Search for Resonances in the Reaction $Li^7(He^3,\alpha)Li^6$†

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Angular distributions and cross sections for the reaction $Li^7(He^3,\alpha)Li^6$ leading to the ground state and the first two excited states of Li^6 have been measured in the energy range 0.8 to 3.0 MeV. The data are discussed with regard to resonances previously observed in the radiative capture of He^3 by Li^7. Some indication of these resonances is seen. Their alpha-particle widths are apparently small compared to their total widths.

I. INTRODUCTION

IT has been shown in the preceding paper[1] (hereafter referred to as I) that the cross section for radiative capture of He^3 by Li^7 displays distinct resonances at bombarding energies of 1.1, 1.4, and 2.2 MeV. Each is observed in several γ decay modes in B^{10}. Although all final states of the strong transitions observed in I are known to have isotopic spin $T=0$, the observed gamma transitions do not allow definite conclusions to be drawn about the isotopic spins of the initial states unless multipoles higher than dipole can safely be excluded. This is because the isotopic spin selection rule $\Delta T=1$, which applies to dipole transitions in self-conjugate nuclei such as B^{10}, does not hold for higher multipoles.[2] The lower limits for the transition strengths obtained experimentally in I make dipole character very likely, but electric quadrupole is not entirely excluded.

This short note presents the results of an attempt[3] to look for the above mentioned resonances in additional decay channels and, if possible, to learn something about spin, parity, and isotropic spin assignments of the states involved in B^{10}. If resonances are seen in this reaction, the α decay channels should preserve the isotopic spin character within the limits determined by the purity of the final states. The first $T=1$ state in the final nucleus Li^6 occurs as the second excited state,[4] at an excitation energy of 3.56 MeV. This state, as well as the ground state and first excited state (at 2.18 MeV), is well separated energetically from other levels having spin and parity values such as to allow isotopic spin mixing into the levels under consideration. The isotopic-spin impurity of the ground state has been calculated[5] to be about 1 part in 10^4. Unfortunately, the $T=1$ state has $J^\pi=0^+$, and hence α decay from compound states with $J^\pi=0^-$, 1^+, 2^-, $\cdots$, is forbidden even if allowed by isotopic-spin selection rules.

Previously, Wolicki and Knudson,[6,7] Forsythe and Perry,[8] and the authors[3] have reported the differential cross section at several angles of the α decay to the ground state of Li^6 from this reaction for bombarding energies up to 5.5 MeV. Each of the above investigators found, for forward angles, a maximum in the cross section near 2 MeV. The α group to the first excited state, studied at 90° by Forsythe and Perry,[8] showed a smooth energy dependence. The present experiment consists of measuring the α decay to the first three states of Li^6 in detail for bombarding energies from 0.8 to 3.0 MeV.

II. EXPERIMENTAL PROCEDURE

A thin, 99.9% isotopically pure Li^7 target was bombarded with the He^3 beam of the 3-MeV Van de Graaff accelerator at Stanford University. Metallic lithium was evaporated inside the target chamber onto a thin carbon foil. The target thickness was found to be approximately 60 $\mu g/cm^2$, by observing the energy shift of He^3 particles scattered elastically from the carbon backing. The beam was stopped in a Faraday cup behind the chamber and the integrated charge used for monitoring runs. Two pairs of crossed slits limited the beam to a size of 2 mm$\times$2 mm at the target. Angular distributions were measured with a silicon detector having a sensitive area of 7 mm^2 and a maximum depletion depth of 200 μ. The detector could be rotated around the target axis at a radius of 10 cm. The depletion depth was actually reduced by lowering the bias voltage until protons lost only about 3 MeV in the counter. In this way, the 13-MeV protons from the reaction $Li^7(He^3,p)$ (which could not be stopped in 200 μ) were eliminated from the region of the particle spectrum of interest in the experiment. The detector output was amplified in a charge sensitive system and stored in a 400-channel pulse-height analyzer. The

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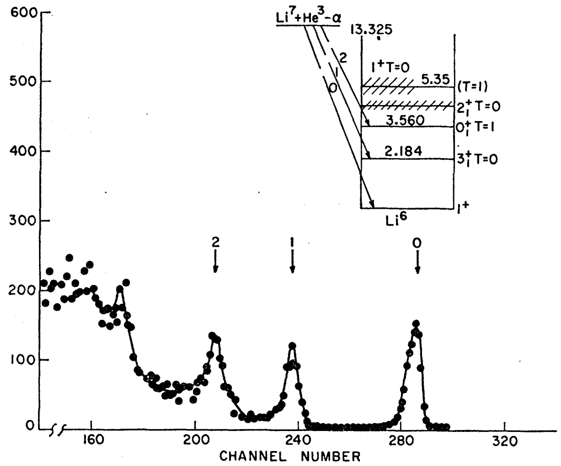

