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[10] An improvement in χ^2 can be achieved for medium-weight elements if the nucleon-nucleon force parameters are allowed to depart from the "free" values in a manner which increases the surface isospin potential. This effect is most marked for ^{40}Ca where χ^2 is improved by a factor of 4 (V. Hnizdo, Ph.D. thesis, Birmingham University). This suggests a need for a surface-peaked real potential in these cases but it is not clear that such a peaking is in any way related to an isospin effect. It may, however, be a method of representing some of the effects neglected in the model.

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Measurement of Magnetic-Substate Populations Following the Reactions ^{16}O(^{7}Li, t)^{20}Ne and ^{16}O(^{6}Li, d)^{20}Ne†

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Particle-γ angular correlations using the reactions ^{16}O(^{7}Li,$t\gamma$)^{20}Ne and ^{16}O(^{6}Li,$d\gamma$)^{20}Ne have been measured. The populations of the various magnetic substates in the residual nucleus were extracted from the data. The results indicate the presence of other reaction mechanisms competing with direct transfer of an α particle.

I. INTRODUCTION

Attempts have been made to understand the structure of certain states in light nuclei by regarding them as made up of clusters of smaller composite groups for some time.[1,2] α particles form a natural unit for such a cluster; the tight binding of the α particle makes plausible the idea that α-like clusters can exist within a larger nucleus. It has also been pointed out that states with large α-cluster structure are often members of rotational bands.[3] Many resonant states have been observed with large α-particle widths, largely by measuring elastic scattering and reactions induced by α particles. Among the more interesting of these were the highly excited rotational states in ^{16}O, observed as resonances in the ^{12}C(α, α)^{12}C reaction by Carter, Mitchell, and Davis.[4]

More recently interest has centered on the study of α-particle structure in both bound and unbound states using nuclear reactions in which an α particle is transferred. There has been quite a bit of recent experimental work[5] involving the (^{7}Li, t) and (^{6}Li, d) reactions, among others. If such processes can be considered a direct reaction, i.e., one in which only a few nucleons participate, they can clearly be extremely useful in exploring the α-particle parentage of nuclear energy levels.

There are many problems involved in the analysis of the particle angular distributions using conventional distorted-wave theory. For example, in the ^{7}Li nucleus the α and triton clusters are in a relative p state, making the usual zero-range approximation impossible to apply. Nevertheless, in many cases the angular distributions do show the forward peaking expected qualitatively from a direct process[5]; furthermore, recent calculations using Coulomb-distorted plane-wave theory[6] have met with some success in predicting the observed behavior, especially the dependence of the cross section on excitation energy.

Because of the interest in this type of reaction it was considered desirable to investigate the reaction mechanism in more detail. The method of particle-γ angular correlations was chosen. In the present work the aim of the correlation measurements was not to elicit spectroscopic information, but rather to shed light on the mechanism of the reaction.

Specifically, angular distributions of γ rays have been measured in coincidence with outgoing charged particles in the reactions $^{16}O(^7Li, t\gamma)^{20}Ne$ and $^{16}O(^6Li, d\gamma)^{20}Ne$. The charged particles were detected at 0° with respect to the beam; this type of experiment is usually referred to as method II of Litherland and Ferguson.[7] The geometry of the system implies that the maximum magnetic substate which can be populated in the reaction is given by the sum of the spins of the target, projectile, and outgoing particle. Thus, for a spin-0 target magnetic substates with $M = 0, \pm1, \pm2$ can be populated by both the $(^7Li, t)$ and $(^6Li, d)$ reactions. For states of definite parity the positive and negative substates will be equally populated; this implies that two unknown parameters completely describe the alignment of the state in the residual nucleus, for example the ratios $P(1)/P(0)$ and $P(2)/P(0)$. The purpose of the present work is to determine these quantities by measuring the particle-γ angular correlation and to use the results to study the mechanism of the $(^6Li, d)$ and $(^7Li, t)$ reactions.

