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Comparison of the ^{6}Li(t, ^{3}He)^{6}He and ^{6}Li(t, t')^{6}Li reactions to supermultiplet members

J. D. Sherman,* E. R. Flynn, Nelson Stein, J. W. Sunier, and D. G. Burke†
University of California, Los Alamos Scientific Laboratory,‡ Los Alamos, New Mexico 87545

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The ^{6}Li(t, ^{3}He)^{6}He(0.0) and ^{6}Li(t,t')^{6}Li(3.56) transitions have been studied at 17 MeV triton incident energy. Differential cross sections have been obtained from 10° to 90° c.m. angle, with 12 angles common to both reactions. The experimental ratio of $\sigma(t,\ ^3\mathrm{He})$ to $\sigma(t,t')$ is 2.28 ± 0.16, while geometrical isospin considerations for this reaction pair would predict a ratio of 2.0. Corrections based on a microscopic distorted-wave Born-approximation calculation of charge exchange and inelastic scattering do not account for a deviation of this magnitude.

[NUCLEAR REACTIONS ^{6}Li(t, ^{3}He)^{6}He(0.0), ^{6}Li(t, t')^{6}Li(3.56) $E_t=17.0$ MeV; measured $\sigma(\theta)$; DWBA analysis.]

I. INTRODUCTION

The mass six system is a convenient physical situation in which to study isotopic spin conservation in low energy nuclear reactions. The ground states of ^{6}He, ^{6}Be, and the second excited state of ^{6}Li at 3.56 MeV form an isospin triplet,[1] and these levels are accessible by charge exchange or inelastic scattering via spin-isospin flip transitions ($\Delta S=1$, $\Delta T=1$). These transition strengths should then be related by the geometrical couplings of the isospins involved, if the charge dependent components of the forces are not large. Previous investigations using the ^{6}Li target have included charge exchange reactions and inelastic scattering induced by ^{3}He ions,[2] and by proton and neutron beams.[3] We report here the first such investigation in the $A=6$ system with triton beam induced reactions. Angular distributions of the triton and ^{3}He projectiles emerging from the ^{6}Li(3.56) and ^{6}He(g.s.) have been measured in the 10°–90° c.m. angular range. A previous investigation of the ^{6}He level structure[4] had utilized the ^{6}Li(t, ^{3}He) reaction, although no angular distributions were reported.

In the present case, vector coupling of isospins predicts that $\sigma(t,\ ^3\mathrm{He})/\sigma(t,t')=2.0$. Small deviations from these considerations may be expected due to the different reaction channels, and these may be corrected by use of the distorted-wave Born approximation (DWBA). Thus the correct experimental ratio (within this approximation) should be

$$R=\sigma(t,\ ^3\mathrm{He})/\sigma(t,t')=2.0\sigma_{\mathrm{DW}}(t,\ ^3\mathrm{He})/\sigma_{\mathrm{DW}}(t,t')\ , \tag{1}$$

where σ_{DW} are distorted-wave predictions.

II. EXPERIMENT AND RESULTS

The experiment was executed using a 17 MeV triton beam obtained from the Los Alamos tandem Van de Graaff accelerator. The target was isotopic ^{6}Li, and was vacuum transferred from the target preparation apparatus to the scattering chamber. The target was metallic throughout the experiment. The reaction products were momentum analyzed in a quadrupole-dipole-dipole-dipole (Q3D) type II magnetic spectrometer and were detected at the focal plane by a 50 cm helical cathode proportional chamber.[5] The spectrometer was operated at the full solid angle of 14.3 msr, resulting in rapid data accumulation. A typical run with 50–100 nA beam current for the ^{6}Li(t, ^{3}He)^{6}He(g.s.) reaction was 3–5 min in duration which resulted in sufficient counts to make statistical errors negligible. The ^{6}Li(t, t')^{6}Li(3.56) data runs were two or three times longer than the (t, ^{3}He) reaction due to the complication of a large three body background from the $^6\mathrm{Li}^*\to\alpha+d$ process. Figure 1 shows a triton spectrum with an energy resolution of 40 keV [full width at half maximum (FWHM)]; nearly identical resolution was observed for the (t, ^{3}He) reaction. The very large kinematic broadening associated with this reaction required significant corrections from the Q3D multipole,[5] and in order to obtain substantial improvements in energy resolution, the sextupole and octupole elements of the multipole were utilized in addition to the normal quadrupole element. Figure 1 also shows that the heavier ^{12}C target impurity has a broader line width since the multipole element was optimized for the lighter ^{6}Li target.

