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Determination of two-nucleon spectroscopic amplitudes from (d,α) analyzing powers

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Tensor and vector analyzing powers and cross sections have been measured for low-lying levels populated by the ^{89}Y(d,α)^{87}Sr reaction at 9.0, 12.0, and 16.0 MeV. Angular distributions of $d\sigma/d\Omega$, A_y, A_{yy}, A_{xx}, and A_{xz} have been analyzed using full finite-range distorted-wave Born approximation calculations including α-particle D-state effects. It is shown that the sign and amplitude of two-nucleon spectroscopic amplitudes corresponding to different L and J transfers can be determined from the angular distributions of the tensor analyzing powers.

The (d,α) reaction has long been recognized as a valuable spectroscopic tool for the study of two-hole states in nuclei.[1] Most nuclear structure studies have been performed using differential cross section data to identify the orbital angular momentum L of the transferred n-p cluster. The vector analyzing power iT_{11} has been shown[2] to also be sensitive to the total angular momentum transfer J. In the present paper we show that the tensor analyzing powers (TAP) of (d,α) reactions have a distinct and strong dependence on the coherence properties of the two-nucleon wave functions. Previously the usefulness of the TAP for spectroscopic applications has been limited by the problem of evaluating the effects of the α particle D state.[3-5] At low energies these effects are determined by the value of D_2, which is approximately proportional to the asymptotic D to S state ratio for d-d relative motion in the α particle.[3] Independent determinations of D_2 using different ($\vec{d}$,α) reactions[6,7] and also the ^{2}H(d,γ)^{4}He reaction[8] indicate a value close to $D_2 = -0.3$ fm^2.

The strong dependence of the TAP on L and J is essentially a consequence of the spin $S=1$ of the transferred n-p cluster. To clarify this dependence we consider the analyzing power A_{yy} which, by time reversal invariance, is identical to $P_{yy} = \langle 3S_y^2 - 2\rangle$, where S_y is the y component of the deuteron spin vector in the inverse (α,$\vec{d}$) reaction. Since the spin of the transferred n-p cluster is necessarily antiparallel to the outgoing deuteron spin as a result of the coupling in the spinless α particle (neglecting α-particle D-state effects), we can write $A_{yy} = \langle 3S_y^2 - 2\rangle$ where now S_y is the y component of the n-p cluster spin in the composite nucleus. Because of strong absorption, the reaction is peripheral and therefore **L** tends to be perpendicular to the reaction plane. Thus **L** is perpendicular to the Z axis and, using the Madison coordinate system,[9] this means that only $|LM\rangle$ states where $M=0$ contribute to the transfer. With this condition, and using standard angular momentum algebra,[10] we obtain

$$A_{yy} = \langle SJL0|3S_y^2 - 2|SJL0\rangle$$

$$= (-1)^2\sqrt{3/2}(L0L0|20)\,W(L1L1;J2)\ . \qquad (1)$$

For $J=L$, $L\pm 1$ Eq. (1) gives for $(A_{yy})_{L,J}$

$$(A_{yy})_{L,L} = -\tfrac{1}{2}\ , \qquad (2a)$$

$$(A_{yy})_{L,L+1} = \frac{L}{2(2L+3)}\ , \qquad (2b)$$

$$(A_{yy})_{L,L-1} = \frac{L+1}{2(2L-1)}\ . \qquad (2c)$$

The A_{yy} predicted by Eqs. (2) are large and strongly L and J dependent.[11] The same model predicts a vanishing A_y because the expectation value of S_y between $M=0$ states is zero. Furthermore, the matrix element in Eq. (1) is nonvanishing only for spin ≥ 1. For instance in (d,p) reactions, where $S=\frac{1}{2}$, the TAP are essentially a manifestation of the deuteron D state.[12]

In unnatural parity transitions the orbital angular momentum of the transferred n-p cluster can be $L=J\pm 1$. The effect of this mixing of L values on the TAP can be studied using a peripheral plane wave model,[13] which predicts that

$$(A_{yy})_J = \frac{(J+2)x^2 - 6[J(J+1)]^{1/2}x + J - 1}{2(2J+1)(1+x^2)}\ , \qquad (3)$$

where x is proportional to the ratio $G_{J+1,J}/G_{J-1,J}$ of the cluster spectroscopic amplitudes G_{LJ}. It is the presence of the linear term in x, in the numerator of Eq. (3), that makes the TAP very sensitive to the relative sign of the G_{LJ}. Notice that for pure L transfers ($x=0$ and $x=\infty$) Eq. (3) reproduces the previous Eqs. (2b) and (2c). The effect of the α-particle D state is generally to increase A_{yy} relative to the value given by Eq. (3).[6]