In the simplest approximation, if the $(^7Li, t)$ and/or $(^6Li, d)$ stripping reactions proceed by direct transfer of a real α particle with $(J, T) = (0, 0)$, then for spinless targets only magnetic substates with $M = 0$ can be populated in the residual nucleus. This result is obtained by neglecting spin-orbit coupling; however, it has been pointed out[8] that the influence of spin-orbit coupling is expected to be much less on the polarization of the residual nucleus in a direct reaction than on the polarization of the light outgoing particle. The restriction to $M = 0$ substates makes a definite prediction for the angular correlation; comparison of this prediction with the experimental correlations should then serve as some indication as to the validity of the picture of the reaction as a simple α transfer. It is interesting to note in this connection that a recent study[9] of the relative population of $M = 0$, ±1 magnetic substates in the $^{40}Ca(^3He, p\gamma)^{42}Sc$ reaction was in very good agreement with the predictions of a simple direct-reaction model in which either a deuteron or quasideuteron was transferred to ^{40}Ca.

II. EXPERIMENTAL PROCEDURE AND DATA REDUCTION

The experimental apparatus used in the present work has been described[10] at length elsewhere, and need only be briefly discussed here. Targets of WO_3 of thickness ~400 $\mu g/cm^2$ evaporated on carbon backings were bombarded with beams of $^6Li^{+++}$ and $^7Li^{+++}$ ions from the University of Pennsylvania tandem accelerator. Outgoing deuterons or tritons were detected at 0° with respect to the incident beam by a position-sensitive surface-barrier detector located in the focal plane of a magnetic spectrometer. Coincident γ rays were detected using four 3-in. × 4-in. NaI(Tl) crystals. The data were accumulated using an online computer-analyzer system. For each event four digital words were generated, corresponding to particle energy (position), γ energy, time difference between particle and γ pulses, and a word containing routing information, i.e., which of the four crystals received the event. The data were stored in a buffer memory and periodically written on magnetic tape. The buffer tapes were subsequently reduced using the same PDP-9 computer. Angular correlations corresponding to true-plus-chance and chance-only coincidences were extracted from the raw data and combined to give the angular correlations in true coincidence with a given state. The experiments were performed at beam energies of 13 and 14 MeV for the $(^7Li, t)$ reaction and 15 MeV for the $(^6Li, d)$ reaction. In the $(^7Li, t)$ work the requirement that the emergent tritons be bent through 90° by the magnetic spectrometer sets an upper limit to the beam energy; this limit is somewhat higher in the $(^6Li, d)$ case and it might be interesting to extend the measurements to higher energy in the future.

III. EXTRACTION OF POPULATION PARAMETERS

The theoretical form for the angular correlation applicable to the present work is[11]

$$W(\theta_\gamma) = \sum_K \sum_{M_B} P(M_B)\rho_{KM_B}(J_B) \times F_K(LL'J_BJ_A)\, Q_K P_K(\cos\theta_\gamma). \qquad (1)$$

Here $P(M_B)$ is the population of the M_Bth magnetic substate in the residual nucleus; it is a diagonal element of the density matrix describing the final state. The $\rho_{KM_B}(J_B)$ and $F_K(LL'J_BJ_A)$ depend only on the spins, tabulated coupling coefficients, and multipolarities of the decay γ rays. In the case where the decay γ ray is of pure multipolarity, the expression for the correlation is an extremely simple linear function of the population parameters $P(M_B)$ and known coefficients. Since in both the $(^6Li, d)$ and $(^7Li, t)$ reactions the sum of the spins of the projectile and outgoing particles is 2, magnetic substates with $M_B = 0, \pm1, \pm2$ can be populated by these reactions (on a spinless target, observing the outgoing deuterons or tritons at 0°). The equality of the populations of positive and negative substates and the normalization of the population parameters leaves two unknown numbers to be extracted from the data. Since the overall normalization must also be fitted from the data, there are three numbers to be obtained from the experimental angular correlations, which consist of four measured points. One degree of freedom thus remains in the fits. In practice the experimental angular correlations were fitted to even-order Legendre polynomials. These fits yielded coefficients a_0, a_2, a_4, where $W(\theta) = a_0[1 + a_2P_2(\cos\theta) + a_4P_4(\cos\theta)]$. It can be seen from Eq. (1) that the coefficients a_K are linear functions of the population parameters $P(M_B)$; i.e.,

$$a_K = \sum_{M_B} P(M_B) B_{KM_B} \ , \qquad (2)$$

where the B_{KM_B} are known coefficients. Solution of these linear equations provided the best-fit values of the population parameters. The population parameters were always required to be positive. In all cases but one investigated in the present work, the solution to the linear Eq. (2) corresponded to a physically possible set of population parameters. In the one case where the solution to the linear equations gave a negative value for one of the $P(M)$, the best-fit values were obtained by a grid search of the physically allowed region of the parameter space.

