4] The particle detection and identification system was modified to accommodate the greater range and smaller specific ionization of protons and deuterons compared to the alpha particles previously studied. The proportional counter gas pressure was increased to 74 cm Hg to reduce the fluctuations in pulse size caused by the Landau effect.[5] The drifted lithium silicon junction detector used to measure the energy of the charged particles had a sensitive region thick enough to stop the most energetic protons encountered. However, a "dead layer" on the front surface prevented it from responding to any but the most energetic alpha particles present.

The pulse multiplication circuit used previously was modified for greater stability. Multiplication made use of the logarithmic current-voltage characteristic of a semiconductor; since this characteristic is temperature sensitive, the transistors were placed in an oil bath cooled by tap water. In our laboratory, the water temperature has long-term variations but is quite constant for several days. The response of the multiplier was checked before the start of each day's work and showed 1 to 2% day-to-day stability.

Figure 1 shows a typical spectrum of multiplier output pulses. The groups produced by the highest energy alpha particles, the deuterons, and the protons are labeled. The pulses below the proton group were due to alpha particles which lost most of their energy in the "dead layer" of the junction detector. These pulses did not appear when the alpha particles were screened out by suitable absorbers or when a surface barrier detector was used in place of the drifted lithium junction detector. A calculation of the spread in pulse heights expected from the Landau effect in the proportional counter indicates that the multiplier resolution is limited by that effect. In normal operation, a single-channel analyzer (with separately adjustable upper and lower channel boundaries) selected the multiplier output pulses corresponding to the desired particle. These then gated the 100-channel analyzer which recorded the energy spectrum of the particles.

In this work, several runs were taken at 10° intervals from 10° to 160°, at bombarding energies of 3.5, 3.7, 3.9, and 4.1 MeV. At each angle proton and deuteron spectra were recorded alternately. Figure 2 shows the spectra obtained at 4.1 MeV and 20°. For purposes of comparison, the proton and deuteron data from successive runs are plotted together. As can be seen from the histograms, the identification circuit allowed a mixing of the proton and deuteron spectra which did not exceed 1 or 2%. As the angle of observation was increased the energy of the deuteron groups decreased more rapidly than the proton energy, so that the groups would have been inseparable without the particle identification system. The energy resolution shown in Fig. 2 reflects the spread of Li^6 energy due to the 200-keV-thick carbon target.

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* Supported in part by the Office of Naval Research.
† This work was reported briefly at the April, 1962 meeting of the American Physical Society; Bull. Am. Phys. Soc. 7, 336 (1962).
[1] R. K. Hobbie and F. F. Forbes, Phys. Rev. **126**, 2137 (1962).
[2] Obtained from Solid State Radiations, Inc., Culver City, California.
[3] J. J. Leigh and J. M. Blair, Phys. Rev. **121**, 246 (1961).
[4] R. K. Hobbie, C. W. Lewis, and J. M. Blair, Phys. Rev. **124**, 1506 (1961).
[5] R. M. Eisberg and G. Igo, Rev. Sci. Instr. **25** ,450 (1954).