Angular distributions were measured for the ^{6}Li triton elastic scattering as well as for the

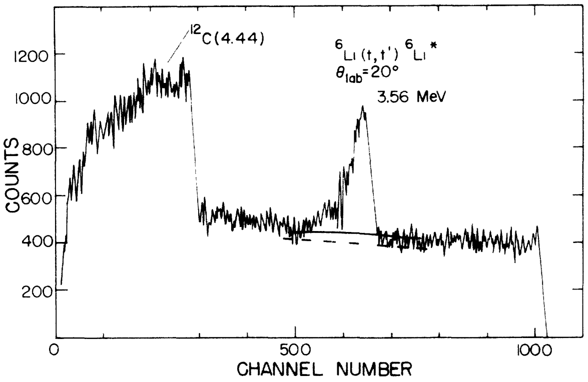

FIG. 1. Inelastic triton spectrum over the range of excitation including the 3.56 MeV $J^\pi = 0^+$ $T = 1$ level in ^{6}Li. The solid line shows the actual background subtracted, while the dashed line indicates the lower limit on the amount of background that could be subtracted.

(t, t') and (t, ^{3}He) analog transitions. These results are shown in Figs. 2 and 3. The elastic scattering cross sections were measured under conditions identical with the (t, t') and (t, ^{3}He) reaction except for beam intensity, thus providing a normalization for the latter reactions by using absolute cross sections extracted from an optical model (OM) analysis of the elastic scattering. This procedure should yield absolute cross sections accurate to ±15%. The OM analysis used the automatic search code PEREY[6] with Woods-Saxon potential wells to obtain the fit shown in Fig. 2; starting parameters were those from the ^{9}Be(t, t_0) measurement.[7] Table I gives the optical model potentials found in this work for ^{6}Li(t, t_0).

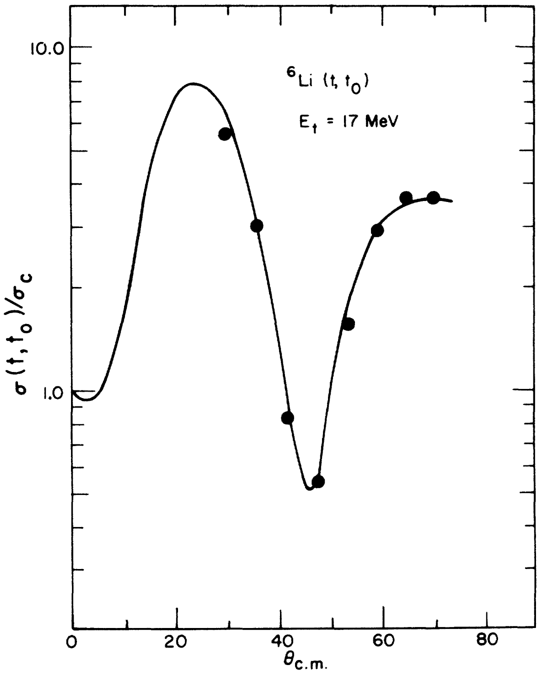

FIG. 2. The elastic triton scattering from ^{6}Li divided by the Rutherford scattering. The solid curve is the optical model fit averaged over the ±3° of the spectrometer aperture opening.

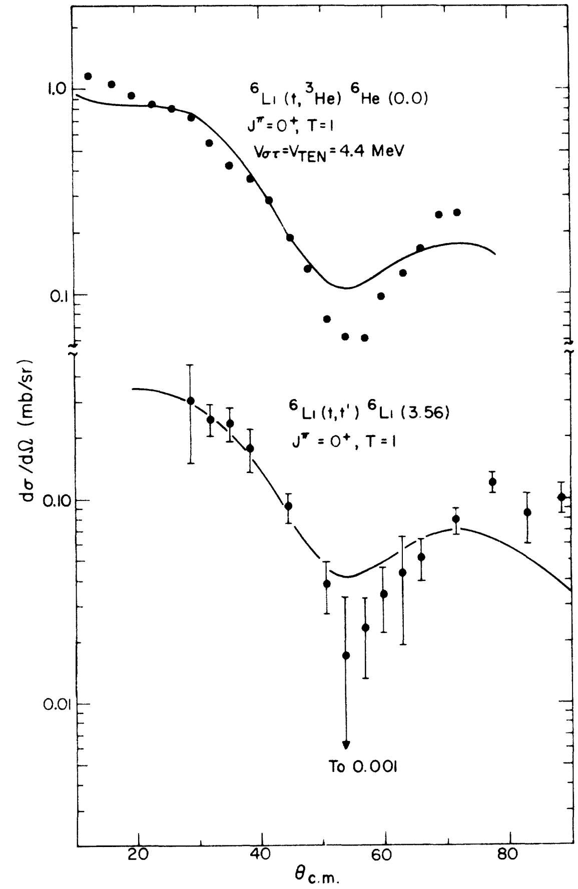

FIG. 3. Differential cross section measurements from the (t, ^{3}He) and (t, t') reactions on ^{6}Li. The solid curves are microscopic DWBA calculations which include a tensor force in the effective interaction (see text).