The errors for the population parameters were computed using the errors in the Legendre-polynomial coefficients obtained from the fitting procedure; correlations between the coefficients were taken into account in obtaining the errors in the reduced Legendre-polynomial coefficients $a_k = A_k/A_0$, but were neglected in obtaining the error in the population parameters as linear functions of the errors in the reduced coefficients. In the one case where the best fit was for an unphysical value of the population parameters no error is quoted; the correlation in this case is in fact not very sensitive to these parameters.

IV. RESULTS AND DISCUSSION

A. 1.63-MeV 2^+ State

The angular correlation for the $^{16}O(^7Li, t\gamma)^{20}Ne$ reaction leading to the first excited state in ^{20}Ne is shown in Fig. 1. This measurement was made at a beam energy of 14 MeV. The solid curve represents the best fit obtained by varying the population parameters; the dashed curve represents the theoretical correlation expected if only the $M_B = 0$ magnetic substate is populated in the residual nucleus, as would be expected from a simple picture of the reaction mechanism in which a spinless α particle is transferred to the target in its ground state. The population parameters giving the best fit are $P(0) = 0.567 \pm 0.025$, $P(1) = 0.346 \pm 0.015$, $P(2) = 0.087 \pm 0.036$, where $P(1)$ is the sum of the populations of the $M_B = \pm 1$ substates, and $P(2)$ is the sum of the $M_B = \pm 2$ substates.

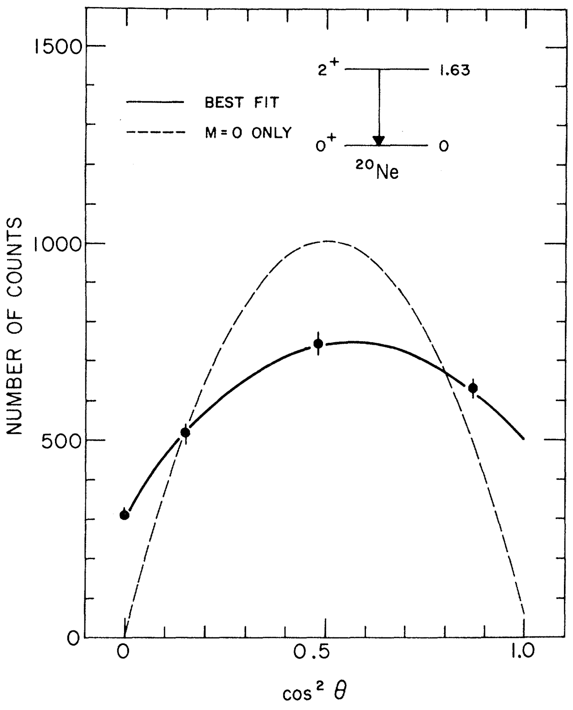

FIG. 1. Angular correlation for the $^{16}O(^7Li, t\gamma)^{20}Ne$ reaction measured at $E_{^7Li} = 14$ MeV leading to the 1.63-MeV state in ^{20}Ne.

The angular correlation for the same reaction leading to the same state measured at $E_{^7Li} = 13$ MeV is shown in Fig. 2. The angular correlation is qualitatively similar to that measured at $E_{^7Li} = 14$ MeV, although the fit to Legendre polynomials is somewhat worse. Again the full curve represents the best fit, while the dashed curve is that predicted by $M_B = 0$ only. The population parameters giving the best fit in this case are $P(0) = 0.643 \pm 0.033$, $P(1) = 0.331 \pm 0.020$, $P(2) = 0.026 \pm 0.036$. The results are quite similar to those obtained at $E_{^7Li} = 14$ MeV. The fact that the angular correlations do not change much as a function of bombarding energy, at least in this specific case, is interesting, and is perhaps suggestive of a direct-reaction mechanism.

