Differential Cross Sections for the Reactions $C^{12}(Li^6,\alpha)N^{14}$ and $C^{12}(Li^7,\alpha)N^{15}$†

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Differential cross sections have been measured for the reactions $C^{12}(Li^6,\alpha)N^{14}$ and $C^{12}(Li^7,\alpha)N^{15}$ with the residual nuclei in their ground or first few excited states. The total cross section for the 2.31-Mev $T=1$ state of N^{14} is 0.1 mb at 4.0 Mev, compared to a cross section of 2.9 mb for the ground state; this violation of the isotopic spin selection rule is probably due to mixing of different isotopic spin states in the compound nucleus F^{18}. The differential cross sections for the other levels have general features suggestive of a direct interaction.

INTRODUCTION AND PROCEDURE

To continue the investigation of reactions[1,2] induced in light nuclei by Li ions, we have measured the differential cross sections for the reactions $C^{12}(Li^6,\alpha)N^{14}+8.79$ Mev and $C^{12}(Li^7,\alpha)N^{15}+12.39$ Mev.

The equipment for producing the beam of Li ions, the target chamber and the beam current integrator have been described in an earlier paper.[1] The target was a self-supporting carbon film[3] whose thickness when traversed at an angle of 45° was 200 ± 30 kev for 3.4-Mev Li^6 ions.

Light reaction products traversed a proportional counter and stopped in a silicon junction detector whose amplified output E was displayed on a 100-channel pulse-height analyzer. Alpha particles were selected by choosing only events which had the appropriate value of the function $(E^{0.6}\Delta E)$, where ΔE was the energy lost in the proportional counter.[2]

Angular distributions were measured at laboratory angles between 10° and 160° in 10° steps, for bombarding energies of 3.3, 3.5, 3.7, 3.9, and 4.1 Mev. A vector normal to the target plane was always at a 45° angle with the beam and lay in the quadrant containing the counter. Measurements taken with the counter at 90° were repeated with both target orientations so that the large-angle data could be corrected for a difference in yield caused by target irregularities.

Absolute cross sections were determined by comparing the yield of α particles with that of Li ions scattered by the Coulomb field of the target nuclei.[2]

RESULTS

The peaks of the typical α-particle spectra shown in Figs. 1 and 2 agree with the known energy levels[4] in N^{14} and N^{15} which are marked at the bottom of the figures. Differential cross sections for the levels which could be resolved from the $C^{12}(Li^6,\alpha)N^{14}$ reaction are displayed in Figs. 3–5, while the results for $C^{12}(Li^7,\alpha)N^{15}$ are shown in Figs. 6–8. A few angles were omitted in some of the N^{15} data because of contamination by α particles from the reaction $p(Li^7,\alpha)\alpha$. Error bars indicate standard deviations due to counting statistics. Smooth curves have been drawn to follow the trend of the data.

Total cross sections obtained by numerical integration are shown in Fig. 9. The absolute values of the differential and total cross sections have an estimated error of 10%.

The rapid increase of cross section with energy makes necessary a correction for the thickness of the target. This is most easily done by specifying the average energy $E_0=E_{\text{machine}}-\delta E$, where $2\delta E$ is the energy