FIG. 1. Particle spectrum showing the α groups to the ground (0) and first two excited states (1) and (2) of Li^6 from the reaction $Li^7(He^3,\alpha)Li^6$ at $E(He^3)=3.0$ MeV. The spectrum was observed in a solid state detector at 90°. High-energy protons from the competing reaction $Li^7(He^3,p)Be^9$ are suppressed by the thin depletion layer of the detector and recorded only below channel 160.

horizontal symmetry axis of the chamber was aligned with the beam until left-right asymmetry of the elastic scattering yield was not more than 2%. Particle spectra were measured for a fixed beam energy, every 15° from 30° to 165° in the laboratory system. This procedure was repeated for bombarding energies from 0.8 to 3.0 MeV in steps of 200 keV. Figure 1 shows a typical spectrum. The groups associated with the α decay to the first three states in Li^6 are indicated. Transitions to higher excited states in Li^6 which are also contained in the spectrum have been reported by Allen *et al.*,[9] and will not be discussed here.

As is evident in Fig. 1, the ground-state group is well isolated while the groups associated with the first and second excited states are superimposed on a background. In this respect the data at 90° are characteristic of spectra taken at all angles less than 150°. At larger angles this background also reaches the ground-state group. The background subtraction in the determination of the areas under each peak was made with the aid of a consistent set of line shapes for the α groups at each angle. These areas were corrected for dead time, and, if obtained at a different beam energy, for charge exchange of the He^3 beam in the target foil. The effect of the latter on the integrated beam charge was measured at several energies and the corrections found to be in reasonable agreement with calculations based on equilibrium charge distributions as given in Ref. 10.

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III. RESULTS AND DISCUSSION

Examples of angular distributions, in the center-of-mass system, obtained for the alpha decay to the first three states of Li^6 [hereafter referred to as (0), (1), (2)], are given in Fig. 2. The general character of the distributions for all bombarding energies up to 3 MeV is well represented by the examples shown. The angular distributions are in most cases not symmetric about 90° but do not show pronounced forward or backward peaking. This latter fact and the observed energy dependence suggest that direct reaction processes do not dominate over compound nuclear reactions. Up to 3 MeV, the angular distributions cannot be fitted, in plane-wave approximation, with light and/or heavy particle stripping. Results by Wolicki,[7] for the ground-state decay, show that at 4.5 MeV the reaction has clearly changed to a direct mechanism. As far as these data can be compared with the present work in the energy range from 1.8 to 3.0 MeV, the relative differential cross sections are in agreement.

A series of Legendre polynomials was fitted to each angular distribution by means of a least-squares procedure. Inclusion of polynomials up to fourth order produced fits with chi-squared probabilities of better than 0.05 for all distributions. Resonance effects, if present, should show up in the energy-dependent coefficients $A_0, \cdots, A_4$, obtained from these fits. These coefficients are plotted in Fig. 3. The errors on each value are calculated from the appropriate angular distribution. An absolute scale for $\sigma_{tot}=4\pi A_0$ was established by matching the relative differential cross section for the ground state transition at 2.0 MeV and $\theta_{lab}=103°$ to the corresponding value given by Wolicki.[7] From the A_0 curves shown in Fig. 3, the total cross section is obtained by setting 30 scale units equal to 1 mb.

The total cross sections of all three transitions yield no unambiguous evidence for resonances. On the basis of the results in I, the search for resonance structure in the coefficients $A_1, \cdots, A_4$ centers around bombarding energies of 1.1, 1.4, and 2.2 MeV. Near 1.1 MeV there is no evidence for a resonance in any of the three α-decay modes, and an upper limit of 0.5 mb is estimated for any possible resonance cross section. This would imply

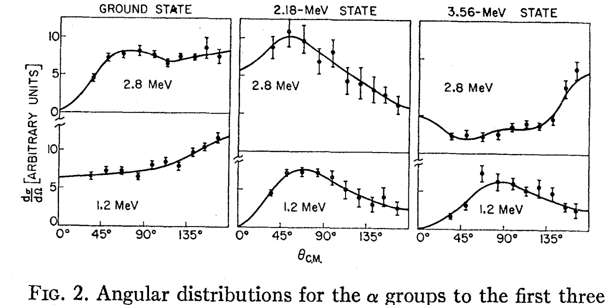

FIG. 2. Angular distributions for the α groups to the first three states of Li^6 from $Li^7(He^3,\alpha)Li^6$ at bombarding energies of 1.2 and 2.8 MeV. Errors shown are due to counting statistics and background subtraction uncertainties. Curves represent least-squares fits with series of Legendre polynomials up to fourth order.

