Experimental Evidence for the Direct Nature of the Reaction $^{12}C(^6Li, \alpha)^{14}N$ at $E(^6Li) = 33$ MeV*

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The reaction $^{12}C(^6Li, \alpha)^{14}N$ has been studied in the energy range 32.5–35.2 MeV. As estimated from the back-angle cross section to the 3.94-MeV 1^+ state, the compound-nucleus contribution to the other $T=0$ transitions in ^{14}N is small. A distorted-wave Born-approximation analysis was performed with the usual zero-range approximation and with a full finite-range treatment. Only the finite-range calculations gave cross sections in phase with the data at forward angles.

Spectroscopic studies using the (^{6}Li, α) reaction have been hampered by uncertainty as to the reaction mechanism involved.[1] Some authors have argued that because of the small binding energy between the α and deuteron clusters forming ^{6}Li that the (^{6}Li, α) and (^{6}Li, d) reactions must be direct,[2] while other authors have indicated large compound contributions exist for $^{12}C(^6Li, \alpha)^{14}N$ at $E(^6Li) = 20$ MeV[3] and for $^{12}C(^6Li, d)^{16}O$ at $E(^6Li) = 28$ MeV.[4] A recent review[5] of the (^{6}Li, d) and (^{6}Li, α) reactions indicated that existing experimental data are insufficient to make definitive statements on the nature of ^{6}Li-induced reactions at energies below 36 MeV. In the present work, the reaction $^{12}C(^6Li, \alpha)^{14}N$ is investigated in detail to determine the compound contribution present.

Self-supporting ^{12}C targets whose thicknesses were 100–150 μg/cm^2 were bombarded with 300 nA of $^6Li^{+++}$ beam from the Florida State University FN tandem Van de Graaff accelerator. The outgoing reaction products were detected using cooled Si surface-barrier detectors. No particle identification was necessary. Carbon buildup on the target was corrected for by taking an excitation function in 600-keV steps measuring only the ^{6}Li elastic scattering yields as well as using a monitor counter for the angular distribution measurements. Absolute cross sections were obtained by comparison with the proton elastic scattering data of Bernard, Swint, and Clegg[6] at $E_p = 6.77$ MeV and, based on the reproducibility of the data, are accurate to 15%.

Figure 1 shows excitation functions taken in the energy range 32.2–35.2 MeV in steps of 200 keV at $\theta_{lab} = 15°$ for the first nine $T=0$ states in ^{14}N. The $T=1$ state at 2.31 MeV showed no noticeable excitation at any angle. The data show

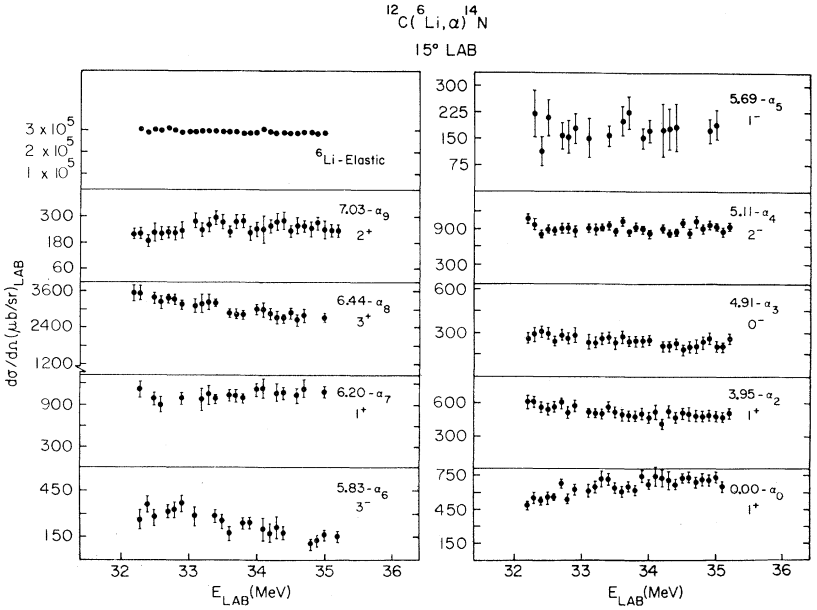

FIG. 1. Excitation functions at $\theta_{lab} = 15°$ for the first nine $T=0$ states.

