in which the pion absorption is certainly not negligible. Finally the effect of P_L in our calculation and in FR should be further investigated.

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Determination of Angular-Momentum Transfers for (d, α) Reactions Using Polarized Beams

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The angular distribution patterns of vector analyzing powers for (d,α) reactions on s-d shell nuclei at energies near 16.5 MeV depend distinctly on the orbital angular momentum L and total angular momentum J transferred. Examples of $L=0$, $L=2$, and $L=4$ transfers have been obtained for ^{28}Si, ^{32}S, and ^{40}Ca targets, and these compare well with distorted-wave calculations. These measurements provide information useful in establishing the spins and parities of the levels populated in (d,α) reactions.

The (d,α) reaction involves the pickup of two nucleons (sometimes considered as a deuteron cluster) from a nucleus. It is useful in spectroscopic studies of the residual nuclei, which are frequently odd-odd, and for studying the neutron-proton correlations in the ground state of the target nucleus. The analysis of these reactions is considerably more complicated than single-nucleon transfer reactions, since most final states can be populated by several orbital angular momentum transfers (L). Each L and J value transferred, where J is the total angular momentum of the pair, can also involve a combination of two-particle configurations. Since differential cross sections are often inadequate to unravel the relative contributions of different angular momenta to the (d,α) reaction, it is important to investigate the extent to which vector-analyzing-power (VAP) measurements using polarized beams can improve understanding of the reaction and the final states involved. Several VAP measurements for the (d,α) reaction have been reported recently.[1-3] These measurements, however, do not comprise as complete a study of a given mass region as is contained in the present work.

It is by now well-established that VAP measurements for single-nucleon pickup and transfer reactions distinguish between $j=l+\frac{1}{2}$ and $j=l-\frac{1}{2}$ transfers[4] (where j and l are total and orbital angular momenta of the transferred nucleon). The present Letter shows that analogous effects exist in VAP distributions for a two-nucleon transfer reaction depending on the J and L of the transferred pair of nucleons. For a spin-zero target nucleus, the L and J transferred from the nucleus determine the spin and parity of the final nuclear state and for each L involved in populating this state, J may equal either $L+1$, L, or $|L-1|$. Earlier theoretical work[5] stated that, in the absence of spin-dependent distortions of the incoming and outgoing waves and for a unique L and J, the vector analyzing powers will be proportional to $-L$, 1, and $L+1$, respectively, for the above J values.

In order to consider cases involving only one important angular-momentum component to the reaction, measurements were made with spin-zero self-conjugate ($N=Z$) target nuclei. For these targets the neutrons and protons picked up from the same shell preferentially couple their angular momenta so the reaction populates states of maximum J,[6] and transitions characterized by the transfer $L=2l$ and $J=2j$ will therefore tend to predominate. Thus from a classical viewpoint, the reactions proceed strongly when the conditions for the pickup of a deuteron cluster from the nucleus are satisfied. An example is the reaction ^{28}Si$(d,\alpha)^{26}$Al(g.s.) involving the pickup of $1d_{5/2}$ nucleons coupled to transfer $L=4$ and $J=5$ in populating the 5^+ ground state relatively strongly.

Angular distributions of the VAP might, from semiclassical arguments, be expected to indicate the total angular momentum transfer. If an observer looking down on the reaction plane sees a "spin-up" deuteron incident on a spin-zero nucleus which removes two spin-down nucleons in forming the α particle, the orbital motion of the transferred particles is restricted to the clockwise direction when a state having $J=L+1$ is populated. Since the incident deuteron momentum is generally much less than the α momentum, the two-particle transfer occurs predominantly on one side of the nucleus to enable momentum conservation. α particles emerging mainly from one side of the nucleus will tend to produce a left-right asymmetry in the scattering yields. This asymmetry would be expected to change when the final state populated has $J=|L-1|$ since, by similar arguments, the particles would be expected to emerge from the opposite side of the nucleus. Distorted-wave Born approximation (DWBA) calculations of the VAP for the reaction ^{28}Si$(d,\alpha)^{26}$Al(g.s.) ($L=4$) for J transfers of 3, 4, and 5, shown in Fig. 1(a), show strong differences for the various J values. The calculations use only real, central, deuteron and α-particle potentials. The $J=5$ ($=L+1$) transfers show predominantly negative analyzing power values while $J=3$ ($=|L-1|$) transfers have opposite signs of analyzing powers, as predicted in Ref. 5.

Another factor which influences the analyzing power angular distributions is the absorption of part of the deuteron and α flux by the target and residual nucleus. This effect has been presented by Newns[7] as responsible for the j dependence of (d,p) polarization measurements. The effect of including absorptive potentials in the calculation is to change the analyzing power values most remarkably at forward angles, with opposite effects for $J=L+1$ and $J=|L-1|$ in typical cases calculated here. The inclusion of the deuteron spin-orbit potential generally makes the VAP values more positive. The combined effect of including these potentials is to produce the predictions in Fig. 1(b). The main features for the calculations of (d,α) analyzing powers for several L values and bombarding energies are that the analyzing powers for $J=|L-1|$ are more positive than those for $J=L+1$ and out of phase with each other especially at forward angles. The calculations for $J=L$ transfers show smaller VAP magnitudes than those for $J=L\pm 1$. In short, predictions of the VAP for the (d,α) reaction show clear distinctions between angular-momentum transfers of $J=L+1$, L, and $|L-1|$, both with and without spin-dependent distortion.

