ondly, if the source of the discrepancies is the deuteron optical potential, changes may affect the spectroscopic results of deuteron-induced reactions, many of which have been done in the same energy range as the present experiment.

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Supermultiplet Symmetry in the Reaction $^3H + ^9Be \rightarrow ^6Li + ^6He$, $^6Li^* + ^6He$

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The reactions ^{9}Be(t, ^{6}Li)^{6}He and ^{9}Be(t, ^{6}Li*)^{6}He have been measured at a bombarding energy of 23.5 MeV. The reaction products ^{6}He(ground state), ^{6}Li(ground state), and ^{6}Li(3.56 MeV) are members of a spin-isospin supermultiplet, and the observed differential cross sections are dominated by a symmetry expected from such considerations. Significant deviations from symmetry are, however, seen, especially in the isospin-multiplet channel.

In light nuclei the nucleons are coupled in the L-S coupling scheme—the result of a weak spin-orbit interaction. If it is then assumed that the nucleon forces in these cases are independent of both spin and isospin (charge independence), supermultiplets of the type proposed by Wigner[1] should be observed. The lightest bound nuclear system which should be described by such assumptions is the mass-six system: ^{6}He, ^{6}Li, and ^{6}Be. The nuclei ^{6}He, ^{6}Li* ($T=1$), and ^{6}Be form the spin singlet, isospin triplet, with $T=1$ and $S=0$, whereas the ^{6}Li ($T=0$) ground state is the degenerate isospin-singlet, spin-triplet multiplet member. Together these states form the supermultiplet, and they would be degenerate in energy if the nuclear forces were completely spin and isospin independent. Actually the masses (energies) of the three states of the isospin triplet differ by ~2.0 MeV, which is ~0.05% of the total mass, and the isospin triplet and spin triplet differ by 3.56 MeV, the observed energy of the excited state of ^{6}Li ($T=1$, $S=0$).

This Letter reports an experiment in which different combinations of two members of the mass-six supermultiplet are produced in the final channel of the reaction induced by tritons incident on a ^{9}Be target. The reactions observed were

$$^9\mathrm{Be}(t,\,^6\mathrm{Li})^6\mathrm{He}, \qquad (1)$$

$$^9\mathrm{Be}(t,\,^6\mathrm{He})^6\mathrm{Li}, \qquad (2)$$

$$^9\mathrm{Be}(t,\,^6\mathrm{Li}^*(3.56))^6\mathrm{He}, \qquad (3)$$

$$^9\mathrm{Be}(t,\,^6\mathrm{He})^6\mathrm{Li}^*(3.56). \qquad (4)$$

The c.m. scattering angles of the Reactions (1),(2) and (3),(4) are connected by $\theta(^6\mathrm{He}) = \pi - \theta(^6\mathrm{Li})$. Equality of the cross sections in a given transition for the yield of ^{6}He and ^{6}Li implies symmetry of the angular distribution about 90° for a given species (^{6}He or ^{6}Li). The supermultiplet picture relates the relative magnitude and the angle variation of the cross sections for the various exit channels involving two supermultiplet members. If the supermultiplet picture is strictly valid the yields in Reactions (1) and (2) or (3) and (4) should be the same, and the ratios between Reactions (1) [or (2)] and (3) [or (4)] should be given by simple phase-space factors. The present experiment shows deviations between the predicted and observed relative magnitudes in the various exit channels which vary from 40% to well over a factor of 2. Large asymmetries (with respect to 90° c.m.) are observed in the angular distribution for the Barshay-Temmer channel,[2-4] i.e., an exit channel containing members of an isospin multiplet [Reactions (3) and/or (4)]. The deviations from symmetry about 90° derived from the Barshay-Temmer relations are significantly larger than the near agreement observed for $T=\frac{1}{2}$ isospin analog product nuclei in studies of the reactions $d+\alpha \to t+{}^3\mathrm{He}$,[5] $^{10}\mathrm{B}+\alpha \to {}^7\mathrm{Li}+{}^7\mathrm{Be}$,[6] and $^{14}\mathrm{N}+{}^{12}\mathrm{C} \to {}^{13}\mathrm{N}$.[7] In contrast to the previous experimental tests of this relation, the present study involves members of a $T=1$ isospin multiplet in the final state and proceeds through a channel having nonzero (but definite) isospin. In addition, this Letter also reports (for the first time) an experimental study of symmetry relations for final states of two supermultiplet members which are not isobaric analogs.

