case of the Ni^{57}/Co^{57} ratios at the excitation-function peaks, we conclude that the anomalously low yields of Ni^{56} with respect to Co^{56} must be explained within the framework of the compound-nucleus reaction model, rather than as a direct process. As with the $Ni^{57}-Co^{57}$ excitation functions, we suggest a probable explanation of low Ni^{56} yields is a decrease in level densities for the 28-nucleon closed shell.

The $Ni^{58}(\alpha,\alpha 2n)Ni^{56}$ recoil ranges are consistent with a compound-nucleus mechanism up to the peak of the excitation function; beyond this point there is an increasing contribution from a low-momentum transfer reaction mechanism, accompanied by an increase in cross section at the highest energies studied. We feel that this data, when compared with $Fe^{54}(\alpha,2n)Ni^{56}$ and $Fe^{54}(\alpha,pn)Co^{56}$ excitation functions, implies that the direct process in question is between the incident helium ion and one or both neutrons, rather than an (α,α') inelastic scattering process followed by nucleon evaporation.

ACKNOWLEDGMENTS

We are grateful to Herman Grunder and the crew of the Lawrence Radiation Laboratory 88-in. cyclotron for the bombardments of this work, and to the Chemistry Division of the Lawrence Radiation Laboratory for permitting us to use the facility while one of the authors (M.B.) was a visitor at the laboratory. We sincerely appreciate the permission given by Professor T. T. Sugihara to quote his and Dr. Matsuo's unpublished results, and we appreciate helpful discussions with Professor Sugihara as well. We are grateful for additional thought provoking discussions in the course of this work with Professor J. M. Alexander, Professor J. M. Miller, and Dr. G. Merkel. Our thanks to L. Schwartz and J. Cooper for the drawings used in this work. We are grateful to Professor J. M. Alexander for a critical review of this manuscript. We appreciate the help of Mrs. R. Lorimer in setting up equipment for the helium-ion bombardments.

PHYSICAL REVIEW VOLUME 134, NUMBER 4B 25 MAY 1964

Differential Cross Sections for the Reaction $C^{13}(Li^6,\alpha)N^{15}$†

J. M. BLAIR, PHAM-DINH-LIEN, AND RUSSELL K. HOBBIE
School of Physics, University of Minnesota, Minneapolis, Minnesota

(Received 3 January 1964)

Differential cross sections have been measured for the reaction $C^{13}(Li^6,\alpha)N^{15}$ with the residual nucleus in its ground and first two excited states, the bombarding energy ranging from 3.4 to 4.0 MeV. They have general features suggesting a direct interaction.

INTRODUCTION AND PROCEDURE

To further the investigation of reactions induced in light nuclei by Li ions,[1–4] we have measured the differential cross sections for the reaction $C^{13}(Li^6,\alpha)N^{15}+14.69$ MeV.

The equipment for producing the beam of Li ions has been described in an earlier paper.[1] The target chamber has been designed by Pinsonneault for studying the elastic scattering Li on Li.[5]

The carbon target was made by cracking methyl iodide onto a 5×10^{-6}-in. thick nickel foil.[6] By varying the heating time and the pressure of the methyl iodide vapor, targets with different thicknesses were obtained. The target used in this experiment was produced using a pressure of 10 Torr and a heating time of 4 sec. The total thickness of the target when traversed at an angle of 45° was 380±30 keV for 3.6-MeV Li^6 ions.

Alpha particles from the reaction stopped in a silicon-junction detector whose amplified output was displayed on a 512-channel pulse-height analyzer. The angular width of the detector as seen from the target was 0.4°.

Angular distributions were measured at laboratory angles from 20° to 160° in 10° steps, for bombarding energies of 3.4, 3.6, 3.8, and 4.0 MeV.

The total number of C^{13} and C^{12} target nuclei was obtained from the yield of Li ions which underwent Rutherford scattering from carbon. The number of C^{12} nuclei in the target was determined from the yield of α particles from the reaction $C^{12}(Li^7,\alpha)N^{15}$, whose cross section is known.[3] By comparing these we found that the carbon in the target contained $(52\pm13\%)$ C^{13}. Absolute cross sections were determined by comparing the yield of α particles from the reaction $C^{13}(Li^6,\alpha)N^{15}$ with that of Li ions scattered elastically by the target nuclei.

RESULTS

We have corrected the energy by using the average energy $E_0=E_{\mathrm{machine}}-\Delta E$, where $2\Delta E$ is the energy lost

---

† This work was supported in part by the U. S. Office of Naval Research.