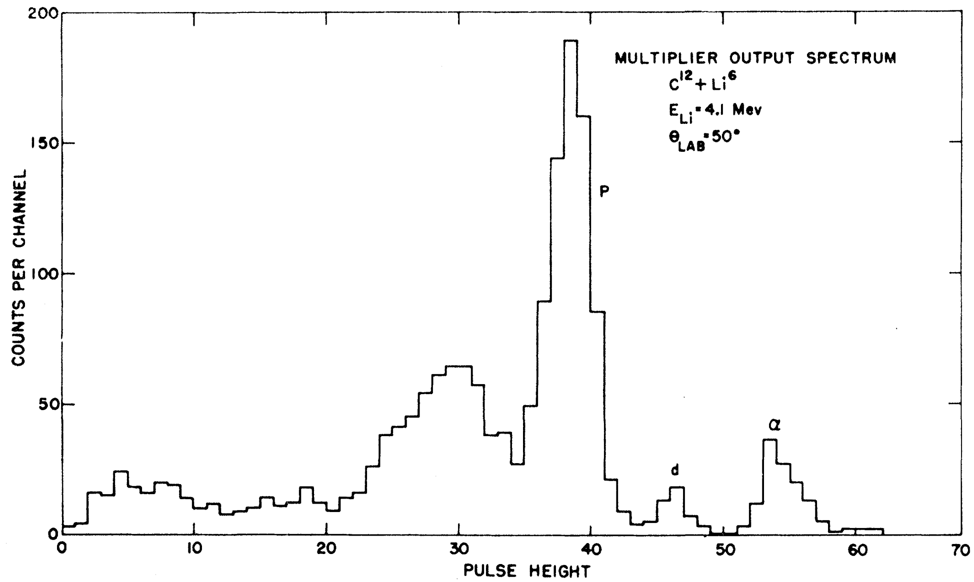

FIG. 1. Spectrum of pulses from the particle identification circuit. The output is proportional to $0.6\log(E)+\log(dE/dx)$.

In addition to the well-defined groups of protons, there are also protons produced by two reactions involving three-body breakup. These are $C^{12}(Li^6,np)O^{16}+3.46$ MeV and $C^{12}(Li^6,\alpha p)C^{13}+1.25$ MeV. The proton pulses from the former reaction spread from 9 to 43 V in Fig. 2, while the latter reaction produced proton pulses below 21 V. These wide groups and the decrease of level spacing with increasing excitation energy limited our analysis to the d_0, p_0, p_1, p_2, and p_3 groups.

The targets were fragile, and several were used during the experiment. The data from these different targets were normalized to 50° data taken at each energy with a single target.

Absolute differential cross sections were measured by comparing the proton and deuteron yields to the yield of alpha particles from the reaction $C^{12}(Li^6,\alpha_0)N^{14}$. The absolute cross section for this reaction has been measured[1] by comparison with 3.3-MeV Li^6 ions elastically scattered from the same target.

RESULTS

The angular distributions of deuterons from the $C^{12}(Li^6,d)O^{16}$ reaction which leave O^{16} in its ground state are shown in Fig. 3. The cross sections and angles have been converted to the center-of-mass system. The energies quoted are the effective incident ion energy, considering the target thickness and the variation of yield with energy. Figures 4–7 present the corresponding results for protons from the $C^{12}(Li^6,p)O^{17}$ reaction in which O^{17} is left in its ground, or first three excited states. The error bars represent the standard deviations

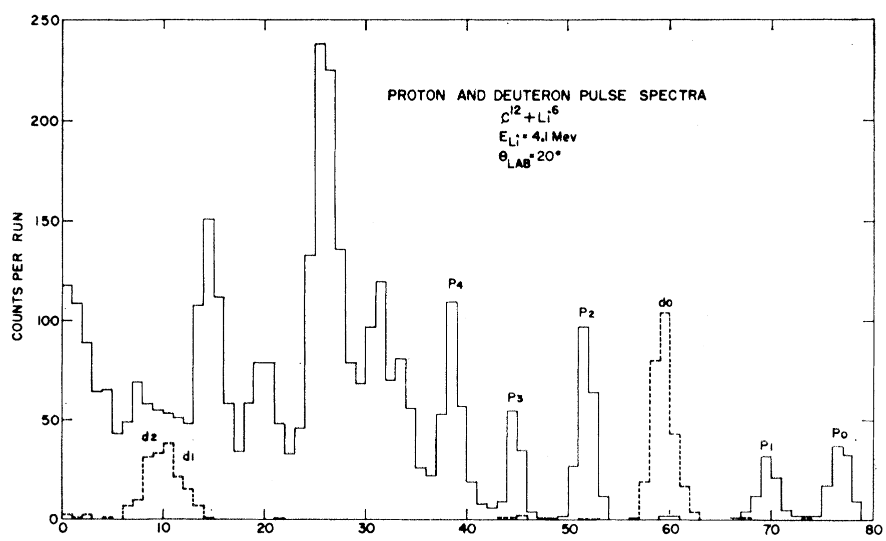

FIG. 2. Spectrum of proton and deuteron pulses from the solid-state detector.

