J-Dependent Effects in Tensor Analyzing Powers for the (d, α) Reaction

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Angular distributions of the cross section, vector analyzing power, iT_{11}, and the tensor analyzing powers, T_{20} and T_{22}, have been obtained for the (d,α) reaction on targets of ^{32}S, ^{36}Ar, and ^{38}Ar at 16 MeV. The present results show that the angular distribution patterns for T_{22} provide unique information for distinguishing among possible angular momentum transfers.

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The (d,α) reaction has been useful for providing spectroscopic information on states populated in the residual nuclei, as well as for providing sensitivity to neutron-proton correlations in the ground states of the target nuclei.[1] Experimental knowledge of the transferred orbital angular momentum L and total angular momentum J can lead to spin and parity assignments for states populated in the residual nuclei. Here we present a new experimental technique which removes the ambiguity in such assignments.

Previous work at our laboratory demonstrated that vector-polarized deuteron beams could be used to determine angular momentum transfers on s-d-shell nuclei.[2] As a logical extension of this work, and following the predictions[3] without spin-dependent distortion (SDD) terms in the optical-model potentials, additional information on angular momentum transfers is expected from the T_{2q}, the tensor analyzing powers.[4] These measurements are, however, technically difficult and hence there have been relatively few angular distributions of tensor moments obtained, and none for transfer reactions involving more than one transferred nucleon. In this work we report measurements of the tensor analyzing powers T_{20} and T_{22} for (d,α) reactions. We measured cross sections and analyzing powers at 16 MeV for $^{32}S(d,\alpha)^{30}P$, $^{36}Ar(d,\alpha)^{34}Cl$, and $^{38}Ar(d,\alpha)^{36}Cl$. We find that T_{22} angular distributions for simple direct pickup processes provide unique spectroscopic information, quite different from that provided by vector analyzing powers.

The neutron and proton transferred from the target nucleus in a (d,α) reaction carry away angular momentum $\vec{J}=\vec{L}+\vec{S}$ where S, the spin transfer, is equal to 1. When the target nucleus has spin and parity $J_i^{\pi}=0^+$, the spin of the final state $J_f=J$ and the parity of the final state is simply $(-1)^L$. For natural-parity states, only $J=L$ can satisfy the conservation relations. However, if $J=L\pm 1$, there are always two L values which can contribute.

Goldfarb and Johnson[3] give expressions for T_{kq} for transfer reactions with no SDD. For a unique J, L, and S transfer, distorted-wave Born-approximation (DWBA) calculations for (d,α) analyzing powers factor into two parts: (1) a Racah coefficient, describing the coupling of angular momentum to form the polarization tensors; and (2) a kinematical factor which depends on J only weakly through Q-value effects and through the radial wave function of the transferred particles. The L dependence of the analyzing powers from the first factor is, for the vector analyzing power,

$$iT_{11} \propto \begin{cases} -L, & J=L+1 \\ 1, & J=L \\ L+1, & J=L-1, \end{cases} \tag{1}$$

with large differences resulting for $J=L+1$ and $J=L-1$. For the tensor analyzing powers with $q=0$, 1, and 2,

$$T_{2q} \propto \begin{cases} L/(2L+3), & J=L+1 \\ -1, & J=L \\ (L+1)/(2L-1), & J=L-1, \end{cases} \tag{2}$$

with significant differences between $J=L\pm 1$ and $J=L$.

The distinction between different transfer possibilities is qualitatively indicated by the equations above, but is more accurately predicted by DWBA calculations,[5] which show large differences between the possible J transfers, both with and without SDD. In the calculations shown in Fig. 1 using the DWBA parameters of Ref. 2 and including SDD, the tensor analyzing power T_{22}, as compared to iT_{11} (Ref. 2) and T_{20}, has greater sensitivity to differences between $J=L$ and $J=L+1$. This is also true to a lesser extent for $J=L$ compared with $J=L-1$ transfers.

