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^{13}C(^{6}Li,α_0)^{15}N reaction for $E_{^{6}\mathrm{Li}} = 7-17$ MeV*

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The ^{13}C(^{6}Li,α_0)^{15}N reaction has been studied in the incident-energy range of 7–17 MeV at laboratory angles of 5 and 172.5°. These data are compared with previously reported ^{12}C(^{7}Li,α_0)^{15}N data over the same energy range in the compound system ^{19}F. Resonant structure is observed in both reactions at $\theta = 5°$ with correlated structure at 24.7, 27.3, and 28 MeV excitation in ^{19}F. Interpretation of this structure in terms of the resonant-cluster transfer model of Carlson and Johnson is discussed.

[NUCLEAR REACTIONS ^{13}C(^{6}Li,α_0)^{15}N, $E = 7-17$ MeV; measured $\sigma(E)$; $\theta = 5$ and 172.5°.]

During the last decade, numerous studies of the reaction mechanism for lithium-induced transfer reactions have been made. The most extensive series[1-7] of such measurements in the incident-energy range of 4–20 MeV have been made by the group at the University of Iowa on targets of 1p-shell nuclei. The most striking common feature of these data is the appearance of strong resonance-like structure in all the transfer-reaction channels. The quantitative and qualitative interpretation of this structure in terms of existing reaction models has been unsatisfactory. As has been pointed out in the Iowa work, the high excitation energy of the compound nucleus (from 20–33 MeV) would argue against the observed structure being a result of isolated states in the compound nucleus. The width and regularity of the structure argue weakly against an interpretation in terms of Ericson fluctuations. Finally, the cross-section variation with bombarding energy is much different than one normally finds for direct reactions.

These qualitative observations led Carlson and Johnson[6] (hereafter referred to as CJ) to propose the interpretation of the structure seen in the excitation-function measurements as being due to resonances in the system composed of the target and the clusters comprising the lithium projectile. Specifically, for the case of the ^{12}C(^{7}Li,α_0)-^{15}N reaction studied by Carlson and Johnson in

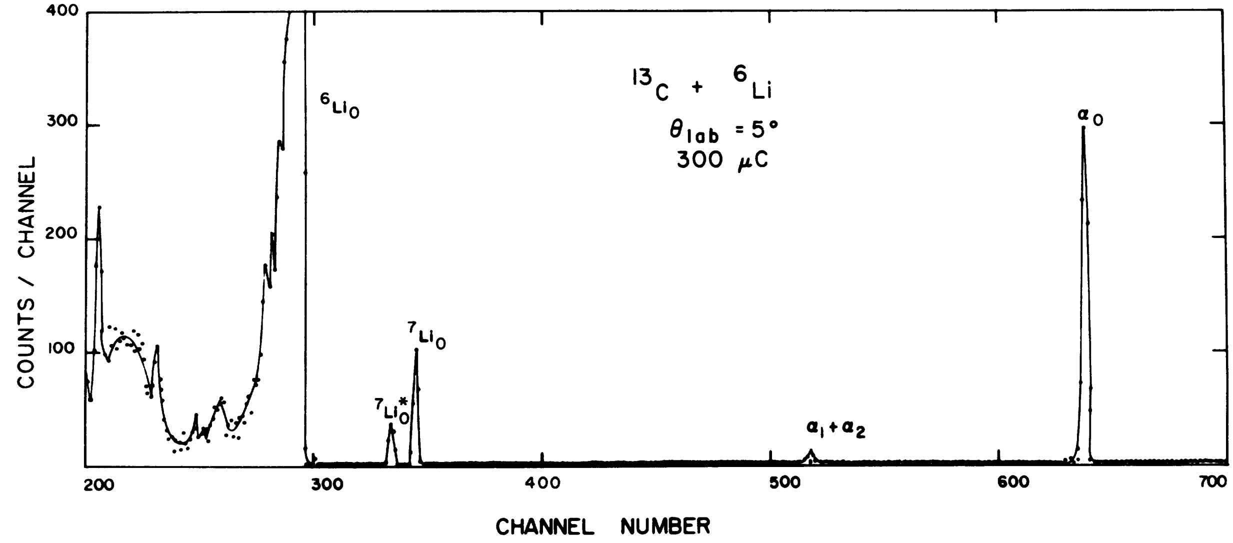

FIG. 1. Spectrum of charged particles from the bombardment of ^{13}C with 13.5-MeV ^{6}Li ions. The particles were detected in a Si surface-barrier detector at the focus of a magnetic quadrupole spectrometer with the focus set for the α_0 group.

the incident-energy range of 4–14 MeV at a lab angle of 0°, the resonances occur in the ^{12}C-t-α system. A semiquantitative evaluation of the resonant-cluster transfer model is in agreement with the data.

