Reaction $T(^3He,\gamma)^6Li$ in the Energy Range 0.5–11 MeV*

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γ-ray spectra from the radiative capture of ^{3}He particles by tritons have been obtained over the energy range $0.5 \leq E(^3He) \leq 11.0$ MeV. Strong transitions were seen to the ground and first two excited states of ^{6}Li; excitation curves and angular distributions are presented. The integrated cross section for the inverse reaction $^6Li(\gamma_0,t)^3He$ up to $E_\gamma = 25$ MeV is found to be 9.3 ± 1.4 MeV mb. Evidence is also found for a transition to the second $T=1$ state of ^{6}Li. The results are discussed in the framework of the direct-capture model. Substantial $T+^3He$ clustering is evident in the four observed ^{6}Li final states.

1. INTRODUCTION

The radiative capture reaction $T(^3He,\gamma)^6Li$ has been investigated below 3 MeV by Kohler and Austin,[1] and between 2 and 18 MeV by Nüsslin *et al.*[2] The reaction $^6Li(\gamma,t)^3He$, inverse to the ground-state capture reaction, has been reported by Bazhanov *et al.*[3] and by Sherman *et al.*,[4] in an energy range equivalent to 6–16-MeV ^{3}He bombarding energy. In the regions of overlap, there is no agreement among these sets of cross-section data, with some discrepancies up to a factor of 20. These discrepanices make if difficult to compare the data with the general theoretical predictions of the dipole sum rule for ^{6}Li. Other considerations also point up the necessity for obtaining additional data. Although some data on the relative capture rates to the first three states of ^{6}Li are given by Kohler and Austin, further data on captures to these states, as well as to higher excited states, are necessary for an evaluation of the importance of ^3He+T cluster structure[5,6] in the low-lying states of ^{6}Li. The single previously measured angular distribution,[2] for the ground-state transition only, needs to be supplemented by data at several energies and for the other transitions in order to obtain an understanding of the mechanism through which the capture reaction proceeds, and possibly of the structure of ^{6}Li at high excitation energies.

In the present experiment, some data for clarification of the problems stated above have been obtained. Measurements have been made of the ground-state capture cross section from 0.5 to 11.0 MeV (laboratory energy of the incident ^{3}He particles). Cross sections for transitions to the first two excited states were studied up to 5.3 MeV. Possible transitions to higher excited states were investigated by runs with good counting statistics, and a γ ray which appears to go to the second $T=1$ state was discovered. Finally, angular distributions were recorded for the three strong transitions at energies of 1.0, 2.7, and 5.0 MeV.

2. EXPERIMENTAL PROCEDURE AND RESULTS

The beam of ^{3}He ions, obtained from the 6-MeV Ohio State University Van de Graaff accelerator, was analyzed magnetically and directed onto targets of tritium in thin evaporated films of titanium on copper backings.[7] γ rays were detected in a 4-in.-diam×6-in.-long NaI(Tl) spectrometer surrounded by a NE102 plastic scintillator used in anticoincidence. Use of this anticoincidence shield enhances the full-energy peak of the monoergic NaI(Tl) γ-ray response, and also serves as an efficient cosmic-ray suppressor. Details of this detection system have been reported earlier.[8] The response of this system to 20.5-MeV γ rays, produced in the $T(p,\gamma)^4He$ reaction, is shown in Fig. 1. The upper curve shows the NaI(Tl) crystal "singles" response. The middle curve is that portion of the

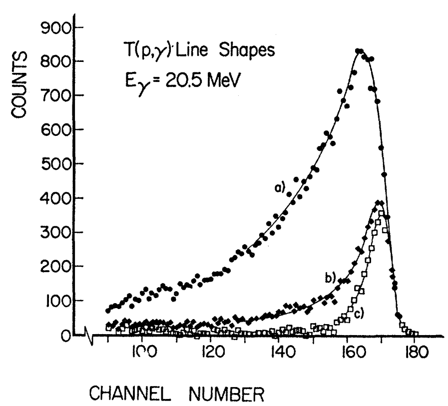

FIG. 1. Response of detector system to monoergic 20.5-MeV γ rays. Curve (a) is the response of the NaI(Tl) crystal alone, with a full width at half-maximum resolution of 16%. In curve (b), the anticoincidence requirement has been added, giving a resolution of 6.8% and a peak height, relative to (a), of 0.47. Curve (c) shows the improvement gained by subtracting 20% of the coincident spectrum from (b); the resolution becomes 4.7%, and the relative peak height is 0.43.

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[2] F. Nüsslin, H. Werner, and J. Zimmerer, Z. Naturforsch. 21a, 1195 (1966).
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[6] D. R. Thompson and Y. C. Tang, Phys. Rev. Letters 19, 87 (1967).
[7] Obtained from U. S. Radium Corp., Morristown, N. J.
[8] S. C. Ling, A. M. Young, and S. L. Blatt, Nucl. Phys. A108, 221 (1968).