Angular distributions for vector and tensor analyzing powers and cross sections have been measured for three well-separated low-lying levels in ^{87}Sr; the ground state with $J^\pi = \frac{9}{2}^+$, the 0.388 MeV $\frac{1}{2}^-$ state and the 0.873 MeV $\frac{3}{2}^-$ state. The data were taken at the Triangle Universities Nuclear Laboratory using a vector and tensor polarized deuteron beam from a Lamb-shift polarized source. The beam was incident on a 260-μg/cm^2-thick ^{89}Y target and viewed by four pairs of 300-μm-thick solid state detectors situated at 10° intervals to the right and left of the beam. A ^{3}He polarimeter was used to monitor the beam polarization during each eight-step measurement that determined $d\sigma/d\Omega$, A_y, A_{yy}, and A_{xx}. At 12 and 16 MeV, A_{xz} was also measured.

The $^{89}Y(d,\alpha)^{87}Sr$ reaction to the low-lying states of ^{87}Sr is particularly suitable to study L-mixing effects because the nuclear states involved are relatively well described by the single particle shell model.[14] In particular, the ^{89}Y ground state is found to be 88% a $\pi(2p_{1/2})$ proton coupled to a ^{88}Sr closed shell. The low-energy spectrum of ^{87}Sr has been successfully described[15,16] by coupling the single neutron hole motion in the $1g_{9/2}$, $2p_{1/2}$, $1f_{5/2}$, and $2p_{3/2}$ orbitals to collective vibrations of the even core. This suggests that the $^{89}Y(d,\alpha)^{87}Sr$ reaction to the lowest $\frac{9}{2}^+$, $\frac{1}{2}^-$, and $\frac{3}{2}^-$ states in ^{87}Sr is populated predominantly by pickup from the $1g_{9/2}$, $2p_{1/2}$, $1f_{5/2}$, and $2p_{3/2}$ neutron and proton shells. If it is assumed that the proton $(1f_{5/2})$ and $(2p_{3/2})$ shells in the ground state of ^{87}Sr are fully occupied, the $^{89}Y(d,\alpha)^{87}Sr$ reaction to the $\frac{9}{2}^+$ ground state can only involve the shell-model configuration $\pi(2p_{1/2})\nu(1g_{9/2})$ and this circumstance has been previously used[6] to estimate α-particle D-state effects. However, mixing of different shell-model configurations is likely to occur in the transitions to the 0.388 MeV $(\frac{1}{2}^-)$ and 0.873 MeV $(\frac{3}{2}^-)$ states.

The present (d,α) data were analyzed using the cluster model of two-nucleon transfer reactions[1,17] in which the spectroscopic amplitudes G_{LJ} for the allowed (L,J) transfers are given as a sum over shell-model configurations $\eta=(n_1l_1j_1,n_2l_2j_2)$

$$G_{LJ}=\sum_{\eta}\mathscr{S}(\eta)G_{LJ}(\eta) \quad . \tag{4}$$

Here $\mathscr{S}(\eta)$ is the spectroscopic amplitude for the configuration η and $G_{LJ}(\eta)$ is an amplitude equal to the product of a symmetrized $LS-jj$ recoupling coefficient by a Talmi-Moshinsky coefficient.[17] The $^{89}Y(d,\alpha)^{87}Sr$ reaction to the 0.388-MeV state can be populated by (L,J) transfers of (0,1) and (2.1), corresponding to the amplitudes G_{01} and G_{21}. The A_{yy} angular distribution data at $E_d=12.0$ MeV are positive and oscillate around an average value of $A_{yy}\cong 0.5$, as shown in Fig. 1. According to Eq. (2c), this indicates that the transition is predominantly $L=2$. The inclusion of the α-particle D state increases A_{yy} but this effect is compensated by a small admixture of the $L=0$ amplitude. DWBA calculations were performed with the code PTOLEMY[18] using measured optical model parameters, as in Ref. 6. Figure 1 shows the result of calculations with fixed $D_2=-0.30$ fm^2 and for different values of G_{01}/G_{21}. We find that the sensitivity to variations in G_{01}/G_{21} is considerably larger in the TAP than in the cross section or vector analyzing power. Furthermore, only the TAP depend strongly on the relative sign between G_{01} and G_{21}. The best fit to the angular distributions at the three energies is obtained for $-0.15\leq G_{01}/G_{21}\leq -0.05$. Assuming that the population of the 0.388-MeV state results primarily in the pickup from the two shell-model configurations $\eta_1=\pi(2p_{1/2})\nu(2p_{1/2})$ and $\eta_2=\pi(1f_{5/2})\nu(1f_{5/2})$ the solution of Eq. (4) gives for the corresponding spectroscopic amplitudes (normalized to unit probability) $\mathscr{S}(\eta_1)=0.69\pm 0.07$ and $\mathscr{S}(\eta_2)=-0.72\pm 0.07$.

