α-Particle D-State Components from (d, α) Analyzing Powers

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A D-state component in the α particle has been extracted from angular distributions of tensor analyzing powers for $^{89}Y(d, \alpha_0)^{87}Sr$ at 9, 12, and 16 MeV. Exact finite-range distorted-wave Born-appproximation analyses including the effects of L and J mixing have been performed. The D-state parameter D_2, closely related to the asymptotic D- to S-state ratio for d-d relative motion in the α particle, requires a value of $D_2 = -0.3 \pm 0.1$ fm^2 in order to fit the tensor analyzing power data.

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Nonspherical wave-function components of very light nuclei are sensitive to noncentral interactions in the nucleon-nucleon force. Such components of the α-particle ground state, breaking its high symmetry under spin and isospin exchange, are of great interest.[1-3] This Letter describes the first determination of the D-state admixture in the simplest configuration of the α particle that has a relative orbital angular momentum $L' > 0$, namely, a bound state of two deuteron clusters. Such a d-d configuration can form an α-particle ground state either in an S state with $L' = 0$ and the d spins antiparallel, or in a D state with $L' = 2$ and spins parallel to each other and antiparallel to L'. This D-state component can be revealed by a (d, α) reaction initiated by a tensor-polarized deuteron beam.

The diagonal elements of a tensor analyzing power (TAP) are defined by $A_{ii} = 2(\sigma_i - \sigma_0)/\sigma_0$, $i = x,y,z$, where σ_i is the cross section measured with the incident deuteron spin aligned in the i direction and σ_0 is the spin-averaged cross section. We now give an intuitive description of the d-pickup reaction that clarifies why it is sensitive to D-state effects. Consider the reaction as taking place peripherally so that the orbital angular momentum transfer $\vec{L} = \vec{r} \times \vec{q}$ is perpendicular to the reaction plane, as shown in Fig. 1. Classically, for a pure S state in the emerging α particle, a spin-up (spin along y axis) incident d will pick up a spin-down d from the target. For total angular momentum transfer between target and residual nuclei of $J = L - 1$, only region R_1 will contribute to σ_y, since $\vec{L}$ is up for that hemisphere, whereas only region R_2 will contribute for $J = L + 1$. The presence of a D-state component allows the alternate regions to contribute to σ_y, so that A_{yy} should generally increase as the D-state component increases. This intuitive description agrees with the full quantal calculations described below and shown in Figs. 2 and 3. These results are also sensitive to interference between S and D components, thus determining their relative sign.

The reaction studied was $^{89}Y(d, \alpha_0)^{87}Sr$ (spin and parity of $\frac{9}{2}^+$) at 9, 12, and 16 MeV. The data were taken at Triangle Universities Nuclear Laboratory with use of a deuteron beam from a Lamb-shift source that had both vector and tensor polarization components. The beam was incident upon a 260-μg/cm^2-thick ^{89}Y foil, and 300-μm-thick solid-state detectors detected the outgoing α particles.

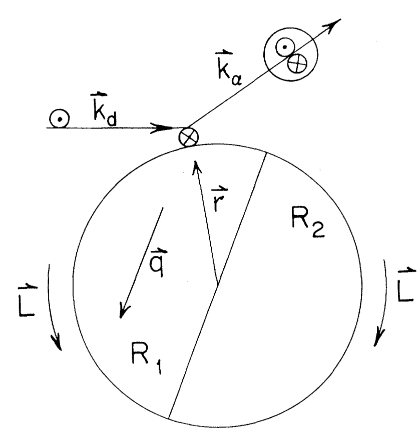

FIG. 1. Classical description of a (d, α) reaction with incident deuteron spin along the y axis (out of page). Pickup of a d occurs at $\vec{r}$ in both regions R_1 and R_2, whose boundary is along the direction of the momentum transfer $\vec{q}$ and passes through the nuclear center. In this figure the α particle has been formed with d-d in an S state.

A ^{3}He polarimeter was used to monitor the beam polarization moments during each eight-step measurement[4] that determined $d\sigma/d\Omega$, the vector analyzing power A_y, and the TAP components A_{xx} and A_{yy}. At 12 and 16 MeV the off-diagonal TAP A_{xz} was also measured.