Figure 3 shows the charge exchange and inelastic scattering measurements. The experimental angular distribution shapes are very similar. The ^{3}He spectra were devoid of any contaminants or other background problems; however, as noted in Fig. 1, considerable three body breakup background occurs in the triton spectra. The large errors shown in Fig. 3 for ^{6}Li(t, t')^{6}Li(3.56) reflect the uncertainty in the precision with which this background could be removed. A 95% confidence level that the true differential cross section lies within these error bars is assigned. This statement does not include the possibility of an overall scale change which would affect all cross sections in the same manner. A monitor detector was used throughout the experiment to provide a normalization from angle to angle. A

TABLE I. Optical model parameters for elastic triton scattering from ^{6}Li. The real (V_R) and imaginary (W_I) potentials are given in MeV. The real and imaginary radii and diffuseness parameters (r_R, r_I, a_R, a_I) are in fm. The quantity r_C is the Coulomb radius. The quantity λ is the Thomas spin-orbit strength which was used only in the bound state potential.

	V (MeV)	r_R (fm)	a_R (fm)	W (MeV)	r_I (fm)	a_I (fm)	r_C (fm)	λ
OM	−211.3	1.16	0.45	−15.5	1.57	1.05	1.30	
Bound state		1.27	0.67					32.0

comparison of the background subtraction procedure and the monitor results indicates that the relative errors between the charge exchange reaction and the inelastic scattering are predominantly due to the background encountered in the triton spectra.

Figure 3 shows that the data were taken for the ^{6}Li(t, ^{3}He) and ^{6}Li(t, t') reactions at 12 common angles. In Fig. 4 the experimental value of R as defined in Eq. (1) is plotted vs c.m. angle. The weighted average of these 12 points yields $R = 2.28 \pm 0.16$, the weights being inversely related to the error bars shown in Fig. 4.

III. ANALYSIS

In order to try to reconcile the experimental results with the simple isospin considerations, corrections due to known violations of the charge independence hypothesis may be made through use of a reaction theory as implied in Eq. (1). Such corrections could be due to different masses in the interacting subsystems which lead to different Q values and separation energies. Further, the Coulomb force will affect the two exit channels differently, while at the same time the isospin symmetry of the optical model[8] predicts the nuclear potential to act equally in the two cases. The reaction model with which we have chosen to study these effects is the single-step distorted-wave Born approximation (DWBA) with inclusion of a tensor force[9,10] in the effective interaction. This model should provide an adequate tool for describing the ratios of charge exchange to inelastic scattering cross sections that we seek to investigate, although the impact of multireaction mechanisms[11] in the following considerations has not been evaluated.

The code DWUCK[12] and the recipe of Ref. 9 for determining the effective interaction parameters [we use the one pion exchange potential (OPEP) tensor form] have been utilized in all DWBA calculations reported here. Furthermore, we used the simple $[(1p_{3/2})_\pi(1p_{3/2})_\nu]_{1^+}$ configuration to represent the ^{6}Li ground state. The bound state wave functions were calculated in a Woods-Saxon well using the separation energy procedure with the energies being determined from the masses[13] of the neighboring nuclei. The bound state parameters are given in Table I; a factor of 32 for the Thomas spin orbit factor was used. The effective interaction was a central spin-isospin flip term plus a tensor term of equal strength. The central interaction term had a Yukawa shape with a range of 1.0 fm^{-1} while the tensor force had the OPEP form with a range of 0.7 fm^{-1}. The solid curves in Fig. 3 are DWBA predictions using the parameters discussed above along with the OM potentials of Table I in both the entrance and exit channels. The DWBA normalization to experiment gave $V_{\sigma\tau}$(central strength) = V_{ten}(tensor strength) = 4.4 MeV, which is similar to the strengths found for the ^{54}Fe(^{3}He, t) reaction.[9]

The sensitivity of these various assumptions was tested in detail for the ^{6}Li(t, ^{3}He)^{6}He angular distribution. The ^{6}Li ground state was assumed to have the $[(1p_{1/2})_\pi(1p_{3/2})_\nu]_{1^+}$ configuration, and this change resulted in a 30% increase of σ_{DW} although the shape remained identical. The bound state parameter set of $r = 1.25$ fm, $a = 0.65$ fm, and a bound state spin orbit strength of 25 times the Thomas term was also investigated. The results showed no change in σ_{DW} for $\theta_{\text{c.m.}} < 50°$, and only small changes in σ_{DW} for $\theta_{\text{c.m.}} > 50°$. The