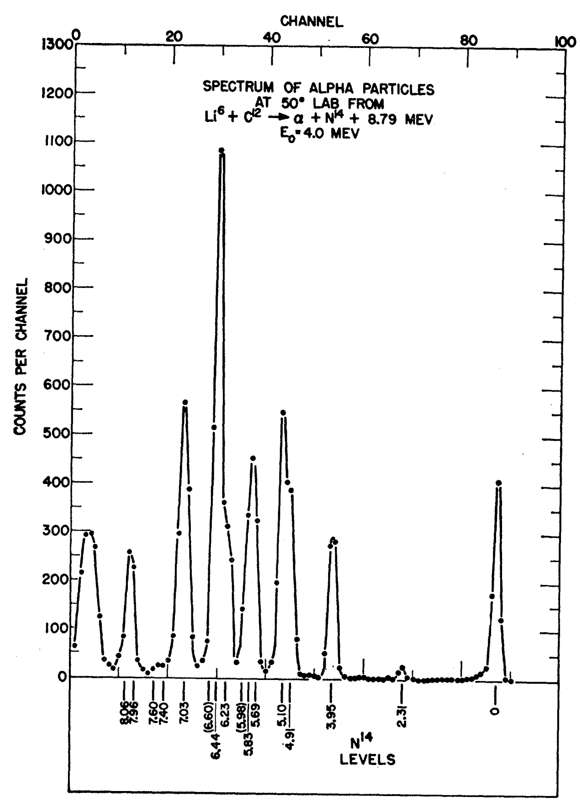

FIG. 1. Typical α-particle spectrum for the reaction $C^{12}(Li^6,\alpha)N^{14}$.

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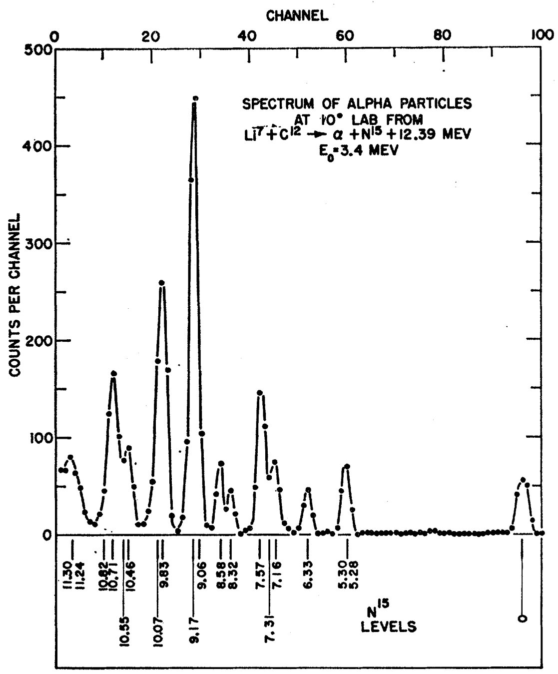

FIG. 2. Typical α-particle spectrum for the reaction $C^{12}(Li^7,\alpha)N^{15}$.

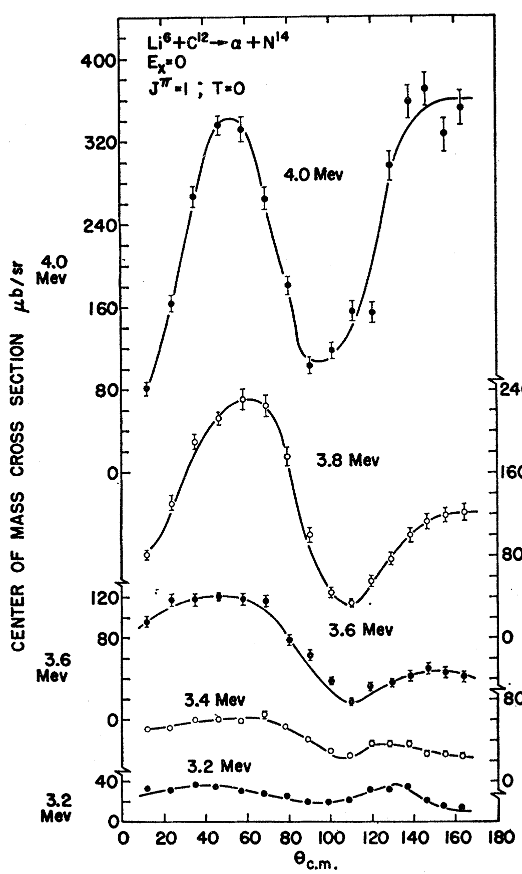

FIG. 3. Differential cross section for the reaction $C^{12}(Li^6,\alpha)N^{14}$ when N^{14} is left in the ground state.