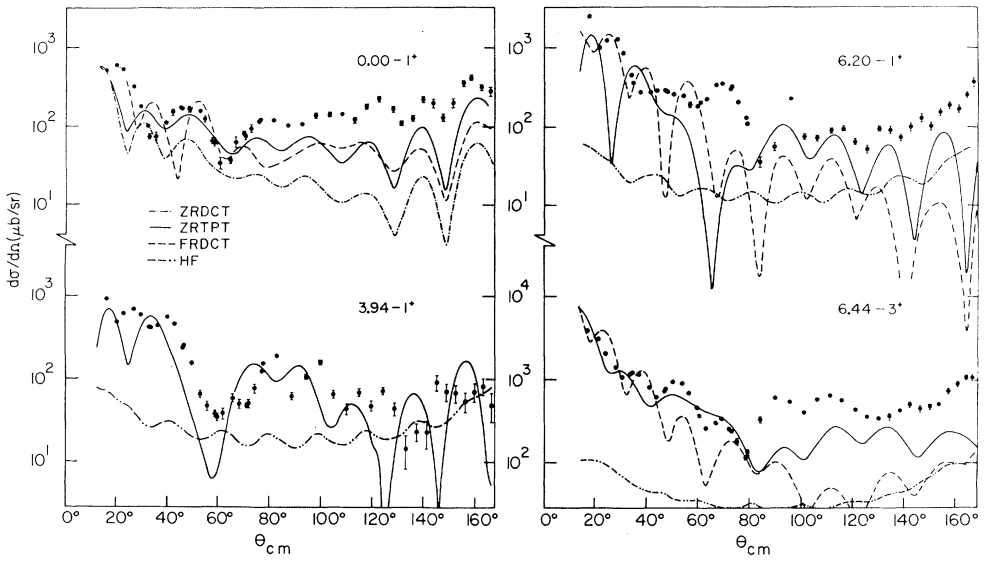

FIG. 2. Angular distributions and DWBA calculations for the first four $T=0$ positive-parity states. For explanation of legend, see text.

no structure other than the slowly varying component suggestive of a direct reaction. Detailed angular distributions were taken at $E(^6\mathrm{Li})=33$ MeV in steps of 2.5° in the laboratory angular range 12.5°–65.0° and in steps of 5.0° from 65°–165°. The angular distributions for the population of the first four positive-parity states in ^{14}N are shown in Fig. 2. These angular distributions are forward peaked and show strong diffraction patterns. The absence of fluctuations in the excitation functions does not rule out the presence of compound-nucleus contributions. However, it does show that sufficient energy averaging is present so that the compound-nucleus contributions are symmetric about 90° and can be determined from Hauser-Feshbach (HF) theory. Comparison of the angular distributions for the $J^\pi=1^+$ ground, 3.94-MeV, and 6.20-MeV states at back angles sets an upper limit on the magnitude of the compound contribution since HF calculations[7] for the three states, shown in Fig. 2, have about the same magnitude at the back angles. Consequently, for the ground and 6.20-MeV states, the compound contribution is negligible.

The angular distributions for the other $T=0$ states below 7-MeV excitation in ^{14}N are characterized by back-angle cross sections as large as the forward-angle cross sections, and HF calculations for these transitions using parameters determined by normalizing the calculation for the 3.94-MeV (1^+) state to the data show that the compound contribution is small for these transitions as well. These states will be treated in a more comprehensive article on this work.

The angular distributions were further analyzed by performing three different types of distorted-wave Born-approximation (DWBA) calculations: (1) zero-range two-particle transfer (ZRTPT); (2) finite-range deuteron-cluster transfer (FRDCT); (3) zero-range deuteron-cluster transfer (ZRDCT). Both types of zero-range calculations were performed by the computer code DWUCK[8] while MERCURY,[9,10] which includes recoil exactly, was used for FRDCT.

TABLE I. Optical-model parameters used in the DWBA calculations.

	V (MeV)	r_{0r}[a] (fm)	a_r (fm)	W_v (MeV)	r_{0I}[a] (fm)	a_I (fm)	J_R (MeV fm^3)
^{6}Li	276	1.050	0.850	9.00	2.21	0.56	498
α	130	1.369	0.625	44.92	1.364	0.35	473

[a] $R=r_0A_T^{1/3}$.

TABLE II. Bound-state parameters used in ZRTPT.

r_0 (fm)	a (fm)	$V_{s.o.}$ (MeV)	Non-locality	E_B(g.s.) (MeV)
1.25	0.65	25	0.85	5.135

The same optical parameters were utilized for all three types of calculations. Those for the ^{6}Li channel were selected from Bassani *et al.*[11] and those for the α channel from Lowe and Barnett.[12] Specific sets were chosen to match the volume integral criterion ($J_R \simeq 450$ MeV fm^3) of Cage, Cole, and Pyle[13] and are shown in Table I.

The bound states for ZRTPT were generated with a Woods-Saxon well, using the parameters shown in Table II, and were assumed to have the configurations given in Mangelson, Harvey, and Glendenning.[14] Both sets of cluster-transfer calculations assume that ^{14}N is a ^{12}C core plus a bound deuteron with the relative motion characterized by a single orbital angular momentum L. This allows the number of nodes to be found by

$$2N = \sum_{i=1}^{2}(2n + l_i) - L,$$

where the sum over i gives the dominant two-particle configuration. The values used for N and L, together with the Woods-Saxon parameters, are shown in Table III. The ^{6}Li nucleus was described as an α core with a bound deuteron. Also shown in Table III is the square of the product of the spectroscopic amplitudes as defined in Ref. 10. They were obtained by normalizing the angular distributions as shown in the figures and were found only for FRDCT.