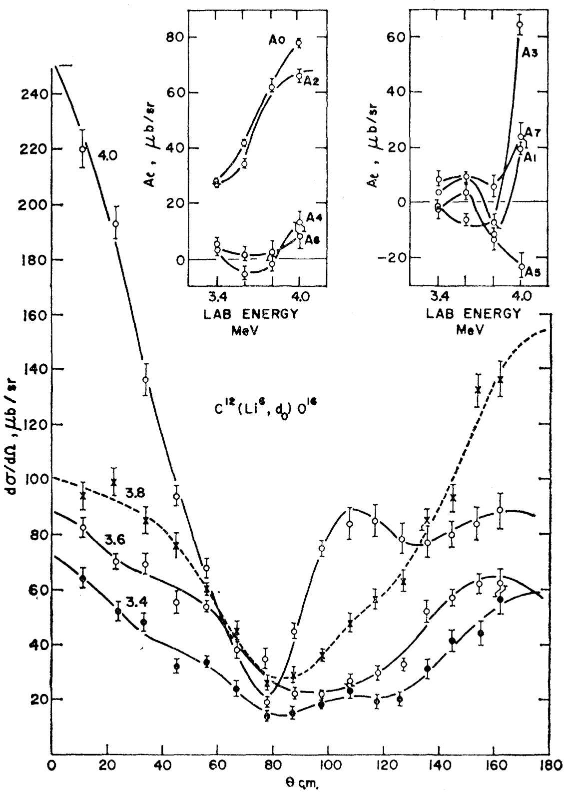

FIG. 3. Center-of-mass differential cross section for $C^{12}(Li^6,d)O^{16}$ when O^{16} is left in its ground state.

calculated from the counting statistics; most points have an uncertainty between 5 and 10%. In addition, the absolute scale of cross sections has an uncertainty of 10 to 15%. The curves are the best fits obtained from a least-squares analysis[6] of the data as a sum of Legendre polynomials, using a Control Data Corporation model 1604 computer:

$$\frac{d\sigma}{d\Omega}=\sum_{l=0}^{L} A_l P_l(\cos\theta). \quad (1)$$

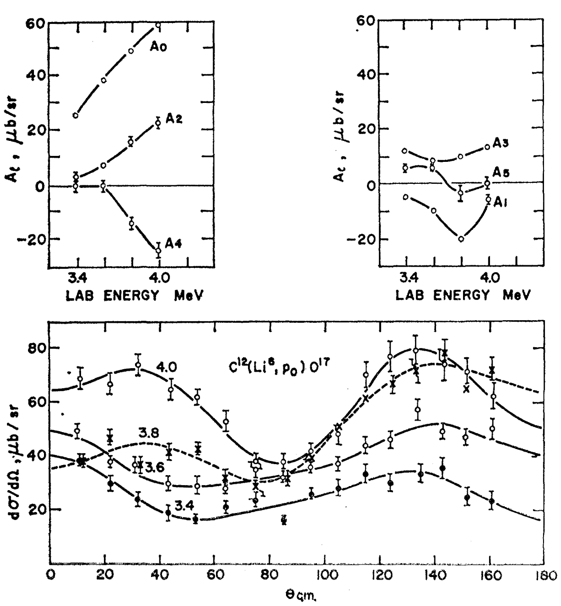

FIG. 4. Center-of-mass differential cross section for $C^{12}(Li^6,p)O^{17}$ when O^{17} is left in its ground state.

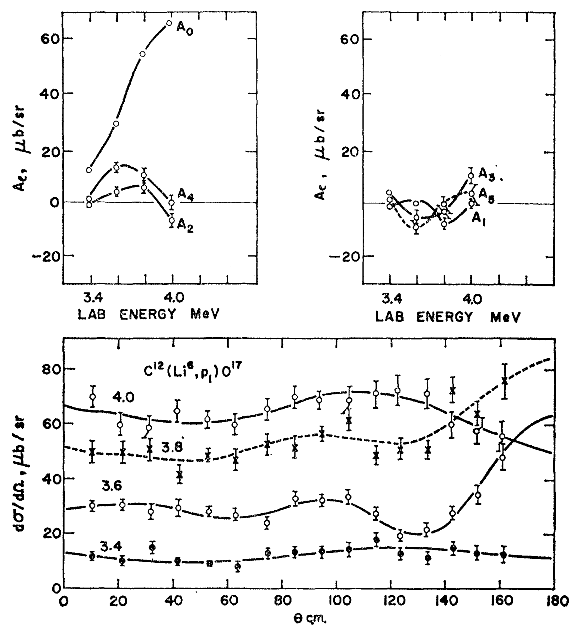

FIG. 5. Center-of-mass differential cross section for $C^{12}(Li^6,p)O^{17}$ when O^{17} is left in its first excited state.