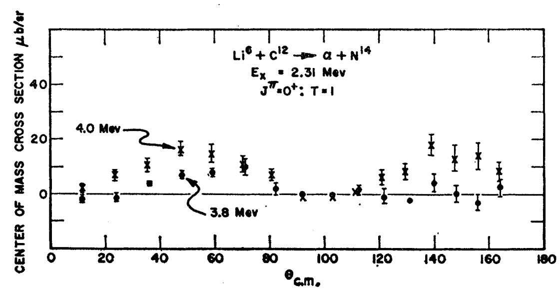

FIG. 4. Differential cross section for the reaction $C^{12}(Li^6,\alpha)N^{1}$ when N^{14} is left in the first-excited state ($E_x=2.31$ Mev).

lost by the beam in traversing the target. The distortion of the differential cross section introduced by this simple procedure is less than 1%. The value $\delta E=100\pm20$ kev was used for all energies with both beams, since the uncertainty in target thickness exceeded the variation of stopping power of the Li ions over the velocity range studied.

DISCUSSION

The first noteworthy feature of the data is the presence of α particles corresponding to the 2.31-Mev first excited state of N^{14}, since population of this level

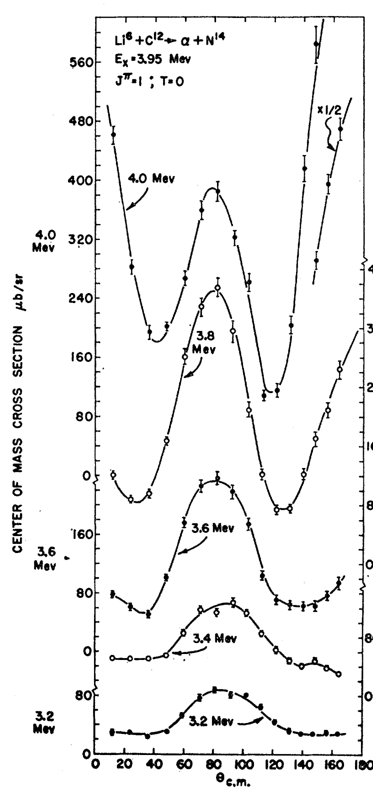

FIG. 5. Differential cross section for the reaction $C^{12}(Li^6,\alpha)N^{14}$ when N^{14} is left in the second-excited state ($E_x=3.95$ Mev).

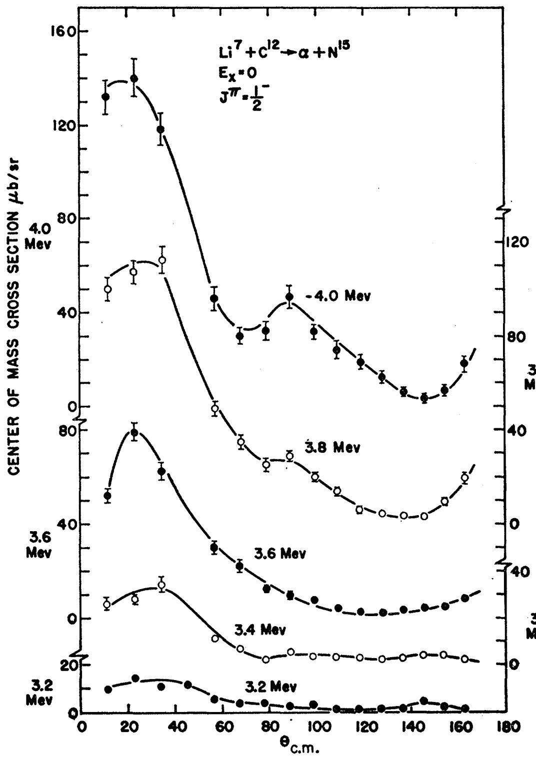

FIG. 6. Differential cross section for the reaction $C^{12}(Li^7,\alpha)N^{15}$ when N^{15} is left in the ground state.

is not expected from isotopic spin conservation. The fact that these α particles were indeed from the desired reaction was confirmed in several ways. Their energy