For the $^{89}Y(d,\alpha)^{87}Sr$ reaction to the 0.873-MeV $(\frac{3}{2}^-)$ state the allowed (L,J) values are (0,1), (2,1), and (2,2) and correspond to the mixing of natural and unnatural parity transitions. This implies that the relative phase between G_{21} and G_{22} cannot be determined because the reaction observables are incoherent summations over J. The analysis of A_y data indicates that G_{01} is the dominant amplitude. On the other hand, the value of A_{yy} is close to 0.5 which shows that G_{21} is nonvanishing. By mixing the amplitudes G_{01}, G_{21}, and G_{22} it is possible to obtain agreement with TAP data both in phase and in magnitude. The best fit is obtained for $0.45\leq G_{21}/G_{01}\leq 0.60$ and $0.55\leq G_{22}/G_{01}\leq 0.70$, as shown in Fig. 2. The three highest-energy shell-model configurations that can contribute to the population of the 0.873-MeV $(\frac{3}{2}^-)$ state are

$$\eta_2=\pi(1f_{5/2})\nu(1f_{5/2}) \quad ,$$

$$\eta_3=\pi(2p_{1/2})\nu(2p_{3/2}) \quad ,$$

$$\eta_4=\pi(2p_{3/2})\nu(2p_{3/2})$$

and the corresponding spectroscopic amplitudes (normalized to unit probability) determined from Eq. (4) with $G_{22}/G_{01}>0$ are $\mathscr{S}(\eta_2)\cong\mathscr{S}(\eta_4)=-0.7\pm 0.17$ and $\mathscr{S}(\eta_3)=0.03\pm 0.004$. If G_{22}/G_{01} is taken to be negative, the amplitudes $\mathscr{S}(\eta_2)$ and $\mathscr{S}(\eta_4)$ are almost unchanged and $\mathscr{S}(\eta_3)$ becomes negative. In both cases we find that the configurations η_2 and η_4 share most of the pickup probability and the corresponding spectroscopic amplitudes have the same sign.

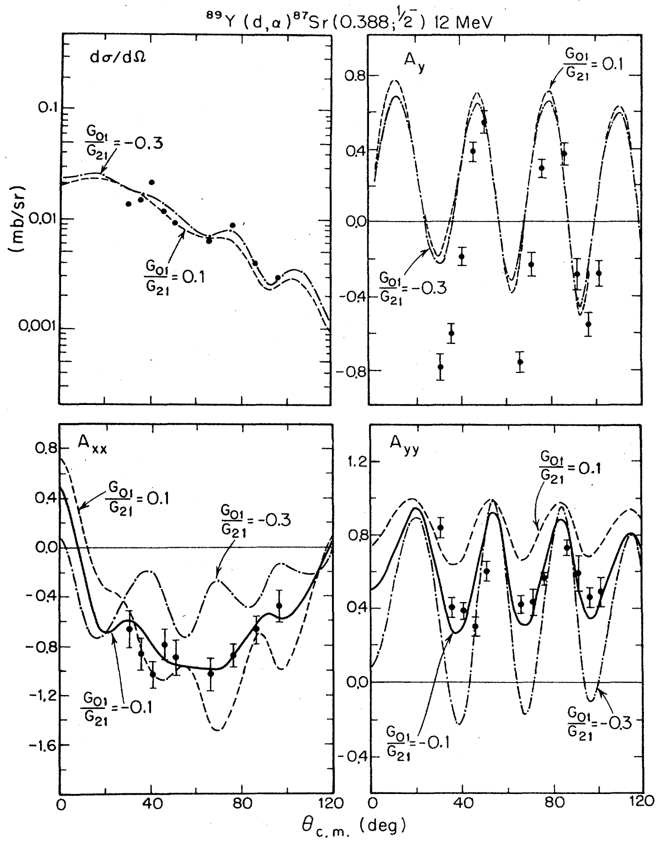

FIG. 1. The angular distributions of cross section, vector, and tensor analyzing power for the $^{89}Y(d,\alpha)^{87}Sr_{0.388\,MeV}$ reaction initiated by 12-MeV polarized deuterons. The curves correspond to $D_2=-0.30$ fm^2 and $G_{01}/G_{21}=0.1$ (dashed curve), $G_{01}/G_{21}=-0.1$ (solid curve), and $G_{01}/G_{21}=-0.3$ (dot-dashed curve). Here, and in Fig. 2, the calculated differential cross section is normalized to experiment.