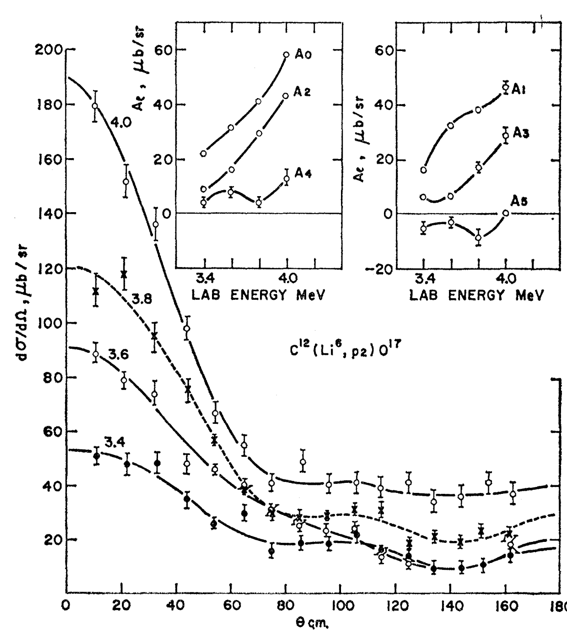

FIG. 6. Center-of-mass differential cross section for $C^{12}(Li^6,p)O^{17}$ when O^{17} is left in its second excited state.

[6] P. Cziffra and M. J. Moravcsik, University of California Radiation Laboratory Report UCRL-8523, 1958 (unpublished).

In each case the smallest value of L was used which gave a satisfactory χ^2 test of the sum of the weighted residuals.[6] The coefficients A_l, with their errors, are plotted as a function of energy at the top of Figs. 3–7.

Total cross sections are plotted as a function of incident beam energy in Fig. 8. This figure also includes the α-particle total cross sections from our earlier work.[1]

DISCUSSION

We begin our discussion by summarizing the conclusions from our earlier study[1] of $C^{12}(Li^6,\alpha)N^{14}$. The α_0 and α_2 angular distributions suggested a direct interaction: The peaks in the distributions did not shift position but increased rapidly in magnitude as the energy was increased (this is expected since the momentum transfer is a slowly varying function of energy because of the large Q of the reaction). The smooth, nearly exponential, increase of the total cross section [Fig. 8(b)] was interpreted as being due to the penetration of the Coulomb barrier. (The classical distance or closest approach of 4.0-MeV ions is 10 F, while the sum of the nuclear radii is 5.2 F.) The total cross sections were too large to be attributed entirely to a compound-nucleus reaction. These facts were all taken as evidence