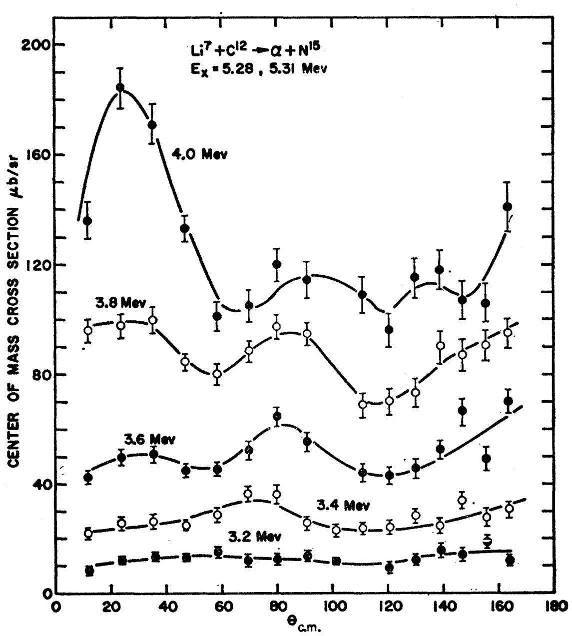

FIG. 7. Differential cross section for the reaction $C^{12}(Li^7,\alpha)N^{15}$ when N^{15} is left in the first and second excited states ($E_x=5.28$ and 5.31 Mev).

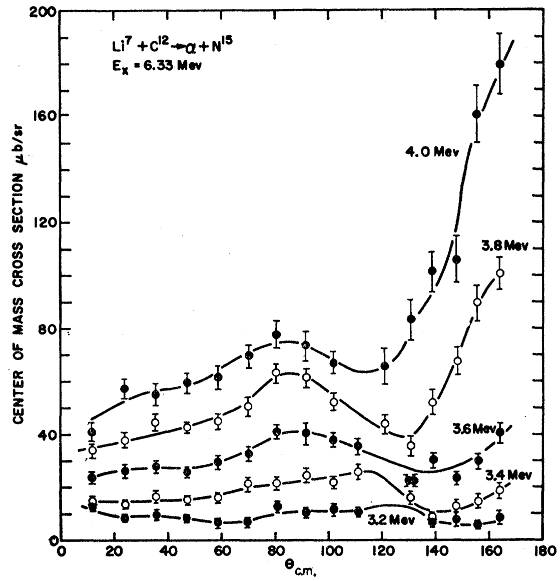

FIG. 8. Differential cross section for the reaction $C^{12}(Li^7,\alpha)N^{15}$ when N^{15} is left in the third excited state ($E_x=6.33$ Mev).

varied with scattering angle in the proper manner over the entire angular range. The only target contaminant which could have given α particles near the proper energy was O^{16} via the reaction $O^{16}(Li^6,\alpha)F^{18}$, and this only at angles near 70° center-of-mass. No α particles from this reaction were observed at neighboring angles

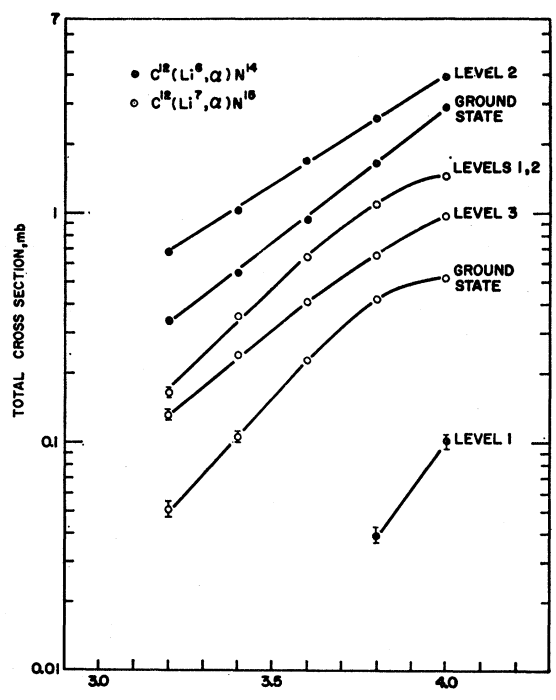

FIG. 9. Total cross sections as a function of energy.

where the peak due to $O^{16}(Li^6,\alpha)F^{18}$ would have been isolated. As a further test, the differential cross section for the $O^{16}(Li^6,\alpha)F^{18}$ reaction at 70° was measured in a separate experiment, while the amount of O^{16} contaminant in the carbon target was determined from the Coulomb-scattering data. Less than 5% of the α particles seen could be attributed to the O^{16} contaminant.