The target nucleus ^{89}Y is particularly good for studying D-state effects because the simple shell-model configurations of the ^{89}Y and ^{87}Sr ground states allow the admixture of various angular momentum transfers to be easily calculated. The ^{89}Y ground-state proton component is well described[5] as $\pi(2p_{1/2})$ coupled to a ^{88}Sr core. The $2p_{1/2}$ protons are expected to predominate in pickup since nuclides with one less proton than ^{89}Y, such as ^{88}Sr, are found to have nearly full ($\geq 90\%$) $1f_{5/2}$ and $2p_{3/2}$ shells and nearly empty ($\leq 10\%$) $2p_{1/2}$ shells.[6] For the neutron orbital in ^{89}Y there is high probability that $\nu(1g_{9/2})$ is involved, since spectroscopic factors near unity have been determined[7] for $g_{9/2}$ transfers in neutron pickup reactions from $N=50$ nuclei. Thus, the ^{89}Y$(d,\alpha_0)^{87}$Sr reaction is predominantly populated by pickup of $\pi(2p_{1/2})$ and $\nu(1g_{9/2})$ from ^{89}Y, which results in allowable (L,J) transfers of (3,4), (5,4), and (5,5). These proton and neutron configurations allow the appropriate parity change and spin change of 4 in the (d,α_0) reaction, and the (L,J)-mixing amplitudes can be calculated by using 9-j and Talmi-Moshinsky coefficients.[8] The calculated (L,J) mixing amplitudes, normalized to unit probability, are 0.59 for (3,4), 0.12 for (5,4), and 0.79 for (5,5).

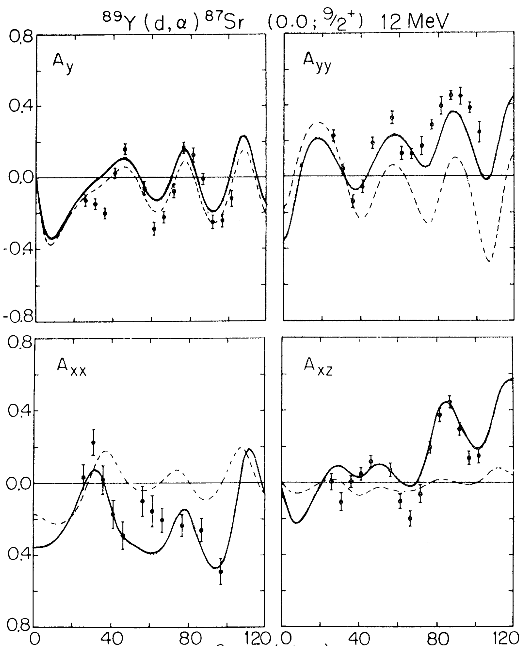

FIG. 2. Analyzing-power data for the reaction ^{89}Y$(d,\alpha_0)^{87}$Sr at 12 MeV with curves from exact finite-range DWBA calculations. The dashed curves ignore the D state of the α particle. The solid curves correspond to $D_2 = -0.3$ fm^2.

The differential-cross-section and analyzing-power data shown in Figs. 2 and 3 were analyzed by exact finite-range distorted-wave Born-approximation (DWBA) calculations with use of the code PTOLEMY[9] and with the assumption of deuteron-cluster transfer. Deuteron internal D-state components are expected to have relatively negligible effects on (d,α) reactions for the same reasons as in (d,t) and $(d,{}^3$He) reactions.[10] The d-d relative motion in the α particle was described by a Woods-Saxon potential consistent with their separation energy and with the α-particle rms radius.[11] The distorted waves were generated from optical potentials determined by measuring and fitting ^{89}Y$(d,d)^{89}$Y angular distributions of $d\sigma/d\Omega$ and A_y at 12 MeV, and 19.5-MeV cross-section angular distributions for ^{87}Sr$(\alpha,\alpha)^{87}$Sr. For the deuterons, the global potential of Daehnick, Childs, and Vrcelj[12] was adjusted to fit the elastic-scattering data. Since the α particles were near the Coulomb barrier, their cross section was rather structureless. Therefore, the α-particle potentials obtained were adjusted to also fit the vector analyzing power for the ^{89}Y$(d,\alpha_0)^{87}$Sr transition. These potentials also led to good agreement of the DWBA calculations with the differential-cross-section and vector-analyzing-power data for transitions to the first two excited states in ^{87}Sr.