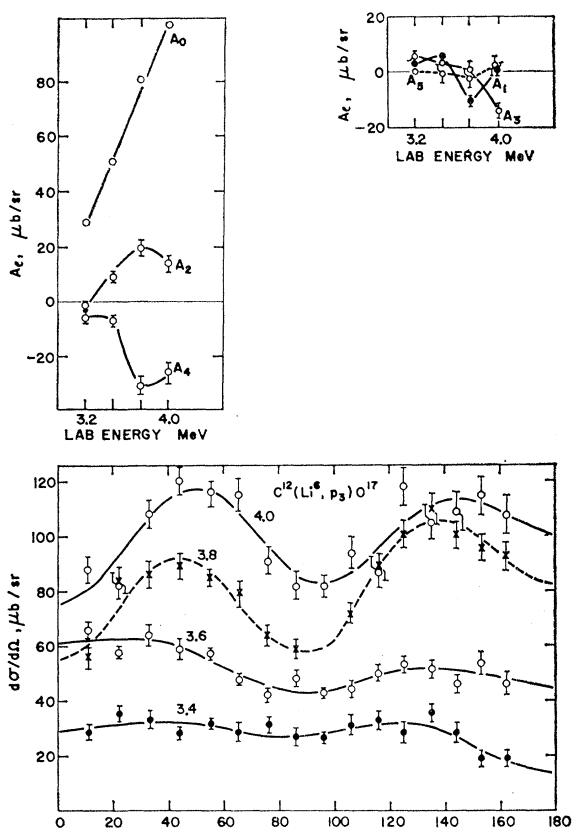

FIG. 7. Center-of-mass differential cross section for $C^{12}(Li^6,p)O^{17}$ when O^{17} is left in its third excited state.

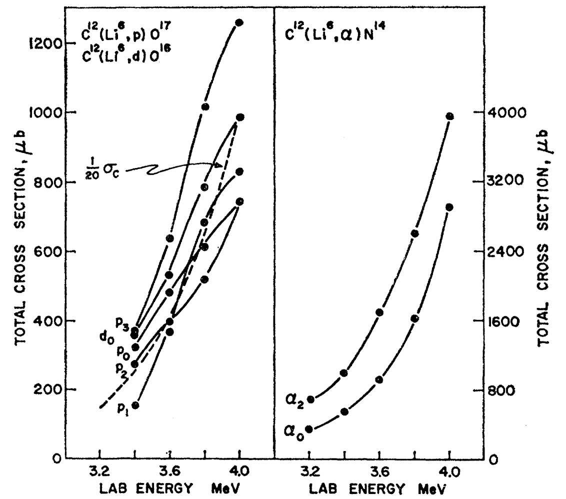

FIG. 8. Total cross sections as a functional of laboratory energy. (a) On the left are cross sections for $C^{12}(Li^6,p)O^{17}$ and $C^{12}(Li^6,d)O^{16}$. The dashed curve is proportional to the cross section for formation of the compound nucleus. (b) On the right are cross sections for $C^{12}(Li^6,\alpha)N^{14}$.

that the reactions proceeded primarily by a direct process, e.g., the transfer of a deuteron cluster from Li^6 to C^{12}. The first excited state ($T=1$) of N^{14} could not be populated by such a direct process without violation of the isotopic spin selection rule, and the small (2% of ground state) cross section for this reaction was assumed to result from the isotopic spin mixing of nearby levels in the compound nucleus, F^{18}.

The proton and deuteron data presented here, however, exhibit fluctuations in the angular distribu-

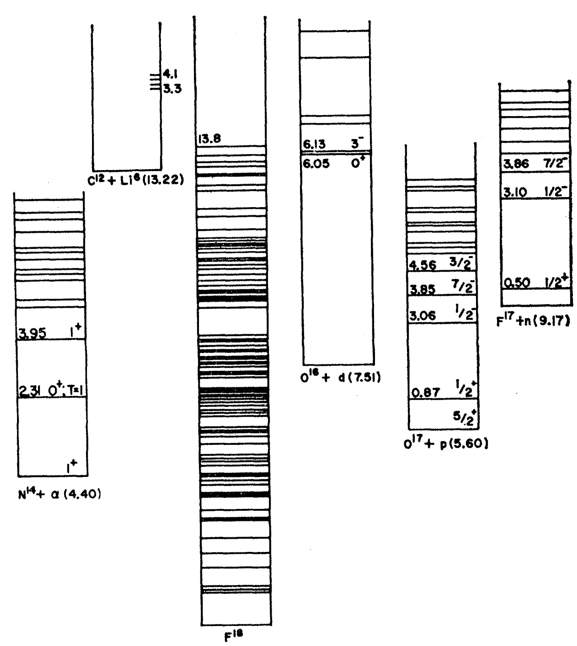

FIG. 9. Energy level diagram for the compound nucleus F^{18} and the reactions discussed in this paper.