Since the 2.31-Mev level in N^{14} has isotopic spin $T=1$ while Li^6, C^{12}, and He^4 all have $T=0$ ground states, the yield of these α particles measures the violation of the isotopic spin selection rule. "Forbidden" excitation of this level is not new; Browne[5] observed it in the reaction $O^{16}(d,\alpha)N^{14}$. Using 7.05-Mev deuterons he found the average yield for the 2.31-Mev level was about 7% of the ground-state yield. This selection rule violation is probably due to mixing of levels in the compound nucleus, F^{18}, having the same spin and parity but different isotopic spins. The conservation of total angular momentum and parity imposes restrictions on the levels in the compound nucleus which can contribute to this interaction and also restricts the partial waves in the incident beam to $l \geq 1$. An upper limit for the formation of the compound nucleus, calculated[6,7] from the barrier penetration of the $l \geq 1$ partial waves of a 4-Mev incident Li^6 beam, is 20 mb. There are about 20 exit channels with $T=1$ for which the emerging particle is above the barrier; if we assume that the cross section for each of these channels is 0.1 mb, as observed for the 2.31-Mev level in N^{14}, then we can estimate that the square of the isotopic spin mixing amplitude is roughly 0.1. This is not an unreasonable value if there are two nearby levels in F^{18} at this excitation energy (15.8 Mev) which have the same spin and parity but differing isotopic spins.[8]

The excitation of the 2.31-Mev level is also not expected in terms of a "lump stripping" model.[9] In this model, N^{14} is formed when either C^{12} captures a deuteron present in Li^6, or Li^6 captures a Be^8 nucleus present in C^{12}. The spin and parity $(0+)$ of the 2.31-Mev level cannot be produced by this process unless the neutron and proton change from a triplet to a single-spin state during the transfer.

Because of the small yield from the first excited state, we conclude that the 2.31-Mev γ rays seen[10] when C^{12} is bombarded by Li^6 are due primarily to population of this level by the γ-decay of more highly excited states.

The tunneling calculation mentioned above shows that the reactions leading to the ground and 3.95-Mev levels of N^{14} cannot proceed exclusively by compound nucleus formation. The total cross section at 4.0 Mev is about 4 mb for each of these levels. Inspection of Fig. 1 shows that at least 7 other levels in N^{14} are populated with comparable yields, while exit channels for n, p, and d emission are also open. The maximum possible cross section of 24 mb (including the $l=0$ partial wave) for formation of the compound nucleus is insufficient to account for all the reaction products observed.

The angular distributions for both reactions are similar to those seen in earlier work[1,2] and are suggestive of a direct interaction. An attempt was made to fit the $C^{12}(Li^6,\alpha)N^{14}$ data using the plane-wave cutoff Born approximation calculation by Leigh[9]; the fits were about as satisfactory as those obtained by Leigh. The greatest difficulty was the need to use $l(d)=2$ to fit the 90° peak for the 3.95-Mev level in N^{14}; this cannot be reconciled with the known ^3S character of this state. The closest approach of a 3.9-Mev Li^6 nucleus to the C^{12} target is 10 f for a Coulomb orbit with zero-impact parameter, while the sum of the nuclear radii is about 5.2 f, and the best values of the cutoff parameter in the unsuccessful plane wave fits were 3 to 4 f. We therefore feel that the first step in a more realistic calculation should be to include the effects of the Coulomb potential on the incident and emerging plane waves.

Measurements elsewhere[11] of the $C^{12}(Li^6,\alpha)N^{14}$ reaction at 1.7 Mev show angular distributions of considerably different character than those reported here. The α particles corresponding to the ground state are peaked only in the backward direction and the angular distribution for the 3.95-Mev level showed a pronounced forward peak and a smaller backward peak.

The total cross sections shown in Fig. 9 illustrate the same increase with energy that has been seen previously, although the slope is steeper, as would be expected for a higher barrier.