Since, in a simple picture, the $(^7Li, t)$ and $(^6Li, d)$ reactions should both proceed by simple α transfer, the angular correlations should be the same for both reactions. The angular correlation for the $^{16}O(^6Li, d\gamma)^{20}Ne$ reaction leading to the 1.63-MeV 2^+ state is shown in Fig. 3. The beam energy in this case was 15 MeV. Also shown are theoretical curves calculated by (a) varying the popu-

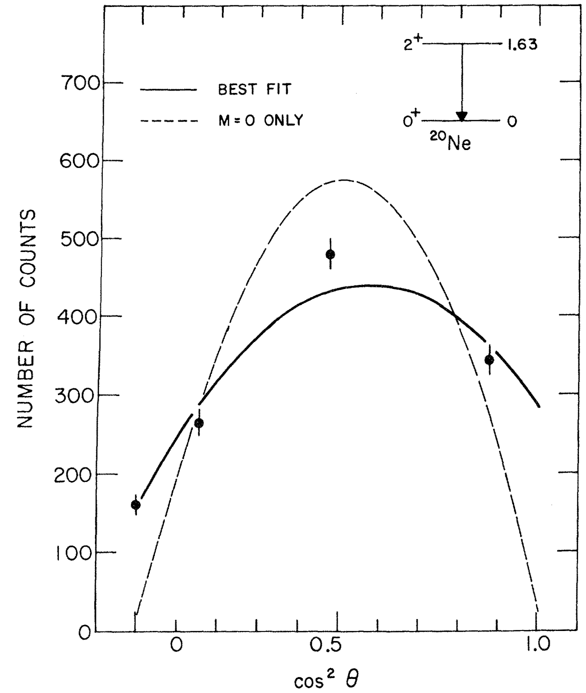

FIG. 2. Angular correlation for the ^{16}O(^{7}Li,$t\gamma$)^{20}Ne reaction measured at $E_{^7\mathrm{Li}}=13$ MeV leading to the 1.63-MeV state in ^{20}Ne.

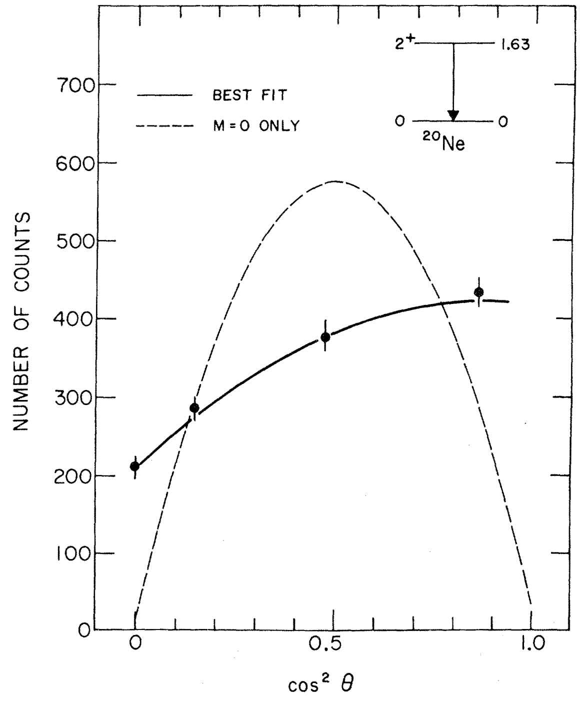

FIG. 3. Angular correlation for the ^{16}O(^{6}Li,$d\gamma$)^{20}Ne reaction measured at $E_{^6\mathrm{Li}}=15$ MeV leading to the 1.63-MeV state in ^{20}Ne.