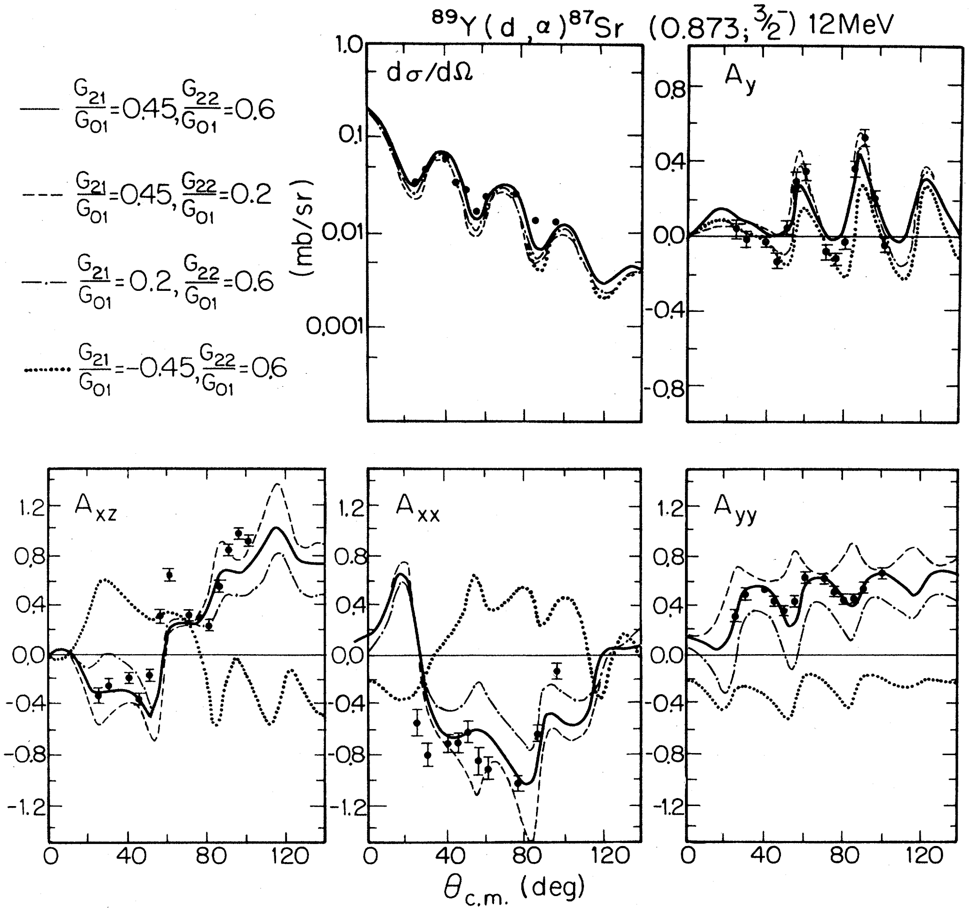

FIG. 2. The angular distributions of cross section, vector, and tensor analyzing powers for the $^{89}Y(d,\alpha)^{87}Sr_{0.873\ MeV}$ reaction initiated by 12-MeV polarized deuterons. The curves correspond to an S- and D- state admixture in the α particle having $D_2 = -0.3$ fm^2. The solid, dotted, dashed, and dot-dashed curves pertain to different values of G_{21}/G_{01} and G_{22}/G_{01}, as shown in the figure.

For both the 0.388- and 0.873-MeV states, the probability of pickup from the η_2 configuration is about half of the total. This probability, which is strongly enhanced by the large occupancy number of the η_2 orbitals in the target, indicates the presence of proton particle-hole excitations in the low-lying states of ^{87}Sr.

Our results show that the analysis of the angular distributions of the tensor analyzing powers in (d,α) reactions provides new information on the phase and amplitude of the two-nucleon cluster amplitudes that is not obtainable from the cross section and vector analyzing power. The sensitivity of the TAP to the coherence properties of nuclear states is found to be a unique feature of transfer reactions where the spin transferred is $S \geqslant 1$. The same type of phenomena is also expected to be present in other reactions transferring spin-one particles, such as (^{6}Li,α).

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