[1] J. J. Leigh and J. M. Blair, Phys. Rev. **121**, 246 (1961).

[2] R. K. Hobbie, C. W. Lewis, and J. M. Blair, Phys. Rev. **124**, 1506 (1961).

[3] R. K. Hobbie and F. F. Forbes, Phys. Rev. **126**, 2137 (1962).

[4] J. M. Blair and R. K. Hobbie, Phys. Rev. **128**, 2282 (1962).

[5] L. L. Pinsonneault, Ph.D. thesis, 1964, University of Minnesota (unpublished).

[6] H. D. Holmgren, J. M. Blair, K. F. Famularo, T. F. Stratton, and R. V. Stuart, Rev. Sci. Instr. **25**, 1026 (1954).

by the beam when traversing the target. The value $\Delta E = 200 \pm 20$ keV was used for all beam energies.

Several of the peaks of the typical α-particle spectrum shown in Fig. 1 agree with the known energy levels in N^{15}.[7] One of the peaks was identified as coming from the reaction with C^{12} in the target: $C^{12}(Li^6,\alpha)N^{14}$. Contamination by tritons from the reaction $C^{13}(Li^6,t)O^{16}$ was seen at a few backward angles. Contaminant peaks were separated from α-particle peaks by least-squares fitting Gaussian shapes to the multichannel analyzer spectra.[8]

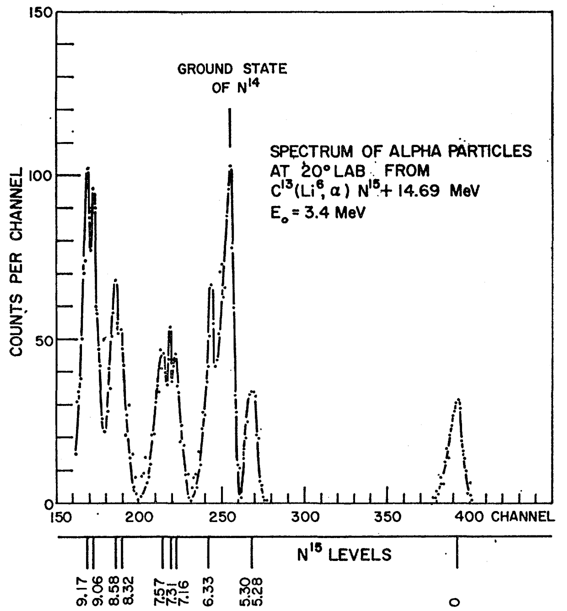

FIG. 1. Typical α-particle spectrum for the reaction $C^{13}(Li^6,\alpha)N^{15}$.

Differential cross sections for the reaction $C^{13}(Li^6,\alpha)N^{15}$ when N^{15} is left in its ground state are shown in Fig. 2. The cross sections for this reaction when N^{15} is left in its first and second excited states are shown in Fig. 3. The error bars indicate standard deviations due to counting statistics. The smooth curves are the best fits obtained from a least-squares expansion of the data in Legendre polynomials:

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

To compensate for the rapid increase of cross section with energy, the ratio A_l/A_0 is plotted in Fig. 4.

Finally, total cross sections, obtained from A_0, are shown in Fig. 5. This figure also includes for comparison the total cross sections from the reaction $C^{12}(Li^7,\alpha)N^{15}$.[3] The relative values of the differential and total cross sections have an estimated error of 10% due to counting statistics. In addition the 24% uncertainty in the C^{13} content of the target affects the absolute cross sections.

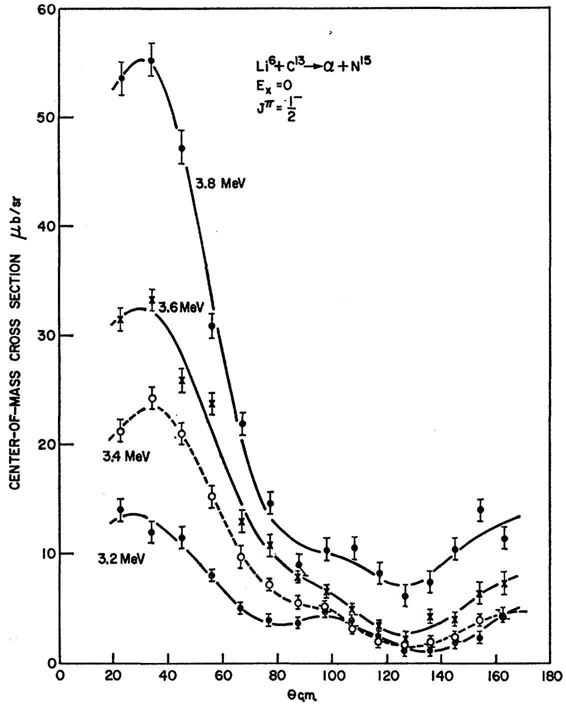

FIG. 2. Differential cross section for the reaction $C^{13}(Li^6,\alpha)N^{15}$ when N^{15} is left in the ground state.