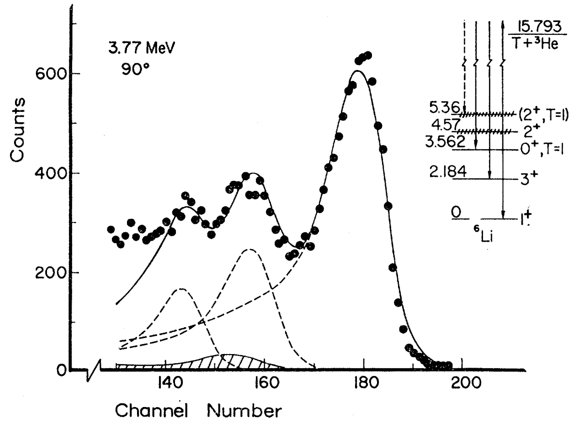

FIG. 2. Anticoincidence-shielded detector spectrum of γ rays emitted at 90° from $T(^3He,\gamma)^6Li$ at $E_{lab}(^3He)=3.77$ MeV. The least-squares fit for transitions to the first three states of ^6Li is shown as a solid line, the components making up this fit are indicated by broken lines. (The small shaded component is from ^{13}C contamination.)

NaI(Tl) spectrum which is anticoincident with escape events seen by the plastic shield. The line shape can be further improved[9] by subtracting about 20% of the coincident spectrum from the anticoincident spectrum, as seen in the lower curve.

Pulse pileup distortion accompanying the high counting rate produced by $T(^3He,n)^5Li$ and $T(^3He,np)^4He$ neutrons interacting in the NaI(Tl) detector was reduced by a factor of over 200 with a fast-logic system.[10]

γ-ray spectra were recorded for 16 bombarding energies between 1.0 and 11.1 MeV at a detector angle of 90° with respect to the beam. A typical spectrum, taken at $E(^3He)=3.77$ MeV in the simple anticoincidence mode, is shown in Fig. 2, together with a ^6Li level diagram. Capture radiations were identified by the following criteria: (a) correct energies as determined by the Q value (15.793 MeV) and energy spacings in ^6Li; (b) dependence on bombarding energy $E_\gamma = Q+\frac{1}{2}E(^3He)$; and (c) angular dependence of γ-ray energy as given by the Doppler-shift formula. The capture radiation to the ground and first two excited states is clearly resolved in Fig. 2. γ-ray intensities were obtained from such spectra with the aid of a least-squares fitting program[11] using monoergic detector line shapes obtained from the reactions $T(p,\gamma)^4He$ and $^{11}B(p,\gamma)^{12}C$. These intensities were corrected for variations of detector efficiency with γ-ray energy and for the fraction of pulses rejected by the pileup circuit. Random coincidences, which have the effect of rejecting valid events, were recorded in a separate coincidence unit during each run, and used as an additional correction factor. Small contributions at 15.11 MeV from the reaction $^{13}C(^3He,\alpha\gamma)^{12}C$ on built-up carbon were also taken into account.

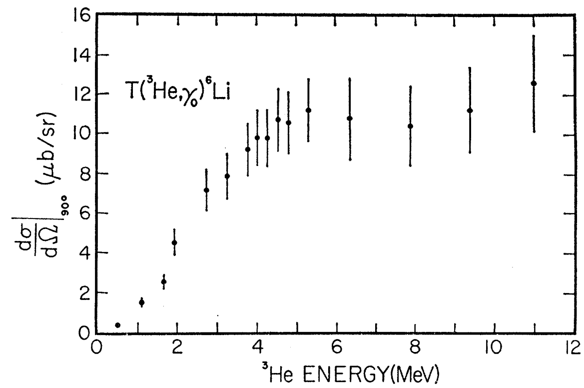

FIG. 3. Measured 90° differential cross section for ground-state capture in the reaction $T(^3He,\gamma)^6Li$.

TABLE I. Measured 90° differential cross sections for the reactions $T(^3He,\gamma)^6Li$ leading to the ground and first two excited states of ^6Li.

$E_{lab}(^3He)$	$d\sigma/d\Omega\|_{90°}$ (μb/sr) γ_0	γ_1	γ_2
0.51	0.38±0.06	0.10±0.02	0.07±0.02
1.10	1.5 ±0.2	0.34±0.06	0.24±0.05
1.65	2.6 ±0.4	0.64±0.12	0.45±0.10
1.92	4.5 ±0.7	1.2 ±0.2	0.86±0.18
2.73	7.2 ±1.1	1.8 ±0.3	1.3 ±0.3
3.25	7.9 ±1.2	1.9 ±0.3	1.5 ±0.3
3.77	9.2 ±1.4	2.5 ±0.4	1.4 ±0.3
4.03	9.8 ±1.5	2.7 ±0.4	1.7 ±0.3
4.28	9.8 ±1.5	2.7 ±0.4	1.5 ±0.3
4.54	10.7 ±1.6	3.1 ±0.5	1.6 ±0.3
4.80	10.6 ±1.6	2.6 ±0.4	1.6 ±0.3
5.30	11.2 ±1.7	3.1 ±0.5	1.5 ±0.03
6.34	10.8 ±2.1		
7.86	10.4 ±2.1		
9.38	11.2 ±2.2		
11.0	12.6 ±2.5		

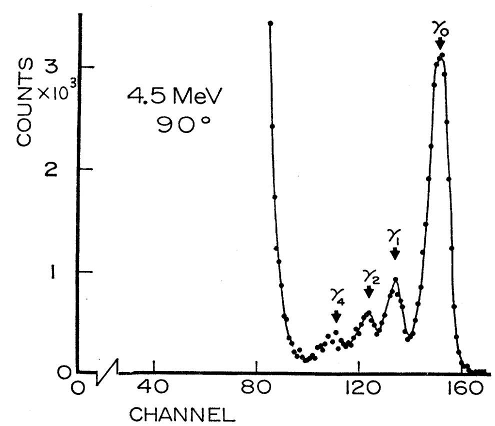

FIG. 4. Good-statistics γ-ray spectrum at 4.5 MeV. The subtraction technique of Ref. 9 has been used to improve the energy resolution.