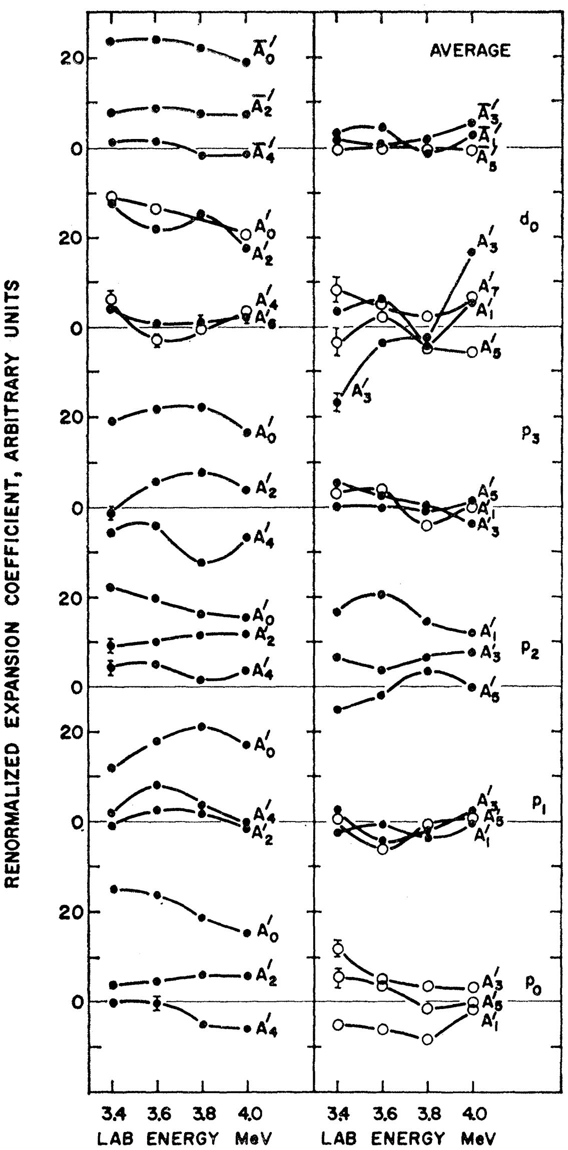

FIG. 10. Plot of the coefficients A_l' as a function of energy. The relation of A_l' to A_l is discussed in the text.

tions and total cross sections which are inconsistent with a direct process. There are abrupt changes in the character of the angular distributions for slight energy variations: The valley in the p_0 cross section shifts from 50° to 80° and the forward peak shifts from 0° to 40°, as the energy changes from 3.6 to 3.8 MeV. The p_1 cross section peaks at the back angles at 3.6 and 3.8 MeV, but not at 3.4 and 4.0 MeV. The plateau near 90° in the p_2 cross section is less pronounced at 3.6 MeV than at other energies. Only at 3.8 MeV is the backward peak larger than the forward peak in the p_3 and d_0 distributions. The d_0 cross section exhibits a peak at 110° whose height varies rapidly with energy. The total cross sections [Fig. 8(a)] do not show the smooth, nearly exponential increase with energy displayed by the α-particle cross sections. The curves are not parallel to one another, and the p_0 and p_1 curves in particular show large fluctuations of slope. Also plotted in Fig. 8(a) is the maximum cross section σ_c for the formation of the compound nucleus. This was calculated[7,8] from Coulomb barrier penetration, assuming a nuclear radius $r=(1.3\text{ F})A^{1/3}$. The total cross section for each proton and deuteron group, which is about $\frac{1}{4}$ of the cross section for α particles, is only twice as large as σ_c divided by the number of open exit channels (≈ 40). Since a Coulomb barrier reduces the cross section for many of these exit channels, this is a reasonable agreement.

One usually associates with compound nucleus processes angular distributions which are symmetric about 90°. The presence of asymmetries in the present data indicates strong interference between levels of opposite parity. Therefore, one must ask whether, at the excitation energies reached in this experiment, it is reasonable to expect such levels to interfere over large energy ranges and, at the same time, whether the lifetimes are still long enough that equilibrium in the compound nucleus can be attained. The excitation energies of the F^{18} reached in this experiment (see Fig. 9) were about 16 MeV; an extrapolation of existing level data[9] indicates that the average level spacing at that excitation is about 5 keV. (Our target thickness causes an average over 130-keV excitation energy, or 20–30 levels.) To answer the question of level width, we estimate the lifetime for neutron emission, using a formula given by Ericson,[10] to be $\tau_n \approx 1.6\times 10^{-20}$ sec or $\Gamma_n \approx 40$ keV. Since the other open exit channels (p,d,t,α) are inhibited by Coulomb barriers, the total level width might exceed this at most by a factor of 2 or 3. Interference between overlapping levels is therefore expected. Since a nucleon can traverse the compound nucleus in about 2×10^{-22} sec, equilibrium of the compound system should be nearly attainable.