DISCUSSION

As in all the Li reactions in which we have observed alpha particles, the reaction mechanism appears to be predominantly direct. This is indicated by the smooth variation of total cross section with energy, and the lack of fluctuation in the positions and relative amplitudes of the peaks, particularly in the reaction leading

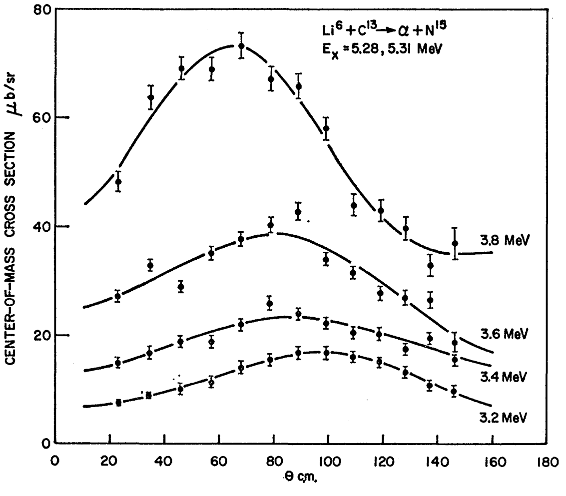

FIG. 3. Differential cross section for the reaction $C^{13}(Li^6,\alpha)N^{15}$ when N^{15} is left in the first and second excited states ($E_x = 5.28$ and 5.31 MeV).

---

[7] F. Ajzenberg-Selove and T. Lauritsen, in *Landoldt-Börnstein Tables*, edited by K. H. Hellwege (Springer-Verlag, Berlin, 1961), Group I, Vol. 1, p. 1 ff.

[8] R. K. Hobbie and L. L. Pinsonneault, Rev. Sci. Instr. **34**, 1445 (1963); P. McWilliams, W. S. Hall, and H. E. Wegner, *ibid.* **33**, 70 (1962).

to the ground state of N^{15}.[8a] The fluctuations of the ratios A_l/A_0 in Fig. 4, however, indicate that some weak compound nuclear effects may be present.[4]

It is interesting to compare these reactions with similar reactions leading to the same final states: $C^{12}(Li^7,\alpha)N^{15}$.[3] Regardless of the reaction mechanism, we would expect no similarity in the differential cross sections. The compound nucleus F^{19} is excited to 17.8 MeV in $C^{12}(Li^7,\alpha)N^{15}$, and to 19.9 MeV in $C^{13}(Li^6,\alpha)N^{15}$, for a laboratory beam energy of 3.8 MeV in each case. This difference greatly exceeds the target thickness. If we consider a "lump stripping" mechanism, the "triton" in Li^7 must be captured by C^{12} with $l=1$ to form the ground state of N^{15} while the "deuteron" in Li^6 must be captured with $l=0$ by C^{13}. (For the first and second excited states, the transfers also occur with different values of l in the two cases.) The expected dissimilarity is evident if one compares the first and second excited-state angular distribution for the present reaction with Fig. 7 of Ref. 3. Such a difference has also been noted[9] in the reactions $B^{10}(Li^7,\alpha)C^{13}$ and $B^{11}(Li^6,\alpha)C^{13}$. There is a remarkable similarity, however, between the ground-state α-particle angular distribution from Li^6 on C^{13} and the corresponding angular distribution from Li^7 on C^{12} (Fig. 6 of Ref. 3). We can only regard this as fortuitous. For example, it is possible to produce a quite good fit to the forward peak of the $C^{12}(Li^7,\alpha)N^{15}$ ground-state distribution by $[j_1(k_1R_1)]^2$, with $R_1=3.06$ F, while a fair fit can be produced to the forward peak of the $C^{13}(Li^6,\alpha)N^{15}$ ground-state distribution using $[j_0(k_1R_1)]^2$, with $R_1=4.5$ F. In each case, $\mathbf{k}_1$ is the appropriate transformed projectile stripping[10] momentum transfer. We mention this, not because a plane-wave lump-stripping model seems applicable, but to emphasize that a fortuitous similarity is possible. Yet, it does seem strange that the shapes should be so similar. One also notes some fluctuation in the slope of the excitation function for $C^{12}(Li^7,\alpha)N^{15}$ (Fig. 5), which does not occur in the case of $C^{13}(Li^6,\alpha)N^{15}$. Perhaps the compound nuclear mechanism is more important in the former case.