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[10] S. L. Blatt, J. Mahieux, and D. Kohler, Nucl. Instr. Methods **60**, 221 (1968).

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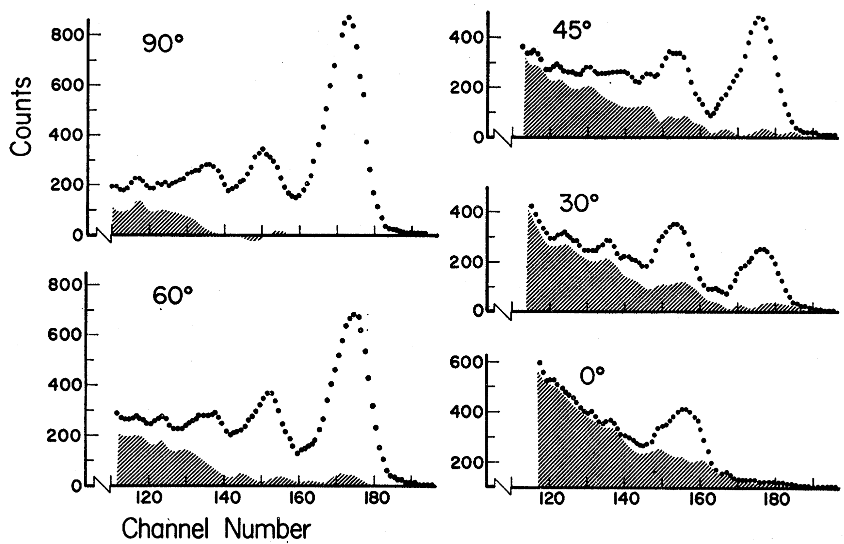

FIG. 5. Spectra taken, using the subtraction technique, to determine angular distributions at 2.70 MeV. The shaded area indicates the residual spectrum after γ_0, γ_1, and γ_2 have been stripped out with intensities given by direct-capture angular distribution calculations.

The γ-ray intensities were calibrated by measuring the 90° yield from the T(p,γ) reaction on the same target employed in the T(^{3}He,γ) measurement, with no changes in detector geometry or electronic processing. Using the value measured by Perry and Bame[12] at $E(p)=1.0$ MeV of $d\sigma/d\Omega|_{90°}=3.65$ μb/sr for the proton capture reaction, the 90° differential cross sections for radiative capture to the first three states of ^{6}Li were obtained. These measured cross sections are displayed in Table I. Figure 3 shows the cross section for ground-state capture. The points have been adjusted along the bombarding-energy axis to account for the finite ^{3}He-particle energy loss within the target. This effective energy thickness, arising primarily from the titanium, was measured by comparing the observed γ_0 resolution with the unbroadened 17.2-MeV detector response obtained from the reaction ^{11}B(p,γ)^{12}C using a thin boron target. Quoted probable errors include statistics, uncertainties in the least-squares fitting, charge collection and current integration, target thickness and nonuniformity, count-rate correction factors, and the estimated error of the T(p,γ) comparison cross section.[12] These errors were combined quadratically. The four data points above 6 MeV were obtained with the ^{3}He^{++} component of the normal accelerator beam; no high-voltage terminal analysis was employed. Due to the very small beam currents obtained (about 10 nA, compared to 0.5 μA typically used with the singly ionized beam), charge integration uncertainties and poor counting statistics produce larger probable errors in these four points, and accurate intensities for γ_1 and γ_2 could not be obtained.

In order to investigate the γ-ray energy region corresponding to transitions to higher excited states in ^{6}Li, the subtraction technique[9] for improving the detector line shape, as mentioned above, was applied to several spectra recorded with good statistics. Such a spectrum, obtained at $E(^3\text{He})=4.5$ MeV, is shown in Fig. 4. Evidence appears for a transition to the state[13,14] at 5.36 MeV in ^{6}Li.