Recently, a group at the University of Pennsylvania reported[8] the extension of the measurement of the $^{12}C(^7Li,\alpha_0)^{15}N$ reaction to the incident-energy region between 14–24 MeV. Again, resonant structure was observed over this energy region with spacing and widths similar to that of the earlier Iowa work.

An interesting test of the CJ interpretation is provided by measuring the $^{13}C(^6Li, \alpha_0)^{15}N$ reaction over the corresponding energy range in the compound nucleus, ^{19}F, since the projectiles, ^7Li and ^6Li, both exhibit features which lead to a description of their ground state in terms of a cluster model. In the case of the ^6Li nucleus this structure is an α deuteron bound by 1.47 MeV. For ^7Li the cluster structure is an α triton bound by 2.47 MeV. If the CJ interpretation is correct, then resonant structure in the $^{13}C(^6Li, \alpha_0)^{15}N$ reaction might be expected in this energy region for resonant states which have large overlaps for ^{12}C-t with ^{13}C-d. In this paper we report a measurement of the $^{13}C(^6Li, \alpha_0)^{15}N$ reaction at the equivalent ^{19}F excitation energies (24–30 MeV) reported in the Pennsylvania work. This measurement required bombarding energies between 7.5–17 MeV for ^6Li on ^{13}C and the difficulties of obtaining usable intensities of low-energy Li beams from a tandem Van de Graaff accelerator precluded an attempt to go to the lower energies studied by CJ.

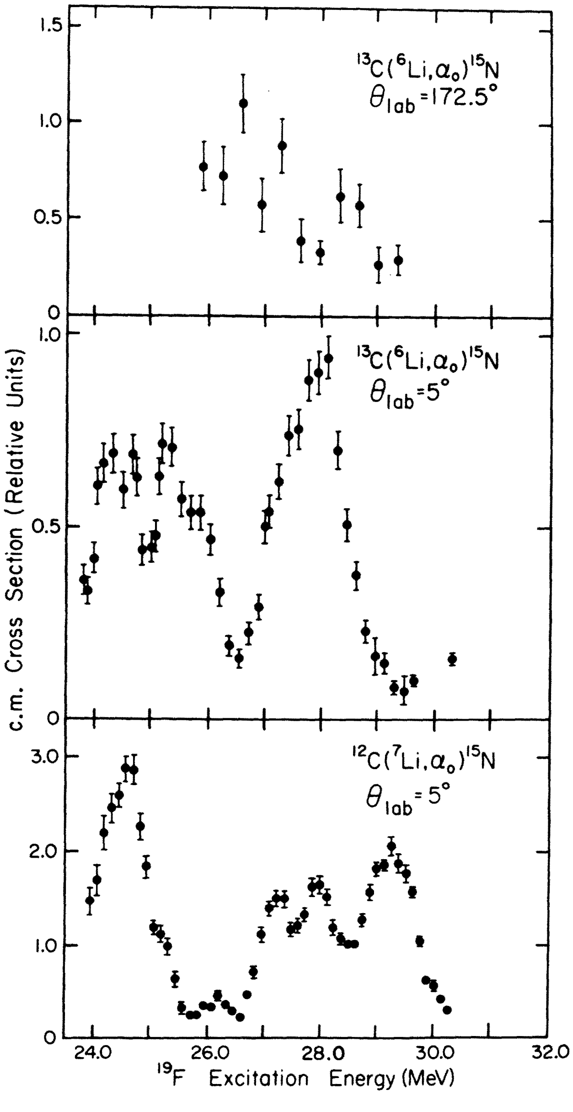

FIG. 2. Excitation functions for the $^{13}C(^6Li,\alpha_0)$ ^{15}N reaction at laboratory angles of 5 and 172.5°. Shown also is the excitation function for $^{12}C(^7Li,\alpha_0)^{15}N$ at a laboratory angle of 5° taken from Ref. 8.