Figure 2 shows the analyzing-power data at 12 MeV with calculations for the α particle in a pure S state, or for the D state included. Both the cross

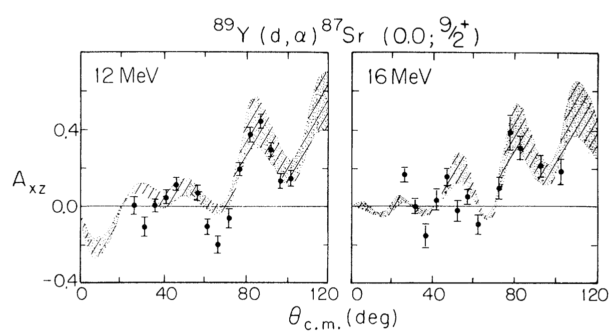

FIG. 3. Variations in the D-state admixture calculated for A_{xz} at 12 and 16 MeV, with the same optical potentials and (L,J)-mixing amplitudes as in Fig. 2. The shaded regions correspond to D_2 in the range -0.2 to -0.4 fm^2.

section (which has a structureless angular distribution) and the vector analyzing power are well described by the present calculations, but they are insensitive to the D state. In contrast, the TAP calculations, especially for A_{xz}, show large D-state effects. Clearly, all the TAP are better described by the calculation with the D state included. Similarly, good results were obtained for the 9- and 16-MeV data by adjusting only the depths of the α absorption potentials. The D-state value shown in Fig. 2 corresponds to a D-state admixture with $D_2 = -0.3$ fm^2, where D_2, defined by Knutson and Haeberli,[13] is approximately proportional to the asymptotic D- to S-state ratio for d-d relative motion in the α particle. Assuming Gaussian wave functions for nucleon motions in the α particle, we estimate a corresponding value for the D-state probability in the α particle of $P_D \simeq 7\%$. This is in reasonable agreement with recent calculations of the structure of the α particle with noncentral forces,[1] which yield $P_D = 5.4\%$ in Goldhammer's calculation and the range $8\% \leq P_D \leq 13\%$ in Ballot's.

Extensive tests were made in which the optical potentials and the (L,J) mixing were varied. The shifts in A_{xx} and A_{yy} and the large effect in A_{xz} introduced by the D state could not be generated by any reasonable change in the optical potentials. Similarly, the D-state effects could not be plausibly obtained by adjusting the (L,J)-mixing amplitudes. By changing the sign and increasing the magnitude of the (5,4) amplitude, it was possible to approximate the effects of the D state in A_{xz}, although the phase did not agree well with the data. However, such changes in the (L,J) mixing significantly worsened the agreement with the A_{xx} and A_{yy} angular distributions. These results emphasize the need to consider a complete set of analyzing-power observables. The inability in the present work to trade off D-state effects against those from mixing of angular momentum transfers contrasts with the results obtained by Tostevin,[11] who found in a case having $L=0$ mixing with $L=2$ that the effects of mixing could be included in either the target or the projectile bound states.

While it is convincing that significant D-state component in the α particle is needed, it is more difficult to extract a precise value for the D-state amplitude. As shown in Fig. 3, the most sensitive TAP, A_{xz}, changes significantly only for relatively large changes in the D-state amplitude, and some of the TAP are better fitted by different D-state amplitudes. From these and similar analyses, we conclude that $D_2 = -0.3 \pm 0.1$ fm^2.

The contribution of two-step processes to (d,α) reactions has recently been estimated.[14] Two-step processes are thought to become important if the one-step transition is weak because of effects such as momentum mismatch between the initial and final channels or violation of isospin conservation. For ^{89}Y$(d,\alpha_0)^{87}$Sr, the momentum-matching condition is well satisfied, as reflected in the substantial cross sections, which range from 10 to 70 μb/sr at 12 MeV. These are much larger than estimates for two-step contributions, which do not exceed a few microbarns per steradian.[14] Therefore, the effects of two-step processes on our value for the D-state amplitude are expected to be negligible compared to the estimated 30% uncertainty.

What other ways can be used to investigate D-state components in the α particle? It has been suggested[15] that the J dependence of (α,d) cross sections could be explained by D-state effects in the α particle with $D_2 = -0.20$ fm^2, but this explanation has been questioned.[16] Measurements of tensor analyzing powers in $d(d,\gamma)\alpha$ are currently underway at both low[17] and intermediate[18] energies. Methods based on analyticity applied to $d(d,d)d$ in the channel-spin 2, $L'=2$ configuration can, in principle, be used,[19] but the α-particle pole is very far from the physical region. The existence of α-particle D-state components implies a finite intrinsic quadrupole moment of the α particle, but this moment could not be measured by conventional Coulomb-excitation methods because the α particle has no bound excited states. Our results should provide impetus to further experiments and to improved understanding of the nucleon-nucleon interaction, especially of noncentral components and their effects in few-nucleon systems.

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