Measurements were made to obtain information on the angular distributions of the capture γ rays at incident energies of 1.0, 2.7, and 5.0 MeV. Spectra at 2.7 MeV are shown in Fig. 5. The γ rays are seen to shift to higher energies at forward angles, in agreement with calculated Doppler shifts for this reaction. The angular distribution for γ_0 is found to be $W(\theta)=1-(1_{-0.12}^{+0.08})P_2(\cos\theta)$; thus within the small experimental error, $W(\theta)=\sin^2\theta$ for γ_0. Due to the background at forward angles arising from high-energy neutrons, the angular distributions of γ_1 and γ_2 cannot be extracted unambiguously from the data; theoretical predictions may nevertheless be compared directly with the data for qualitative agreement or disagree-

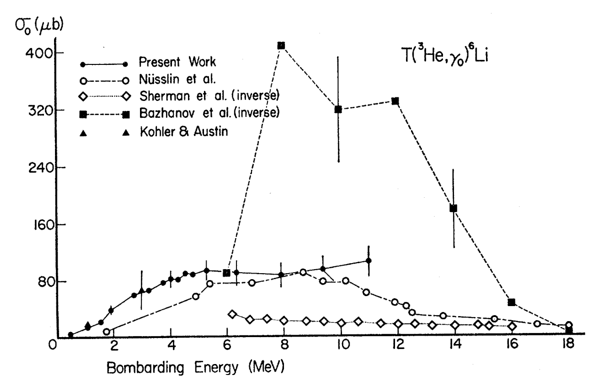

FIG. 6. Total cross section for ground-state capture in the reaction T(^{3}He,γ)^{6}Li as reported in the literature, in comparison with the present experiment.

[12] J. E. Perry, Jr., and S. J. Bame, Jr., Phys. Rev. 99, 1368 (1965).

[13] T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. 78, 25 (1966).

[14] C. L. Cocke, Nucl. Phys. A110, 321 (1968).

ment. The angular distributions obtained at the other two energies appear to be identical. A small departure from a $\sin^2\theta$ dependence for γ_0 at 9 MeV, reported by Nüsslin *et al.*,[2] may arise from an underestimate of the neutron background at forward angles, which the improved γ-ray resolution in the present experiment clearly reveals.

Since the $\sin^2\theta$ distribution for ground-state capture appears to hold at all energies, the total cross section is obtained simply by multiplying the measured 90° differential cross section by $8\pi/3$. Figure 6 shows this total cross section, plus the data of Refs. 1–4. The two photodisintegration measurements were converted to the radiative capture scale by use of the reciprocity relation[15]

$$(2J_{\rm T}+1)(2J_{\rm He}+1)(p_{\rm He})^2\sigma_{\rm cap} = 2(2J_{\rm Li}+1)(E_\gamma/c)^2\sigma_{\rm photo}\,, \quad (1)$$

where $p_{\rm He}$ is the c.m. momentum of the ^{3}He particle, J_x is the ground-state spin of nucleus x, $\sigma_{\rm cap}$ is the $\rm T(^3He,\gamma_0)^6Li$ cross section, and $\sigma_{\rm photo}$ is the $\rm ^6Li(\gamma,T)^3He$ cross section.

The present data agree very well with the values calculated from the 90° measurements of Kohler and Austin,[1] using the $\sin^2\theta$ distribution of the present experiment. The results of Nüsslin *et al.*[2] appear to be in reasonable agreement, but those data include capture to the first and second excited states of ^{6}Li as well as the ground state.[16] Subtracting the contributions of γ_1 and γ_2, as measured in the present experiment and discussed below, the data of Nüsslin *et al.* should be reduced by a factor of about 0.7. Agreement among the three capture measurements, however, is much better than any comparisons with the inverse reaction.[3,4] The $^6{\rm Li}(\gamma,t)^3{\rm He}$ reaction has recently been remeasured by Mahknovskii, and the integrated cross section has been reported.[17,18] This new work indicates that the values reported by Bazhanov *et al.* are in fact too large.

3. DISCUSSION

A. Capture Mechanism

If the ground-state cross section results of the present experiment are combined with the higher-energy data of Nüsslin *et al.*, the reaction exhibits a broad structure, centered around an excitation energy of about 20 MeV, with a c.m. width of about 5.5 MeV. This structure may be a broad compound nucleus resonance, although the analysis given below makes this interpretation doubtful. Consideration will first be given to an estimate of a lower limit for the radiative width of a "resonance" at this energy; then the angular distributions will be discussed.

The peak cross section for a single $(^3{\rm He},\gamma)$ resonance can be written as

$$\sigma_{\rm res}=4\pi\lambda\!\!\!^{-2}\frac{(2J_{\rm res}+1)}{(2J_{\rm He}+1)(2J_{\rm T}+1)}\left(\frac{\Gamma_{^3{\rm He}}\Gamma_\gamma}{\Gamma^2}\right). \quad (2)$$

By using the values $\sigma_{\rm res}=85\ \mu$b and $\Gamma=5.5$ MeV, and noting that $(\Gamma_{^3{\rm He}}/\Gamma)\leq 1$, a lower limit on Γ_γ may be found:

$$(2J_{\rm res}+1)\Gamma_\gamma \geq 4.3\ {\rm keV}. \quad (3)$$

The Weisskopf estimate for a 20-MeV $E1$ transition in ^{6}Li is $\Gamma_{\gamma W}=1.8$ keV. If the radiating "single particle" is taken to be a three-nucleon cluster, the c.m. correction[19] gives a theoretical estimate of $\Gamma_{\gamma W}'=0.45$ keV. For any $J_{\rm res}$ compatible with an $E1$ ground-state transition, the experimental *lower limit* for Γ_γ exceeds this single particle estimate. By comparison, the large number of $E1$ transitions in light nuclei, whose measured radiative widths have been catalogued by Skorka *et al.*,[20] have a typical Γ_γ about 0.5% of the Weisskopf estimate. Since few high-energy electric dipole transitions are catalogued by Skorka *et al.*, one cannot be sure what is really "typical" in the present case. Nevertheless, the present transition appears to be enormously enhanced.