The fact that T_{22}, of all the analyzing powers, is calculated to be most sensitive to J effects can

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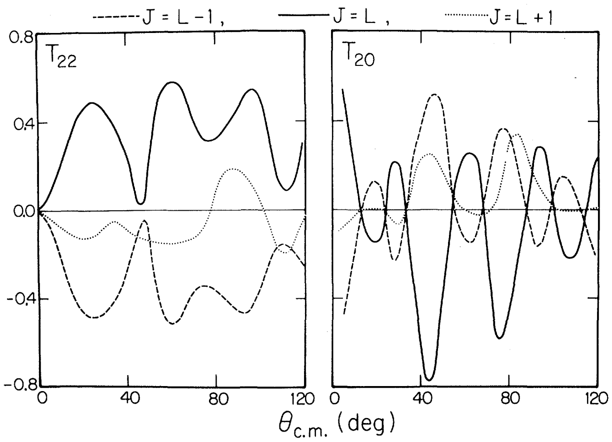

FIG. 1. The T_{20} and T_{22} angular distributions for the reaction $^{38}Ar(d,\alpha)^{36}Cl$ obtained from DWBA calculations for $L = 2$ and $J = 1$, 2, and 3.

be explained by using semiclassical arguments and the operational definition[6] of T_{22} in terms of an aligned deuteron beam (no $m=0$ deuterons) moving along the z axis. Here

$$T_{22} = (\sigma_x - \sigma_y)/(\sqrt{3}\,\sigma_0), \tag{3}$$

where σ_0 is the unpolarized cross section, σ_y is the cross section measured when $\vec{S}$ is along the y axis, taken as $\vec{k}_{in} \times \vec{k}_{out}$, and σ_x is the cross section measured with $\vec{S}$ along the x axis. The quantities $\vec{k}_{in}$ and $\vec{k}_{out}$ are the ingoing and outgoing wave vectors, respectively. From classical considerations, the L transfer will be predominantly along the y axis, perpendicular to the scattering plane. Since the outgoing α particle has zero spin, the spin transfer is antiparallel to the incoming-deuteron spin. When σ_y is measured, $\vec{S}$ is along the y axis, parallel or antiparallel to $\vec{L}$, and a $J=L+1$ or $J=L-1$ deuteron cluster tends to be transferred. A larger σ_y than σ_x implies a negative T_{22}. When σ_x is measured, $\vec{S}$ is along the x axis; $\vec{L}$ and $\vec{S}$ are perpendicular, and there will be a greater probability for transferring a $J=L$ deuteron cluster. A larger σ_x compared to σ_y implies a positive T_{22}. This simple vector-coupling argument correctly predicts the sign of T_{22} and also indicates why T_{22} is the most sensitive tensor moment, since similar coupling arguments do not hold for T_{20} and T_{21}.

For our experiments, gas targets of H_2S, ^{36}Ar, and ^{38}Ar were chosen so that well-separated states in the residual nuclei would be reached via the (d,α) reaction. The final states provide