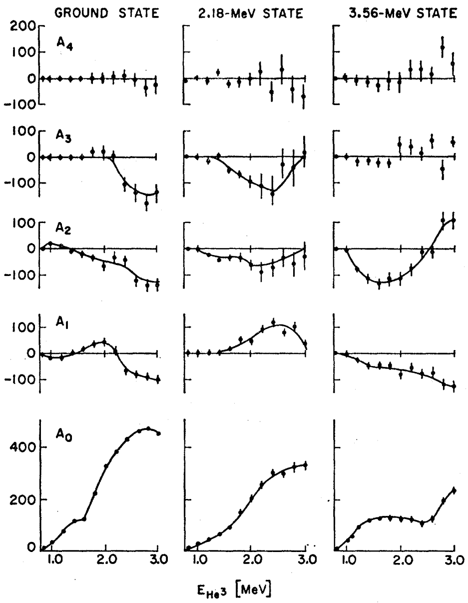

FIG. 3. Energy dependence of the coefficients A_l, defined by $d\sigma/d\Omega=\sum_l A_l P_l(\cos\theta)$, as obtained by a least-squares fit to the angular distributions. Errors are computed from the complete angular distribution and indicated by bars, unless they are smaller than the points. Curves are merely meant to guide the eye. For the curve $A_0 \propto \sigma_{tot}$, the cross section calibration is 1 mb=30 scale units.

that the resonance seen in *I* has an extremely small total α width and/or an isotopic spin $T=1$ and $J=1^+$, 2^-, or 3^+. In neither case can it decay strongly to the first three states of Li^6. These three combinations of spin and parity are compatible with the results of I.

The 1.4-MeV structure observed in I is not readily evident in the alpha decay. The excitation function for alpha decay to (2) shows structure, which could be explained by a 1-MeV wide resonance centered at 1.75 MeV. On the other hand, with the results of I in mind, it appears that one could also fit it with two resonances: one at about 1.5 MeV, with a laboratory width of 650 keV, and the other at 2.2 MeV and a width of 450 keV. The corresponding values in I are 1.4 MeV, $\Gamma<700$ keV, and 2.2 MeV, $\Gamma\approx 500$ keV. Assuming a definite spin and parity for the 1.4-MeV resonance, only two assignments are at all consistent with the observed coefficients A_0, A_2, and A_4. These are $J^\pi=2^+$ (p-wave capture) and 1^- (d-wave capture), both with channel spin $s=2$. Neither choice is in good agreement with the anisotropies quoted in I for the gamma decay modes. However, these anisotropies are not reliable for direct comparison because of interference contributions. The total α-production cross section to (2) at 1.4 MeV is 4.5 mb. The transition to level (0) has an indication of the 1.4-MeV resonance, with an upper limit on the cross section of 2 mb. There is no evidence for or against a 1.4-MeV resonance in the transition to (1), with a maximum possible contribution of about 1 mb.

At 2.2 MeV the cross section for the transition to level (0) at forward angles[6–8] has a peak with a laboratory width of 600 keV. This anomaly shows up in the coefficients A_1, A_2, and A_3, but is obscured in the total cross section. The data at forward angles[7] and the experimental total cross section give the estimated limits 0.4 mb$<\sigma_{tot}<$2.0 mb (where the lower limit results from the assumption that the peak at 2.2 MeV observed at forward angles is due to a resonance). Variations in A_2 and A_3 for the transition to (1) suggest a resonance effect around 2.2 MeV, with a total cross section of less than 1.5 mb. In neither of these two decay modes do the small resonance contributions warrant analysis for possible spins. As noted above, the transition to (2) can be interpreted as having a resonance at 2.2 MeV. This resonance cross section could be as much as 2.7 mb. $J^\pi=2^+$ or 1^- are the only assignments consistent with the large, negative A_2 term.

Above 2.2 MeV, the cross section for the transition to (0) appears to be dominated by a wide resonance around 2.8 MeV. Although no indication of such a resonance is observed in radiative capture,[1] the ground-state proton group of the reaction $Li^7(He^3,p)Be^9$ has a similar resonance near 3 MeV.[6,7]

In conclusion, the data of the present experiment show some correlation with resonances reported in the radiative capture work, but the results are not unambiguous. Although this is certainly not the only possible interpretation, the resonances at 1.4 and 2.2 MeV reported in I appear to be present in α decay, and strongest in the decay to state (2). From this and the fact that (2) has $T=1$ and the smallest available final-state phase space and spin multiplicity of all three final states, it is inferred that $T=1$ is dominant in both resonances. Furthermore, the resonances observed in radiative capture[1] below 3 MeV have only a very small cross section for α decay to the first three states of Li^6. From the cross section measured here for the dominant α decay to state (2) and the sums of radiative capture cross sections reported in I, the ratio $\Gamma_{\alpha(2)}/\sum\Gamma_\gamma$ is found to be smaller than 160 at 1.4 MeV, and smaller than 40 at 2.2 MeV. Assuming a safe upper limit on $\sum\Gamma_\gamma$ of 500 eV, one obtains $\Gamma_\alpha<80$ keV at 1.4 MeV and $\Gamma_\alpha<20$ keV at 2.2 MeV. Thus the alpha-particle width constitutes only a small part of the total width of these resonances.