Additional difficulties arise in trying to explain the observed angular distributions with a compound nucleus model. The observed $\sin^2\theta$ ground-state distribution cannot be duplicated for any single value of $J_{\rm res}$, if incoming partial waves up to $l=2$ and outgoing radiations up to $L=2$ are considered. Theoretical calculations[21] indicate the possibility of a group of states in ^{6}Li in this energy region, with $L=1$, $S=1$, and $T=1$. If all the levels in this group (with $J^\pi=0^-$, 1^-, and 2^-) contribute coherently in the ground-state capture reaction, an angular distribution $\sin^2\theta$ is produced for the unique combination in which the amplitudes from all three states are equal. That the same distribution persists over a wide range of energies then implies a complete degeneracy of the three compound levels, an assumption which does not appear theoretically justified.

Although a broad peak may be present in the excitation curve, the energy variation is slow enough to allow consideration of the "direct" capture mechanism.[22–24] In this model, radiative capture is assumed to be a one-step process. The direct capture and compound-nucleus capture models are two extreme simplifications of the exact capture mechanism. In the present case, these two extremes may not be too far apart; a 5.5-MeV wide compound state has a lifetime of about 7×10^{-22} sec, which is the same order of magnitude as the time

[15] E. Hayward, in *Nuclear Structure and Electromagnetic Interactions*, edited by N. MacDonald (Plenum Press, Inc., New York, 1965), pp. 141 ff.
[16] F. Nüsslin (private communication).
[17] E. D. Mahknovskii (private communication).
[18] V. P. Denisov, A. P. Komar, L. A. Kal'shitskii, and E. D. Mahknovskii, Yadern. Fiz. **5**, 349 (1967) [English transl.: Soviet J. Nucl. Phys. **5**, 498 (1967)].
[19] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, pp. 852 ff.
[20] S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data **A2**, 347 (1966).
[21] R. A. Eramzhyan, Izv. Akad. Nauk SSSR **28**, 1081 (1964).
[22] R. F. Christy and I. Duck, Nucl. Phys. **24**, 89 (1961).
[23] T. A. Tombrello and P. D. Parker, Phys. Rev. **131**, 2582 (1963).
[24] G. M. Bailey, G. M. Griffiths, and T. W. Donnelly, Nucl. Phys. **A94**, 502 (1967).

for an incident ^{3}He particle to transit the nucleus in a direct reaction.

The direct capture cross section can be calculated in first-order perturbation theory by considering matrix elements of the electromagnetic multipole operators between initial scattering states and final bound states of the incident and target nuclei. In the notation of Ref. 24, the differential cross section for direct capture is given by

$$\frac{d\sigma}{d\Omega}=\frac{K}{hV_i(2J_{\mathrm{He}}+1)(2J_T+1)}\times\sum_{m_i,m_f,P=\pm 1}|\langle f,m_f|\mathcal{H}_{\mathrm{int}}{}^P|i,m_i\rangle|^2,\quad (4)$$

where K and P are the wave number and polarization state, respectively, of the γ ray, V_i is the relative speed of the projectile-target system, and i and f refer to the incoming and final state, respectively.

For $E1$ radiation, the interaction Hamiltonian can be written as

$$\mathcal{H}_{\mathrm{int}}{}^P=-i\left(\frac{4\pi}{3}\right)^{1/2}PKe\mu\left(\frac{Z_{\mathrm{He}}}{M_{\mathrm{He}}}-\frac{Z_{\mathrm{T}}}{M_{\mathrm{T}}}\right)\times\sum_M \hat{D}_{MP}{}^{1*}\mathcal{O}_{E1}(r)Y_1{}^{M*},\quad (5)$$

where M is the magnetic quantum number of the radiation and $\mu=M_{\mathrm{He}}M_T/(M_{\mathrm{He}}+M_{\mathrm{T}})$ is the reduced mass. The rotation matrices are functions of the angles describing the direction of γ-ray emission with respect to the beam axis, and the spherical harmonics depend on the orientation of the target-projectile system. $\mathcal{O}_{E1}(r)$ is the radial part of the electric dipole operator.

If only the angular parts of the wave functions are written explicitly,

$$|i,m_i\rangle=\sum_l \frac{R_{lS_i}(k,r)}{r}Y_l{}^0\chi_{S_i}{}^{m_i}\quad (6)$$

and

$$\langle f,m_f|=\theta_f\frac{U_{L_f}(r)}{r}\sum_\beta C(L_fS_fJ_f;m_f-\beta,\beta)\times Y_{L_f}{}^{m_f-\beta}\chi_{S_f}{}^{\beta}.\quad (7)$$

In these expressions, k is the wave number of the incident particle, $\chi_S{}^m$ is the spin function for channel spin S, and θ_f is the coefficient of fractional parentage of the T+^{3}He cluster in the total wave function for state f; other components are assumed to have no overlap with the initial wave function.