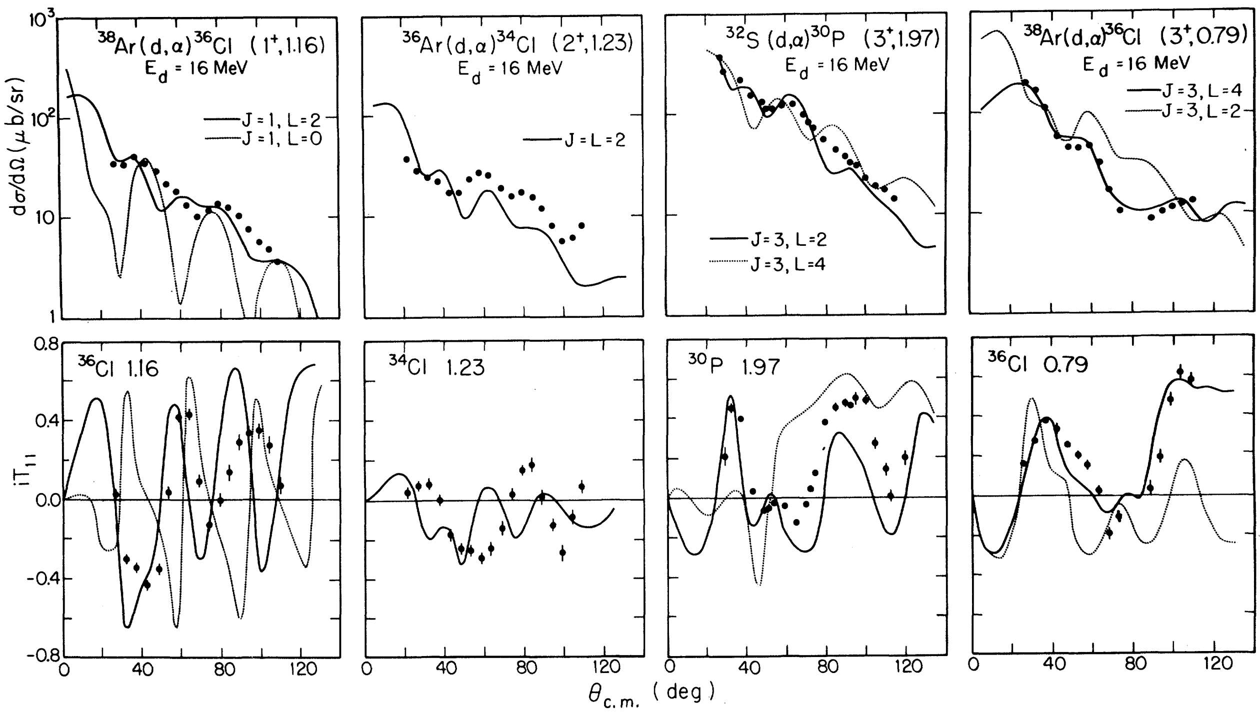

FIG. 2. Angular distributions of cross section and iT_{11} for examples of $L = 2$, $J = 1$, 2, and 3 and $L = 4$, $J = 3$ transfers in the (d,α) reaction for targets in the s-d shell. The solid line represents DWBA calculations for the predominant L transfer, while the dashed line is the prediction for the other possible L transfer.

examples of $J=L-1$, $J=L$, and $J=L+1$ transfers, although few of the latter cases were found in this mass region. The gases were contained in a cell at pressures of 1 atm or less. The reaction $^3\mathrm{He}(d,p)^4\mathrm{He}$ was used to monitor[5] the polarization of the 16-MeV tensor-polarized deuteron beam produced by the Triangle Universities Nuclear Laboratory Lamb-shift ion source. Our measurement scheme for T_{20} and T_{22} requires an eight-step sequence utilizing (1) left-right detector placement, (2) frequent reversals of the spin-quantization axis, (3) rotations of the chamber between horizontal and vertical orientations, and (4) an interchange between the $m=+1$ and $m=0$ deuteron magnetic substates for the beam from the polarized source. This sequence also provides σ and iT_{11}.

Representative angular distributions for σ and iT_{11} for different L- and J-transfer cases are shown in Fig. 2. The solid lines, corresponding to DWBA predictions for the dominant L transfers, follow the trends exhibited by the data. The optical-model parameters are from Ref. 5 for ^{32}S and from Ref. 2 for all other cases. The similarity between the data and predictions, and the close agreement between these experimental distributions and those taken for additional states in the same nuclei, lead us to conclude that one L value strongly predominates in these transfers. The dashed lines are calculations for the other possible L transfer for each state. The tensor analyzing powers T_{20} and T_{22} measured for the same states are shown in Fig. 3. It can be seen that for $J=L+1$ and $J=L-1$ the T_{22} angular distributions are predominantly negative in value, as predicted by the simple arguments presented above, while for $J=L$ transfers the T_{22} patterns are more oscillatory but predominantly positive. These patterns are typical of a large number of cases in these nuclei and illustrate that T_{22} angular distributions can be used to distinguish readily $J=L$ transitions from those corresponding to $J=L+1$ and $J=L-1$.