The reactions were induced using a 23.5-MeV triton beam from the Los Alamos three-stage tandem Van de Graaff facility and a self-supporting ^{9}Be foil target of ~ 100-μg/cm^2 areal density. The reaction products were identified using a solid-state counter telescope consisting of a ΔE counter of 20-μm thickness and an E counter of 500-μm thickness.

The separation of the reaction products was achieved using an on-line computer program,[8] which gave projected energy spectra for the different particles analyzed. The ground-state transitions in the $^6\mathrm{Li}+{}^6\mathrm{He}$ channel were clearly separated. However, extraction of transitions to the $^6\mathrm{Li}^*+{}^6\mathrm{He}$ channel measuring either of the reaction products—^{6}Li* or ^{6}He—was complicated by a strong three-body final-channel continuum occurring at low energies as a result of the low particle-emission thresholds of ^{6}He and ^{6}Li. The 3.56-MeV state in ^{6}Li is particle stable and decays by γ emission. The recoil of the γ rays of the emitted particle leads to a broadening of the line in the ^{6}Li spectrum (not in the ^{6}He spectrum).

Angular distributions for the transitions to the ground states and to the first excited states are shown in Fig. 1. The error bars given in the figure are purely statistical for the transition to $^6\mathrm{He}+{}^6\mathrm{Li}$. For the transitions to $^6\mathrm{He}+{}^6\mathrm{Li}^*(3.56)$

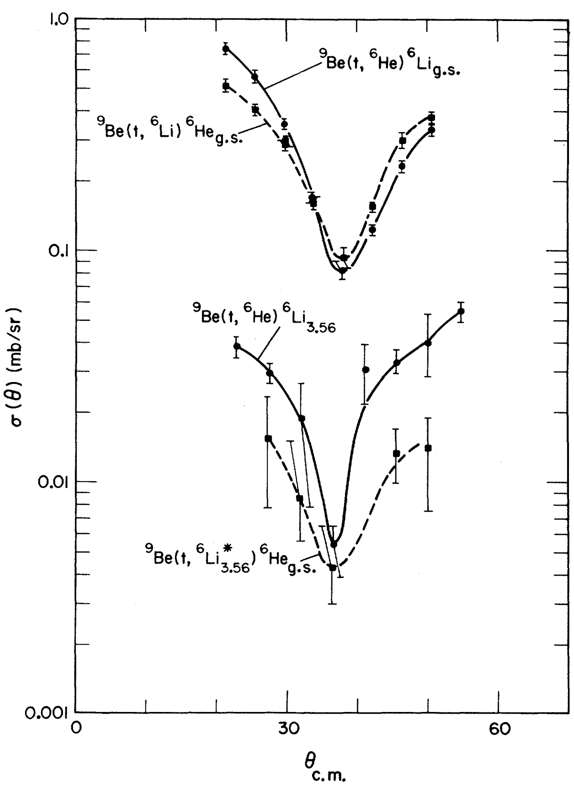

FIG. 1. The observed $^9\mathrm{Be}+t \to {}^6\mathrm{Li}+{}^6\mathrm{He}$ differential cross sections for the outgoing ^{6}Li and ^{6}He particles. The ^{6}Li and ^{6}He reaction products were measured simultaneously by the detector telescope.

these include uncertainties in the subtraction of the background and differences in width due to the γ recoil.

The reaction is suggested to proceed via a direct pickup of a triton or ^{3}He. Structure calculations[9] and related triton and ^{3}He transfer reactions[10-13] support this suggestion.

Figure 1 shows that all four angular distributions have the same general shape; however, there are deviations from simple relations between the yields for ^{6}Li and ^{6}He in the two final channels. In Reactions (3) and (4) the final state is composed of two members of an isospin triplet ($T=1$). The symmetry in this reaction can be derived using the Barshay-Temmer relation.[2-4] Assuming isospin invariance only, the total wave function in this final channel is even with respect to the interchange of mass-six nuclei (with spin $=0$). The isospin wave function is odd (because of the coupling of $t_1=1$, $t_2=1$ to $T=1$), and T, the total isospin, is unique because of the properties of the initial channel.[3,4] There, the spatial part of the total wave function $\psi(R, 1, 2)$ becomes odd, and the angular distribution is required to be symmetric with respect to 90°. The data show deviations from this prediction by ~200%.