If the first three states of ^{6}Li are described in L-S coupling,[25] they are given by ^{13}S, ^{13}D, ^{31}S, for the ground state, first and second excited states, respectively. (The first superscript is the isospin multiplicity, and the second is the spin multiplicity.) Two incoming partial waves are considered, ^{33}P and ^{11}P. $E1$ transitions from the former will go only to the ^{13}S and ^{13}D states, while the transition to the ^{31}S state comes from the latter only. The calculated angular distributions are shown in Table II. These angular distributions should be unchanged over the energy range where p-wave capture is dominant. When these calculated distributions are subtracted from the 3-MeV data, a reasonably smooth spectrum, presumably due to the high-energy neutron background, remains. The data are thus in agreement with these direct-capture angular distribution calculations.

Table II. Direct-capture electric dipole angular distribution calculations. The assumed configurations are given in the notation $^{(2T+1)(2S+1)}L$.

	γ_0	γ_1	γ_2
Final-state configuration	$^{13}S(1^+)$	$^{13}D(3^+)$	$^{31}S(0^+)$
Assumed initial state	^{33}P	^{33}P	^{11}P
$W(\theta)$	$\sin^2\theta$	$1-0.1P_2(\cos\theta)$	$\sin^2\theta$

Without assuming explicit forms for the radial wave functions of Eqs. (6) and (7), the complete energy dependence of the capture cross sections cannot be calculated. However, qualitative conclusions can be drawn from a consideration of ratios of cross sections. Let a "reduced dipole capture cross section ratio" $[\gamma_n/\gamma_m]$ be defined as follows:

$$\left[\frac{\gamma_n}{\gamma_m}\right]\equiv\frac{\sigma_{\gamma_n}/E_{\gamma_n}{}^3}{\sigma_{\gamma_m}/E_{\gamma_m}{}^3},\quad (8)$$

where n and m refer to the various final states. From Eqs. (4)–(7), ratios for γ_0, γ_1, γ_2 have been calculated[26] to be

$$\left[\frac{\gamma_1}{\gamma_0}\right]=\frac{14}{15}\left(\frac{\theta_1}{\theta_0}\right)^2\times\left(\int_0^\infty U_2{}^{(1)}\mathcal{O}_{E1}R_{11}dr\Big/\int_0^\infty U_0{}^{(0)}\mathcal{O}_{E1}R_{11}dr\right)^2$$

and (9)

$$\left[\frac{\gamma_2}{\gamma_0}\right]=\frac{1}{3}\left(\frac{\theta_2}{\theta_0}\right)^2\times\left(\int_0^\infty U_0{}^{(2)}\mathcal{O}_{E1}R_{10}dr\Big/\int_0^\infty U_0{}^{(0)}\mathcal{O}_{E1}R_{11}dr\right)^2,$$

where the superscript on the final-state radial function labels the particular final state involved. Because of identical energy behavior of numerator and denominator, $[\gamma_1/\gamma_0]$ should be a constant over a wide range of bombarding energies. On the other hand, the ratio $[\gamma_2/\gamma_0]$ is not expected to be constant, since the transitions proceed through different initial states. The two reduced cross-section ratios $[\gamma_1/\gamma_0]$ and $[\gamma_2/\gamma_0]$ are shown in Fig. 7, and can be seen to exhibit the qualitative behavior indicated here. In calculating the ratios in Fig. 7, the measured 90° differential cross sections for γ_1 and γ_2 transitions were multiplied by factors of $8\pi/2.1$ and $8\pi/3$, respectively, under the assumption

[25] D. R. Inglis, Rev. Mod. Phys. 25, 390 (1953).

[26] R. G. Seyler (private communication).

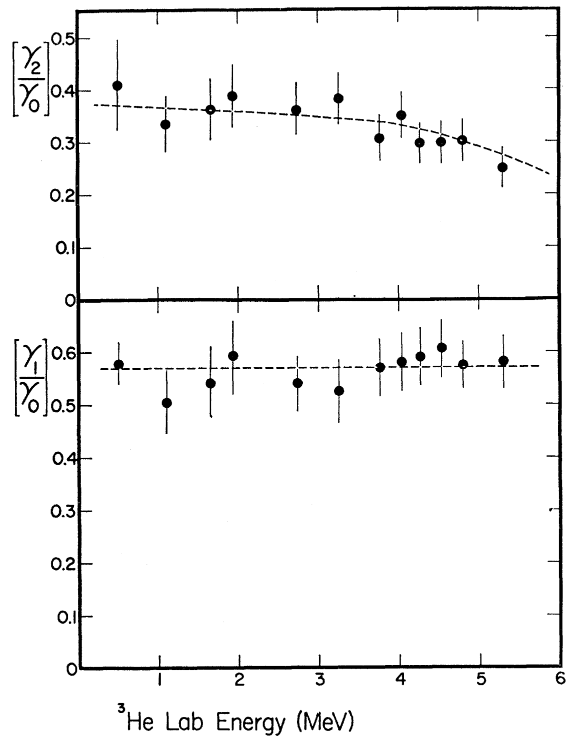

FIG. 7. Reduced cross section ratios for γ_0, γ_1, and γ_2. The ratio is defined as $[\gamma_n/\gamma_m]\equiv(\sigma_{\gamma_n}/E_{\gamma_n}{}^3)/(\sigma_{\gamma_m}/E_{\gamma_m}{}^3)$.

that the angular distributions are well described by the direct-capture calculations.