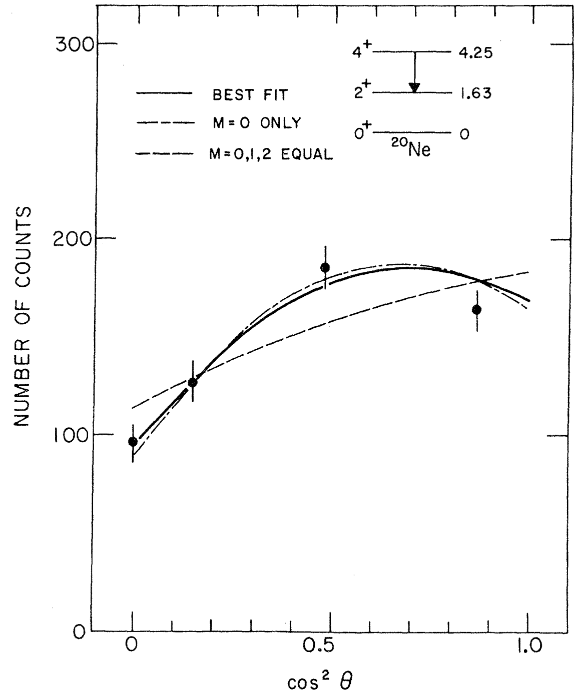

FIG. 4. Angular correlation for the ^{16}O(^{7}Li,$t\gamma$)^{20}Ne reaction measured at $E_{^7\mathrm{Li}}=14$ MeV leading to the 4.25-MeV state in ^{20}Ne.

lation parameters (full curve) and (b) using $M_B = 0$ only. The population parameters yielding the best fit in this case are $P(0) = 0.460 \pm 0.036$, $P(1) = 0.540 \pm 0.020$, and $P(2) = 0.000 \pm 0.051$. In this case the departure from the simple prediction is somewhat greater; the population of the $M_B = \pm 1$ substates is actually greater than the $M_B = 0$ substate population. It can be seen from the figure that the departure from the $M_B = 0$ prediction is somewhat greater in this case.

B. 4.25-MeV State

The angular correlation of the ^{16}O(^{7}Li, $t\gamma$) reaction leading to the second excited state of ^{20}Ne is shown in Fig. 4. This correlation was measured at a beam energy of 14 MeV. The best fit for physically allowed values of the $P(M)$ was obtained for $P(0) = 0.75$, $P(1) = 0.25$. This is the solid curve in the figure. This is quite close to the angular correlation which would result from populating only the $M = 0$ substate, which is also shown. Since the solution to the linear equations describing this state yielded a negative value for one of the population parameters, no errors were calculated. However, for a 4^+ state the angular correlation is much less sensitive to the populations of the $M = 0$, 1, 2 substates than in the case of a 2^+ state. To show this the correlation resulting from equal population of the $M = 0$, ±1, ±2 magnetic substates is also shown in Fig. 4. While it clearly does not fit the data, it is much closer than the corresponding curve for a 2^+ state, which would, of course, be isotropic.

V. CONCLUSIONS

While it would be premature to draw any general conclusions from the limited data presented here, the (^{7}Li, t) reaction leading to the 1.63-MeV state in ^{20}Ne does populate the $M = 0$ magnetic substate about 60% of the time; most of the remainder of the strength goes to the $M = \pm 1$ substates, with a small contribution from the $M = \pm 2$ substates. This behavior was observed at bombarding energies of 13 and 14 MeV. These results would seem to be consistent with competition between an α-particle transfer mechanism and some other processes, either multistep or compound nuclear in nature. Presumably, spin-orbit distortions in either the entrance or exit channels could also produce such an effect. Hopefully, accurate finite-range distorted-wave Born-approximation calculations will be able to indicate whether a reasonable amount of spin-orbit distortion can produce the observed departures from the simple predictions. More experimental data, covering a range of nuclei and excitation energies, would also clearly be useful.

In the case of the (^{6}Li, d) reaction leading to the same final state the $M = 0$ substate, received only 46% of the strength, the remainder going to the $M = \pm 1$ substates. This could perhaps suggest that the direct mechanism is competing somewhat less favorably with other processes in this case, although a general conclusion on this point would certainly require a systematic examination of many final states in different nuclei.

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