CONCLUSION

Differential cross sections have been presented for the reactions $C^{12}(Li^6,\alpha)N^{14}$ (ground and first two excited states) and $C^{12}(Li^7,\alpha)N^{15}$ (ground and first three excited states). The nonzero cross section for the 2.31-Mev level in N^{14} is evidence for isotopic spin mixing in the compound nucleus F^{18}. The reactions to other levels observed in N^{14} and N^{15} probably proceed by a direct process, however.

It is hoped that a stripping calculation including the effects of the Coulomb field would provide a satisfactory fit to the angular distributions.

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Nuclear Moment of Ni^{61}

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A re-examination of the electron spin resonance spectra of nickel in MgO and nickel in germanium is made. It is proposed that the previously estimated value of 0.3 nm for the nuclear moment of Ni^{61} is in error by a factor of three, and that the value of 0.9 nm is more consistent with the published spectra. The internal fields in nickel and nickel alloys are discussed on the basis of this new moment.

THE nuclear magnetic moment of Ni^{61} was estimated from an electron spin resonance experiment on Ni^{+2} in MgO by Orton, Auzins, and Wertz[1] to be (0.30 ± 0.02) nm. We believe this value of the moment is in error by a factor of three, and we propose a moment of 0.9 nm instead. This paper discusses how a reexamination of the electron spin resonance data leads to the higher value for the moment, and the consequences of this result in the understanding of the internal fields in ferromagnetic nickel and nickel alloys.

Using enriched nickel in an electron spin resonance experiment on Ni-doped germanium, Woodbury and Ludwig[2] found four hyperfine lines, giving $I=\frac{3}{2}$, for Ni^{61}. The lines were evenly spaced 10.4 gauss apart. Using unenriched nickel, Orton *et al.*[1] found no hyperfine structure at low powers due to the broad resonance line, but they did find two weak hyperfine lines separated by 23.9 gauss in the considerably narrower double quantum line[3] appearing at high power. They assume the weak lines to be the outer pair of a hyperfine quartet, the inner pair being lost in the central line. This conclusion leads to a separation between adjacent lines of 8 gauss and a nuclear moment of 0.30 nm. We propose that the weak lines are the *inner* pair of a hyperfine quartet, the outer pair being lost in the noise. An examination of their published spectrum does not favor one explanation over the other, but, as we will show, our interpretation is more consistent with the germanium data.[2] An experiment with enriched nickel would test our proposal. If we are right, spacing between *adjacent* lines would then be 23.9 gauss, leading to a Ni^{61} nuclear moment of 0.9 nm.

Since the nickel in the Ni-doped germanium is not isoelectronic with the nickel in the MgO, a direct comparison with Woodbury and Ludwig's experiment[2] is difficult. Two alternate cases arise:

First, if the nickel in the germanium is a single acceptor, the electron configuration would probably be $3d^8\ 4s^2\ 5s$. The contribution to the effective field at the nucleus from the two unpaired electrons in the $3d$ shell should be comparable to the Ni^{+2} result. The observed spacing is reduced, perhaps to one-half its value, by an oppositely directed contribution from the single $5s$ electron. Thus, we should multiply the 10.4-gauss spacing between adjacent levels by approximately two before comparing it with the Ni^{+2} result, in favorable agreement with our suggested interpretation of 23.9 gauss between *adjacent* lines.

On the other hand, if the nickel in the germanium is a double acceptor, the outer electrons would be something like $3d^8\ 4s^2\ 5s^2$. The two closed s shells will not affect the results appreciably and the spacings should be directly comparable to the $Ni^{+2}(3d^8)$. However, there is one difference. For an $S=1$ state, the double quantum transitions are spaced twice as far apart as for a single quantum transition. This is true because the $m_s=0$ state is not split. Hence, we must compare $10.4\times2=20.8$ with the Ni^{+2} case. This again compares favorably with 23.9 gauss between *adjacent* lines.

We make no conclusion concerning the procedure of Orton, Auzins, and Wertz comparing the hyperfine coupling constant in Ni^{+2} with Co^{+1} in MgO. In any case, any error in precision, due to this method, may be

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