B. Energy Levels of ^{6}Li

Shell-model calculations by Eramzhyan[21] indicate that, in the vicinity of 17-MeV excitation in ^{6}Li, there should exist a group of three levels of ^{33}P character which would have large T+^{3}He widths. These levels, with $J^\pi=0^-$, 1^-, and 2^-, should be separated by the spin-orbit coupling. Bazhanov *et al.*[3] suggested that the peak apparent in their photodisintegration experiment at about 22 MeV be ascribed to this group of levels. However, Kurdyumov,[27] in a later calculation, claims that the only ^{6}Li levels that can disintegrate into T+^{3}He have energies between 16 and 18 MeV.

Resonating-group calculations of the ^{3}He+T system by Thompson and Tang[28] indicate that elastic-scattering data are consistent with the presence of a ^{33}P resonance at 22.3 MeV and a ^{11}P resonance at 21.3 MeV. The singlet and triplet phase shifts are sufficiently different to allow the observed behavior of the ratio $[\gamma_2/\gamma_0]$ (Fig. 7).

Calculations[6,28] in the resonating-group model have also been made of bound states with a T+^{3}He cluster configuration; states with *L-S* coupling descriptions similar to the ground and first two excited states are predicted between 3.47 and 10.39 MeV. These levels should have θ_f values near unity (in contrast to the lower states, which are expected to be primarily $\alpha+d$ cluster states[29]). They should therefore have substantial direct-capture transition strengths. No evidence for these states exists in the data of the present experiment. The lowest energy level (which should be correct to within 1 MeV) should show up as a very strong peak somewhere between γ_2 and the high-energy neutron background edge. In this region, only the transition γ_4, discussed below, is seen. Transitions to the higher states would be hidden, in the present experiment, by the neutron background. The strong transitions to the lowest three states of ^{6}Li suggest that there is significant configuration mixing of the higher-energy T+^{3}He cluster states in these lower states.

Berman *et al.*[30] have suggested that there is present in the ground state of ^{6}Li an appreciable mixing of a bound T+^{3}He configuration. Evidence from other reactions[5,31,32] indicates sizeable T+^{3}He clustering in the ground state and somewhat less in the first two excited states of ^{6}Li. Although any attempts to estimate the values of the θ_f parameter for these levels from the present experiment must await completion of a numerical calculation of the direct-capture cross sections,[33] preliminary estimates of ratios of these fractional parentage coefficients can be obtained by comparing the calculated ratios of Eq. (9) with the experimental values of Fig. 7. If all the radial integrals are assumed to have similar values, $\theta_1^2\approx0.6\theta_0^2$ and $\theta_2^2\approx\theta_0^2$. The coefficients θ_1 and θ_2 both appear, in this extreme approximation, to be larger (in comparison with θ_0) than suggested by the results of other reactions.[5]

The one substantial transition to states above the first $T=1$ state appears (Fig. 4) to go to a state at about 5.4 MeV which has been proposed as the analog of the first excited states of ^{6}Be and ^{6}He. If the angular distribution is assumed to be nearly isotropic, $\sigma_{\gamma_4}\approx10\ \mu$b at 4.5 MeV. The reduced cross section ratio for the two $T=1$ states, $[\gamma_4/\gamma_2]$, is of order 1. The second $T=1$ state would be ^{31}D in *L-S* coupling, and an $E1$ transition from the ^{11}P incoming wave would be expected to have a strength, compared to the transition to the first $T=1$ state, given by

$$\left[\frac{\gamma_4}{\gamma_2}\right]=2\left(\frac{\theta_4}{\theta_2}\right)^2\times\left(\int_0^\infty U_2{}^{(4)}\mathcal{O}_{E1}R_{10}dr\bigg/\int_0^\infty U_0{}^{(2)}\mathcal{O}_{E1}R_{10}dr\right)^2, \quad (10)$$

[27] I. V. Kurdyumov, S. Kh. El Samarai, Yu. F. Smirnov, and K. V. Shitikova, Izv. Akad. Nauk SSSR **30**, 292 (1966).

[28] D. R. Thompson and Y. C. Tang, Nucl. Phys. **A106**, 591 (1958).

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[31] P. D. Forsyth and R. R. Perry, Nucl. Phys. **67**, 517 (1965).

[32] A. R. Knudson and E. A. Wolicki, in *Proceedings of the Conference on Direct Interactions, Padua, 1962* (Gordon and Breach, Science Publishers, Inc., New York, 1963), p. 981.

[33] A. M. Young, R. G. Seyler, and S. L. Blatt (to be published).

assuming p-wave capture. If, again, the assumption of nearly identical radial integrals is made, then $\theta_4^2 \approx \frac{1}{2}\theta_2^2$.