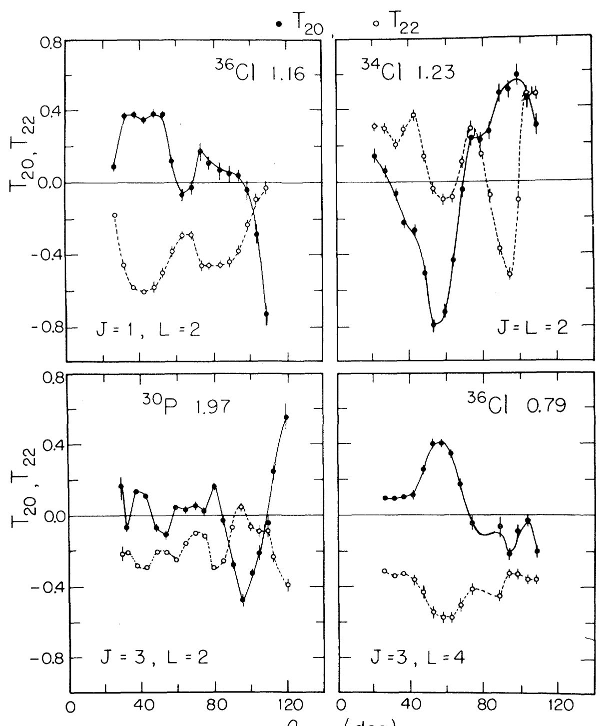

FIG. 3. Measured T_{20} and T_{22} values for the same examples of $L=2$, $J=1$, 2, and 3 and $L=4$, $J=3$ transitions as shown in Fig. 2. Curves are drawn to guide the eye.

A more surprising feature of the tensor analyzing powers, shown in Fig. 3, is that the T_{20} angular distributions measured for $J=L+1$ and $J=L-1$ transfers are out of phase with the T_{22} distributions. The corresponding patterns for $J=L$ transfers do not exhibit this relation, nor do the DWBA calculations for these tensor analyzing powers (Fig. 1). Quantities involving a sum or difference of T_{20} and T_{22} can be constructed again to distinguish clearly between the $J=L$ and $J=L\pm1$ transfers. Combinations found that are particularly sensitive are σ_x/σ_0 and σ_y/σ_0, where

$$\sigma_x/\sigma_0 = 1 + \sqrt{3}T_{22}/2 - \sqrt{2}T_{20}/4, \tag{4}$$

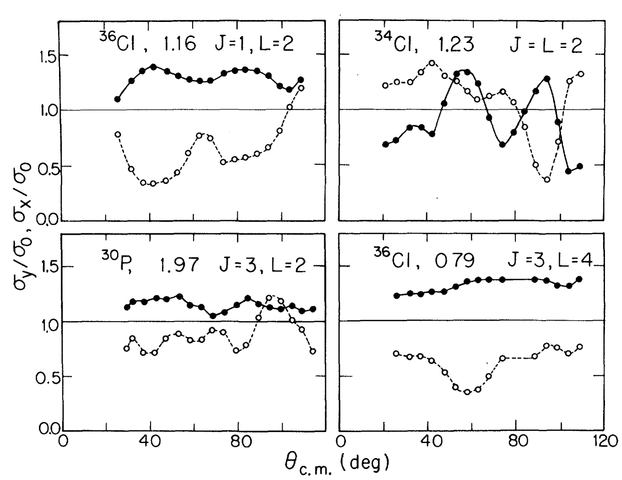

FIG. 4. The ratios of the cross sections with aligned beams, σ_x and σ_y, with those for unpolarized beams, for the transitions shown in Figs. 2 and 3. The solid (open) points are for σ_y/σ_0 (σ_x/σ_0). Curves are drawn to guide the eye.

and

$$\sigma_y/\sigma_0 = 1 - \sqrt{3}T_{22}/2 - \sqrt{2}T_{20}/4. \quad (5)$$

Examples of these quantities are shown in Fig. 4. It can be seen that $\sigma_y/\sigma_0 > 1$ and relatively flat, while $\sigma_x/\sigma_0 < 1$ for $J = L+1$ and $J = L-1$ transfers. Oscillatory patterns of predominantly reversed signs are found for $J = L$ transfers. These patterns persisted for all final states studied in these nuclei, which again illustrates the utility of tensor analyzing powers for distinguishing the J transfer.

Thus, we have shown that the angular distribution patterns of T_{22} in (d,α) reactions clearly distinguish between $J = L$ and $J = L \pm 1$ transfers. The information provided by tensor–analyzing-power distributions complements that from vector analyzing powers, which readily distinguish between $J = L+1$ and $J = L-1$ transfers. In the cases studied, the patterns for T_{20} are out of phase with those for T_{22}, although this effect is not predicted by DWBA calculations performed so far. Tensor potentials and effects of the α-particle D state may be necessary to describe the angular distributions in detail.

Since the simple predictions for T_{22} are independent of factors such as the two-particle configurations involved, it is expected that the effects observed will persist for other mass regions and bombarding-energy ranges. Thus, angular distributions of vector and tensor analyzing powers can distinguish all possible angular momentum transfers for the (d,α) reactions and thereby provide a test for nuclear-structure calculations.

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