Referring to Fig. 2, it may be seen that generally ZRTPT is out of phase with the data at the forward angles by 6° to 8° and overpredicts the ratios of forward- to backward-angle cross sections by factors of 2–4. The FRDCT calculations were performed for levels with large paired components and matched the position of the first maxima more closely but generally gave the same structure. Various values were tried for the finite-range correction factor in ZRTPT to reproduce the same effect, but none was found.

In conclusion, it has been shown by a study of the complete angular distributions that in the energy range investigated, the reaction ^{12}C(^{6}Li, α)^{14}N proceeds primarily by a direct interaction. For the reaction studied, the zero-range assumption gives first-maxima positions that are 6° to 8° out of phase, while finite range does not. For all states except one, the simple DWBA theory overestimates the ratios of forward- to backward-angle cross sections. This could be due to two-step contributions or quite possibly exchange effects. An attempt to calculate these possibilities as well as two-particle transfer in finite range are planned and will be reported at a later date.

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TABLE III. Bound-state parameters, assumed N and L values, and spectroscopic amplitudes for the cluster calculations.

	State	J^π	r_0 (fm)	a (fm)	E_B (MeV)	N	L	$A(^6\text{Li})^2$	$A(^{14}\text{N})^2$
^{14}N	g.s.	1^+	1.94	0.65	10.27	0	2		1.24
	6.20	1^+	1.94	0.65	4.07	2	0		0.31
	6.44	3^+	1.94	0.65	3.83	1	2		0.43
^{6}Li	g.s.	1^+	2.15	0.65	1.47	1	0		

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π Condensation in Nuclear Matter

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It is shown that in nuclear matter at $Z=0$ (neutron star) at a density $n_1<n_{\text{nucl}}$ a π^0 condensate appears. Nearly at the same density an electrically neutral π^+,π^- condensate arises. The π^- condensate assumed by other workers apparently does not arise even at very high densities.

The π condensation in nuclear matter was first considered by the present author.[1,2] Later the problem was considered once more by others[3,4] for the case of a neutron star ($Z \ll N$). Sawyer[3] and Scalapino[4] came to the conclusion that at some nuclear densities, a π^- condensate arises (the charge is compensated by the same amount of protons). The same result is assumed by Kogut and Manassah.[5] A more realistic consideration given below does not confirm these conclusions.

Let us write the condition for the instability of nuclear matter with respect to the reaction $n \to p + \pi^-$. We have

$$\mu_p - \mu_n + \omega(k_0) = 0,$$

where μ_p, μ_n are the proton and neutron chemical potentials, $\omega(k_0)$ is the minimal energy of π^- in nuclear matter, and k_0 is the corresponding wave vector. For small proton densities, $\mu_n - \mu_p \cong \epsilon_F^{(n)}$. Thus the instability arises only when the π^- energy is less than the Fermi energy of the neutrons. A detailed consideration of the pion energy-momentum relation taking into account the pion-pion interaction shows that an instability does not arise up to very high nucleon densities at least. Even if the instability arises, increase of the π^- density in any case would be limited by the pion-pion interaction. Let us start with the case $N=Z$ investigated by Migdal.[6] There are two branches of the meson spectrum: the "meson" branch, which tends to the free meson energy as the nuclear density n tends to zero, and the "spin-sound" branch which coincides with the spin-sound excitations[7] in nuclear matter, when the meson-nucleon interaction is switched off. At $n \cong 0.5 n_0$ (n_0 is the usual nuclear density) the spin-sound branch becomes unstable [$\omega^2(k)$ is negative for some $k \cong k_0$]. This instability leads to formation of an electrically neutral meson condensate $\varphi_1 = \varphi_2 = \varphi_3$, with

$$\varphi_{\pi^\pm} = 2^{-1/2}(\varphi_1 \pm i\varphi_2), \quad \varphi_{\pi^0} = \varphi_3.$$

In the case $Z \ll N$ these results hold for π^0 mesons (Fig. 1) but the spectrum of π^+ and π^- entirely changes.

The polarization operator $\Pi(\omega, k)$ for ω and k of interest ($\omega \lesssim 1$, $k \lesssim m$, $\hbar = c = m_\pi = 1$, m is the nucleonic mass) is given by two types of graphs:

$$\Pi(\omega, k) = \omega^2(k) - 1 - k^2 = D_1 + D_2, \tag{1}$$

where D_x is the term represented by diagram x in Fig. 2. The term D_1 corresponds to the absorption of a pion by a nucleon with the formation of a hole in the Fermi distribution. The shaded vertex means that the nucleon-nucleon interaction is taken into account. This vertex can be ex-