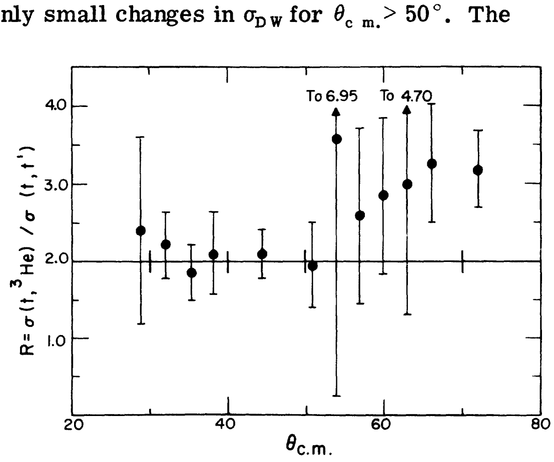

FIG. 4. The ratio of charge exchange to inelastic scattering cross sections as a function of angle for the transitions to the ^{6}He ground state and ^{6}Li 3.56 MeV state.

ratios of the central and tensor strengths of the effective interaction were also varied. The strong tensor force mentioned above gave the shape most similar to the data as shown in Fig. 3. Setting $V_{\text{ten}} = 0.0$ destroyed any resemblance of the calculation to the data, as previously noted in analysis of (^{3}He, t) reactions for $\Delta S = \Delta T = 1$ transitions.[9,14] On the other hand, setting $V_{\text{cen}} = 0.0$ did little to change the results of the calculation.

The effects of varying the central and tensor ranges were also investigated. Increasing the central range from 1.0 fm^{-1} to 1.8 fm^{-1} did not significantly change the DWBA predictions, although decreasing the range to 0.6 fm^{-1} caused the forward angle cross section to rise sharply and simultaneously moved the minimum from 54° to 56° (cf. Fig. 3). The DWBA cross section was found to be quite sensitive to small changes in the tensor force range. Changes of the order of 10% in this range parameter caused 200% or larger changes in the predicted cross section, although the shape remained in reasonable agreement with experiment. Larger changes in r_{ten} destroyed the agreement of predicted shape with experiment.

The sensitivity of the OM wave function description was also tested. Changes of ±10% in the triton real well depth (cf. Table I) resulted in significantly poorer fits to the shape of the ^{6}Li(t, ^{3}He) angular distribution data. Finally, nonlocal corrections using β(triton = β(^{3}He) = 0.25 and β(bound state) = 0.85 were found to cause very minor changes in the DWBA cross sections which were calculated with these parameters set equal to 0.0. The parameters we have chosen thus provide the best description of the ^{6}Li(t, ^{3}He) angular distribution.

Using the parameters of Table I and the interaction described above of equal central and tensor strengths of 4.4 MeV and a central force range of 1.0 fm^{-1} and tensor force range of 0.7 fm^{-1}, the DWBA correction contained in Eq. (1) was evaluated. The ratio $\sigma_{\text{DW}}(t, {}^3\text{He})/\sigma_{\text{DW}}(t, t')$ was calculated first on the assumption that the tritons inelastically scattered from a proton. In each case the experimental binding energy was used to calculate the separation energy. The results produce a DWBA correction of 1.0 and 0.98 for the scattering from a proton and neutron, respectively. This is to be compared with a value of about 1.14 that is necessary to provide agreement between the simple isospin rule and experiment.

Using the same method and the parameters derived from the present ^{6}Li + t reactions, further calculations were performed to analyze previous results on the ^{6}Li + ^{3}He reactions with ^{3}He energies of 24.6 and 27.0 MeV.[2] The experimental value for the ^{6}Li(^{3}He, t)^{6}Be(0.0)/^{6}Li(^{3}He, ^{3}He')-^{6}Li(3.56) ratio had been determined to be 1.59 ±0.08. Our procedure gives a DWBA correction of 0.94 or a corrected R of 1.88 for these two reactions. Isospin coupling would require a ratio of 2.0 between the ^{3}He induced charge exchange and inelastic scattering cross sections, as in the ^{6}Li + t system. Thus both tests of the simple isospin coupling rule have now been performed utilizing ^{3}He and t projectiles on a ^{6}Li target by comparing charge exchange with inelastic scattering. In each case the experimental value of R differs significantly from the predicted value of 2, and simple one-step DWBA calculations cannot account for the difference.

IV CONCLUSIONS

The ^{6}Li(t, ^{3}He) and ^{6}Li(t, t') reactions leading to isobaric analog states have been studied with good resolution. The angular distributions are very similar, but the ratios of cross sections derived from the data deviate from the straightforward predictions of isospin coupling. These deviations in both the present ^{6}Li(t, ^{3}He)/^{6}Li(t, t') and previous ^{6}Li(^{3}He, t)/^{6}Li(^{3}He, ^{3}He') experiments cannot be described by a consistent application of the microscopic single-step DWBA theory. A more detailed study of the mechanisms involved in these processes is thus required.

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*Present address: Carnegie Mellon University Users Group, LAMPF, Los Alamos, New Mexico 87545.

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