Any resonance character exhibited by the expansion coefficients is masked by the rapid increase of these coefficients with energy due to the penetration of the Coulomb barrier. A partial compensation for this (neglecting differences in centrifugal barrier penetration for different partial waves) has been made in Fig. 10 by plotting as a function of energy the quantity

$$A_l'(E) \propto A_l(E)/\sigma_c(E).$$

This shows indications of resonance behavior in several of the coefficients; sharp resonances will not be seen because of the thickness of the target. It is tempting to try to learn something from these data using Ericson's

[7] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 358.
[8] I. Bloch, M. H. Hull, A. A. Broyles, W. G. Bouricius, B. E. Freeman, and G. Breit, Revs. Modern Phys. **23**, 147 (1951).
[9] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[10] T. Ericson, Phil. Mag. Suppl. **9**, 425 (1960), Sec. 10.

statistical theory[11] of compound-nucleus reactions in the region of overlapping levels; unfortunately we do not average over enough levels of the same spin and parity to make this analysis valid.

It would be interesting, if the counting rate were higher, to repeat this experiment with a thinner target to see if levels could be isolated and their spins identified by the behavior of the A_l. It is also clear that, since compound-nucleus processes do occur, α-particle emission from the compound nucleus must take place, and the α-particle data studied earlier[1] should exhibit the effects of interference between compound nucleus and direct processes. This could perhaps explain, for example, the shift in relative magnitude of the forward and backward peaks of the $C^{12}(Li^6,\alpha_0)N^{14}$ data as the energy is changed.

Fluctuating asymmetries about 90° are not a new effect; for example, such asymmetries have been observed[12–14] in the reaction $O^{16}(d,\alpha)N^{14}$, in which F^{18} is again the compound nucleus, and in the reaction[15] $F^{19}(\alpha,p)Ne^{22}$. At slightly lower excitation energies, where the level spacings are somewhat greater, Lee and Schiffer[16] have used the resonance behavior of the expansion coefficients to identify levels in C^{15}, from a study of the reaction $B^{11}(\alpha,p)C^{14}$.

The upper energy limit of the proton continuum can only be associated with a three-body breakup, in which the "α particle" in Li^6 combines with C^{12} to form O^{16}, while the proton and neutron emerge in uncorrelated directions. If the process were the emission of an unstable (singlet) deuteron by the compound nucleus, the proton and neutron, after breakup of the deuteron, would have nearly equal kinetic energies and the continuum would appear in much lower channels.

CONCLUSIONS

Differential cross sections have been presented for the reactions $C^{12}(Li^6,p)O^{17}$ (ground and first three excited states) and $C^{12}(Li^6,d)O^{16}$ (ground state) for laboratory energies from 3.4–4.0 MeV. There are strong indications that these reactions proceed via the compound nucleus F^{18} and that there must therefore be compound-nucleus effects in the previously studied reaction $C^{12}(Li^6,\alpha)N^{14}$, which proceeds largely by a direct process.

ACKNOWLEDGMENTS

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[11] Reference 10, Sec. 11.2.

[12] A. W. Dalton, S. Hinds, and G. Parry, Proc. Phys. Soc. (London) **71**, 252 (1958).

[13] W. M. Gibson and E. E. Thomas, Proc. Roy. Soc. (London) **A210**, 543 (1952).

[14] C. P. Browne, Phys. Rev. **104**, 1598 (1956).

[15] G. F. Pieper and N. P. Heydenburg, Phys. Rev. **111**, 264 (1958).

[16] L. L. Lee, Jr. and J. P. Schiffer, Phys. Rev. **115**, 160 (1959).