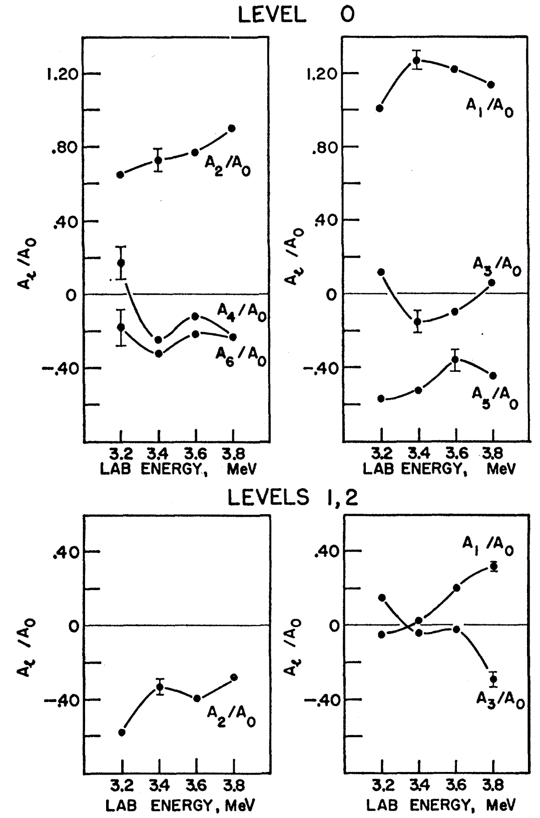

FIG. 4. Plot of the ratios A_l/A_0 as a function of energy.

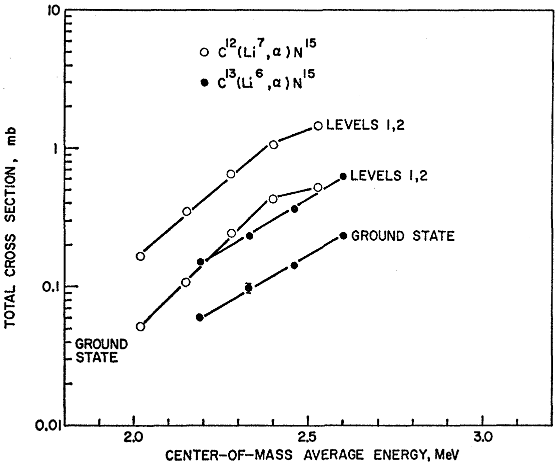

FIG. 5. Total cross sections as a function of energy.

CONCLUSION

Differential cross sections have been presented for the reaction $C^{13}(Li^6,\alpha)N^{15}$ (ground and first two excited states) for laboratory energies from 3.4–4.0 MeV. The reaction appears to be predominantly direct, although there is evidence of small compound-nuclear effects.

ACKNOWLEDGMENTS

We wish to thank F. Forbes, L. L. Pinsonneault, T. Dzubay, R. Jambunathan, D. Bauman, C. W. Lewis, and R. Stryk for helping run the Van de Graaff generator.

[8a] *Note added in proof.* This conclusion has been questioned, since the target thickness (380 keV) is appreciable compared to the energy range studied (600 keV). However, a study of the reactions $C^{12}(Li^6,d)O^{16}$ and $C^{12}(Li^6,P)O^{17}$ with a 200-keV thick target (Ref. 4) over an energy range of 800 keV showed fluctuations, whereas the reaction (Ref. 3) $C^{12}(Li^6,\alpha)N^{14}$ studied over a slightly larger energy region, did not. A lithium ion penetrating the target first loses 110 keV in a C^{13} layer, then 160 keV in the nickel backing, and finally another 110 keV in the other layer of C^{13}. Because of the variation of cross section with energy, the front layer contributes twice as many counts as the rear layer, hence the thick target is not as effective in smearing the energy resolution as it might seem.

[9] G. C. Morrison, in *Proceedings of the Conference on Direct Interactions and Nuclear Reaction Mechanisms* (Gordon and Breach, New York, 1963), p. 885.

[10] J. J. Leigh, Phys. Rev. **123**, 2145 (1961).