A nominally 50-$\mu g/cm^2$ target of ^{13}C (enriched to 99%) was bombarded with a beam of ^6Li ions from the Florida State Super FN tandem Van de Graaff accelerator. This target thickness corresponds to an energy loss in the target of 50–100 keV. Stripper gas was used to produce the Li ions in the 2+ charge state to obtain bombarding energies between 7.0 and 17 MeV. The beam intensity was typically of the order of 100 nA. The reaction α particles corresponding to the ground state of ^{15}N were detected at a laboratory angle of 5° by using a magnetic quadrupole spectrometer[9] to selectively focus particles of the appropriate momentum to charge (p/Z) ratio onto a Si surface-barrier detector. A typical spectrum is shown in Fig. 1. The intensity of the ^6Li elastic scattering group is consistent with the 2+ charge-state equilibrium fraction for the incident energy; the p/Z ratio for the 2+ Li ion is approximately equal to that for the ground-state α group. It should be noted that the quadrupole spectrometer is an ideal instrument for the measurement of transfer reactions at small angles when the p/Z ratio for the particles of interest differ from that of the beam by about 20%. In addition to the 5° data, the yield of the $^{13}C(^6Li, \alpha_0)^{15}N$ reaction at 172.5° was measured over a portion of the same bombarding energy range. These data were obtained by using a Si surface-barrier detector at 172.5° in a large-volume scattering chamber.[10]

In Fig. 2 are displayed the c.m. yield curves for the $^{12}C(^6Li, \alpha_0)^{15}N$ reaction at laboratory angles of 5 and 172.5° and the Pennsylvania $^{12}C(^7Li, \alpha_0)^{15}N$ data at a laboratory angle of 5°. These curves are plotted as a function of ^{19}F excitation energy. The relative normalization between the three curves is as shown and the relative units are approximately 1 mb/sr.

The CJ model predicts forward peaking of the resonant cross section which is present in both sets of data and in addition there is strong similarity between the $^{13}C(^{6}Li, \alpha_0)^{15}N$ and $^{12}C(^{7}Li, \alpha_0)^{15}N$ yields at 5°. No quantitative estimate of the degree of correlation between these data has been made. Indeed the structure in the $^{12}C(^{7}Li, \alpha_0)^{15}N$ reaction at 29.3 MeV excitation in ^{19}F is completely absent in the $^{13}C(^{6}Li, \alpha_0)^{15}N$ reaction. Comparison of the yield curves indicates that the structures at ^{19}F excitation energies of 24.7, 27.3, and 28 MeV are common to both reactions. If the CJ premise is valid, then these energies correspond to resonances in ^{12}C-t which have strong overlap with ^{13}C-d. The lack of common features at other energies in no way contradicts this conclusion. A dynamical two-center shell-model calculation might provide an indication of the validity of the assumption. Similar experimental studies on other ^{A}Z and ^{A+1}Z nuclei might also provide a test.

It is apparent from the comparable magnitudes of the 172.5 and 5° data in the $^{13}C(^{6}Li, \alpha_0)^{15}N$ reaction that the resonant-cluster transfer amplitude is not the only one contributing to the cross section. The structure in the 172.5° data is less pronounced and not correlated with that in the 5° yield curve. Similar backward-angle behavior has been noted by Johnson and Waggoner[5] in their detailed study of $^{6}Li+^{12}C$ reactions. The quantitative analysis presented in their work could confirm neither a direct-reaction nor a statistical compound-nucleus model for the reaction mechanism. It would appear that at least three amplitudes are necessary to explain the data.

The data of the present experiment do not conclusively demonstrate the validity of the CJ model of resonant-cluster transfer but are consistent with the expectations of such a model. Indeed, the data of the present experiment suffer from the difficulty common to all similar studies in that Ericson fluctuations of a large coherence energy (~500 keV) cannot conclusively be ruled out as the cause of the observed structure. As has been noted above, Johnson and Wagonner found that neither the direct reaction nor statistical compound-nucleus model alone is adequate to describe the data. The consistency of the present results with CJ model indicates the necessity of further investigation of the model both experimentally and theoretically.

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[1] W. A. Seale, Phys. Rev. 160, 809 (1967).

[2] M. W. Greene, Phys. Rev. 176, 1204 (1968).

[3] R. R. Carlson and H. W. Wyborny, Phys. Rev. 178, 1529 (1969).

[4] F. D. Snyder and M. A. Waggoner, Phys. Rev. 186, 999 (1969).

[5] D. J. Johnson and M. A. Waggoner, Phys. Rev. C 2, 41 (1970).

[6] R. R. Carlson and D. J. Johnson, Phys. Rev. Lett. 25, 172 (1970).

[7] H. W. Wyborny and R. R. Carlson, Phys. Rev. C 3, 2185 (1971).

[8] D. J. Crozier, H. G. Bingham, W. J. Courtney, and H. T. Fortune, Bull. Am. Phys. Soc. 17, 465 (1972); to be published.

[9] N. R. Fletcher, J. D. Fox, M. B. Greenfield, G. D. Gunn, D. McShan, G. Morgan, and L. Wright, to be published.

[10] G. D. Gunn, T. A. Schmick, L. Wright, and J. D. Fox, Nucl. Instrum. Methods 113, 1 (1973).