Since no isospin singlets should exist in $T_z = \pm 1$ nuclei, analogous dipole transitions in ^{6}Be or ^{6}He are not possible. However, radiative capture of ^{3}He by ^{3}He has been observed recently by Harrison *et al.*[34] No ground-state transition was seen, but capture to the first excited state of ^{6}Be was seen. The reaction was interpreted as direct capture from the ^{31}S partial wave, which would not radiate to the 0^+ ground state but could have an $E2$ transition to the (2+) first excited state. The analog of the transition should contribute to γ_4 in ^{6}Li. The cross section for this contribution at a given γ-ray energy can be estimated by correcting the ^{3}He(^{3}He,γ)^{6}Be cross section at the same γ-ray energy for the different penetrabilities and quadrupole effective charge factors for ^{3}He+^{3}He and ^{3}He+T. (These two effects go in opposite directions.) Using the cross section[34] found by Harrison *et al.* at $E_{\gamma_4} = 12.7$ MeV, the $E2$ s-wave capture would be expected to contribute at least half of the observed T(^{3}He,γ_4)^{6}Li cross section at 4.5-MeV incident energy.

C. Dipole Sum Rule in ^{6}Li

The classical dipole sum rule, calculated from a consideration of the combined dipole strengths of each nucleon within a nucleus, is[15]

$$\int \sigma(E\gamma)dE\gamma = \frac{2\pi^2 e^2 h}{Mc}\frac{NZ}{A}. \tag{11}$$

For ^{6}Li, this rule says that the total $E1$ photoabsorption cross section, integrated over all energies, is ≥ 90 MeV mb. Integrated photoabsorption cross sections in light nuclei have, in general, been found to be lower than the sum rule value,[15] but only photonucleon emission has been taken into account in most of these experiments. The ^{6}Li(γ,n) and ^{6}Li(γ,p) reactions account for only about $\frac{1}{3}$ of this total below $E_\gamma = 32$ MeV,[30] and about $\frac{2}{3}$ when energies up to 60 MeV are included.[3] The phototriton cross section, as measured earlier,[2,3] appeared to be sufficient to account for the remaining $\frac{1}{3}$, but those measurements (or the reciprocity calculations contained in Ref. 2) do not seem to be correct in the light of the present work. The ^{6}Li(γ,t)^{3}He cross section, integrated up to $E_\gamma = 21$ MeV, is 7.1±1.0 MeV mb, while if the data of Nüsslin *et al.*[2] are included above the energy region studied here, the integrated cross section to 25 MeV is 9.3±1.4 MeV mb. This number may be compared to other quoted values in Table III. It should be noted that angular distributions of the ^{6}Li phototriton emission reaction have not been reported; thus the reciprocal nature of the reaction considered here is, to some extent, still an assumption.

[34] W. D. Harrison, W. E. Stephens, T. A. Tombrello, and H. Winkler, Phys. Rev. 160, 752 (1967).

TABLE III. Reported values for the integrated phototriton cross section in ^{6}Li up to $E_\gamma = 25$ MeV.

References	$\int \sigma(E_\gamma)dE_\gamma$ (MeV mb)	Reaction studied
Nüsslin *et al.*[a]	26±9[b]	capture
Sherman *et al.*[c]	<5	photo
Bazhanov *et al.*[d]	30_{-15}^{+10}	photo
Makhnovskii[e]	10–15	photo
Present work	9.3±1.4[f]	capture

[a] Reference 2.
[b] This value disagrees with the data from Ref. 2 converted to the inverse reaction using Eq. (1).
[c] Reference 4.
[d] Reference 3.
[e] References 17 and 18.
[f] Using data from Ref. 2 above 21 MeV.

Integrated cross section for dipole radiation in the T+^{3}He cluster system can be calculated in the manner used[15] to derive (10). The mass M of the radiating particle is set equal to the three-nucleon cluster mass, and the effective charge $\mu[(Z_{\text{He}}/A_{\text{He}}) - (Z_{\text{T}}/A_{\text{T}})]e$ is used instead of the proton and neutron effective charges. If the radiative cross section is summed over the two clusters, one obtains

$$\int \sigma_{\gamma,T}(E_\gamma)dE_\gamma \Big/ \int \sigma_{\gamma,\text{all}}(E_\gamma)dE_\gamma = \tfrac{1}{9}, \tag{12}$$

so that the integrated cross section for the phototriton component alone should be about 10 MeV mb. The facts that this is a substantial fraction of the total sum-rule value and that the measured integrated cross section for ground-state absorption comes so close to satisfying this fraction indicate the importance of T+^{3}He clustering in the ^{6}Li ground state.

4. SUMMARY

The agreement noted among the three sets of ground-state capture measurements indicates that the value of the integrated phototriton cross section calculated from the present data is more accurate than those obtained from direct ^{6}Li(γ,t)^{3}He measurements. The amount of T+^{3}He clustering in the ^{6}Li ground-state wave function appears to be more substantial than has previously been appreciated. Significant T+^{3}He clustering in the first, second, and fourth excited states is also apparent.

A direct-capture model explains the observed angular distributions and, qualitatively, some additional features of the T(^{3}He,γ)^{6}Li reaction. Detailed calculations, using various explicit forms for the radial wave functions, are presently under way to determine the quantitative predictions of this model.

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