The angular distributions of Reactions (1) and (2) leading to the ground states of ^{6}Li and ^{6}He are of the same general shape and are governed by the same spatial symmetry in the relative motion as for the channel previously discussed. (The two nuclei ^{6}Li and ^{6}He, however, now have different spin and isospin.) The symmetry in this case, however, is better fulfilled than in the isospin-multiplet channel (Fig. 1).

The intensities of Reactions (1) and (3) should be connected by simple relations: The spin multiplicity of the ^{6}Li ($S=1$) ground state makes Reaction (1) a factor of 3 more intense [all members of the degenerate spin triplet are formed with equal probabilities in Reaction (1)]; the total isospin $T=1$ gives a Clebsch-Gordan coefficient in reaction channel (3), $(1110|10)$, whose value is $\sqrt{\frac{1}{2}}$. Figure 2 shows the comparison of Reaction (1) with Reaction (3) multiplied by the total phase-space factor of 6. The deviation from the predicted equality is probably related to the difference in Q value of 3.56 MeV (compare also Ref. 10).

The symmetry demanded by the supermultiplet principle appears to dominate the shape of the observed angular distributions as is illustrated in Figs. 1 and 2. Angular distributions obtained for the reactions ^{9}Be(t, ^{6}He)^{6}Li$_{3+}$*(2.18 MeV) and

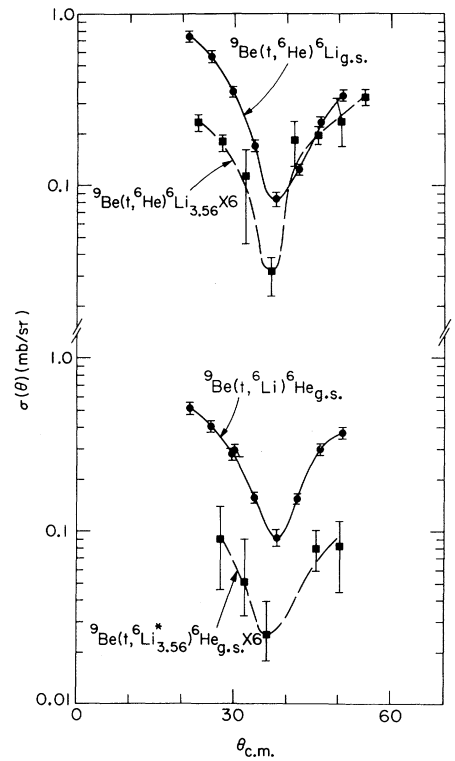

FIG. 2. Comparison of cross sections for various members of the supermultiplet. The factor of 6 is discussed in the text.

^{9}Be(t, ^{6}Li)^{6}He$_{2+}$*(1.8 MeV), which are not members of the supermultiplet, show totally different shapes with less pronounced structure.

Figure 1 indicates that differences from symmetry as great as 40% occur in the ground states at forward angles, whereas deviations greater than a factor of 2 occur at certain angles in the Barshay-Temmer channel. Such discrepancies can be attributed to violations in the isospins of the particles in the entrance channel, violations in the symmetries of the mass-six supermultiplet, or violations in the interaction Hamiltonian. The Barshay-Temmer channel tests for isospin violations, but the remaining channels compared are sensitive to both spin- and isospin-dependent interactions. (For a complete discussion of the possible source of violation see Ref. 4.) It is not surprising that deviations are observed. Spin- and isospin-dependent terms are required in the nuclear Hamiltonian to explain energy differences between supermultiplet members. Also, the Coulomb interaction is expected to have a sizable symmetry-breaking influence on the nuclei ^{6}Li and ^{6}He. However, it is surprising that the deviations are much more pronounced than those observed in previous studies[5-7] of the Barshay-Temmer relation, and that symmetry is better fulfilled in the supermultiplet channel leading to the ground states. Symmetry in the differential cross section is expected in Reactions (3) and (4) only if T is conserved in the reaction, but it is worth noting that $^6Li^*$ ($S=0, T=1$) and ^6He ($S=0, T=1$) can couple to $T=2$, unlike the ground-state channel, and this would add even partial waves in the relative motion. The requirement for symmetry in Reactions (1) and (2) implies invariance under simultaneous interchange of spin *and* isospin (leading to the same spatial symmetry). This requirement seems less severe in the present system and may explain the smaller asymmetry observed in the ground-state channels.

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