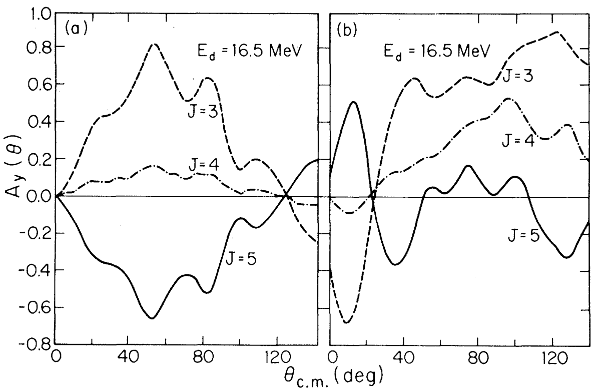

FIG. 1. (a) The VAP for ^{28}Si$(d,\alpha)^{26}$Al(g.s.) from DWBA calculations using only real central potentials for $L=4$, $J=5$ (solid curve), $J=4$ (dot-dashed curve), and $J=3$ (dashed curve). (b) The VAP predictions for the reaction using the optical potentials in Table I. The curves differ from the corresponding curves shown in (a) due to the inclusion of absorptive and spin-orbit potentials.

To test the above predictions, a 16.5-MeV beam of vector polarized deuterons was used to bombard targets of ^{28}Si, ^{32}S, and ^{40}Ca. The polarized source and measurement procedures have been described elsewhere.[8] The silicon targets were of natural SiO evaporated to a thickness of 180 μg/cm^2 on carbon backings. Later, 0.5 atm of silane gas (SiH_4) was used as a target when it was necessary to determine the yields at angles where the peaks corresponding to reactions from silicon and oxygen overlapped. The sulfur target consisted of unenriched H_2S gas at a pressure of 1 atm, while the calcium target was in the form of CaO, 200 μg/cm^2 thick on a carbon backing. α particles were detected in E-ΔE detector telescopes situated at equal angles to the left and right of the incident beam. These detectors supplied signals to mass identify the particles using an on-line computer.

Representative VAP angular-distribution data are shown in Fig. 2. The data for the reaction $^{28}Si(d,\alpha)^{26}Al$(g.s.) are averages of VAP values obtained at each angle for eleven energies differing by 100 keV from 16 to 17 MeV. The errors shown with the points are the standard deviations for those measured points. The size of the error bars indicates a relatively small change in VAP values with energy at a given angle, and indicates that a direct-transfer process predominates for this reaction at these energies. These relatively small VAP changes with energy were typical for the reactions investigated. The errors shown with the other data in Fig. 2 are statistical only.

The reaction $^{32}S(d,\alpha)^{30}P$(g.s.) populates a state with $J^{\pi}=1^{+}$, which can involve a transfer of both $L=0$ and $L=2$. The calculations shown in Fig. 2(a) present a comparison of $L=2, J=1$ and $L=0, J=1$ predictions with the data for this state. The calculations are zero-range DWBA made using program DWUCK [9] with a deuteron-cluster form factor. Two-particle transfer calculations were made which exhibit very similar VAP patterns. The optical-model potentials have the form used by Becchetti and Greenless,[10] and the parameters are listed in Table I. A comparison of theory and experiment in Fig. 2(a) shows good agreement for $L=0$ and hence only small $L=2$ admixtures are probable. In order to determine precise admixtures of L-transfer values in the presence of spin-dependent distortions, it is necessary to add the components coherently.[13] This was not done here since one of the components predominated in each case. Figure 2(b) contains VAP distributions corresponding to predominantly $L=2$ transfers for $J=1$ states (0.71 MeV in ^{30}P and 0.46 MeV in ^{38}K) and $J=3$ states

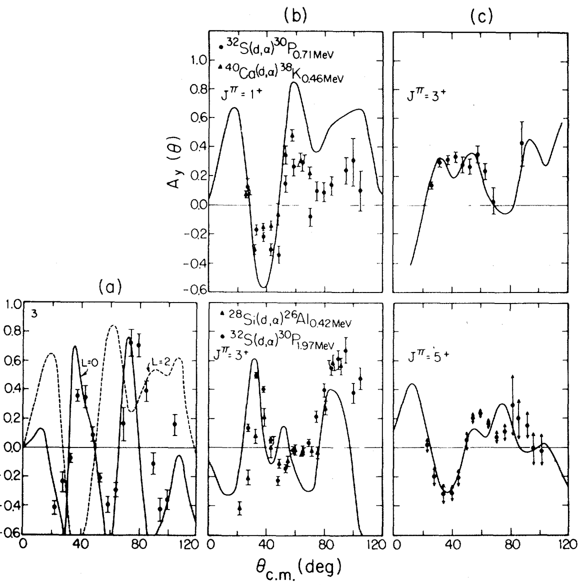

FIG. 2. (a) Measured VAP values for $^{32}S(d,\alpha)^{30}P$(g.s.) ($J^{\pi}=1^{+}$) shown with DWBA predictions for $L=0, J=1$ and $L=2, J=1$. Optical-model parameters are listed in Table I. (b) Measured VAP angular distributions for (d,α) reactions populating 1^{+} states by predominantly $L=2$, $J=1$ transfers (top) and populating 3^{+} states with $L=2$, $J=3$ transfers (bottom). The calculations are DWBA predictions for the reaction $^{32}S(d,\alpha)^{30}P$. (c) Measured VAP values for the (top) reaction $^{40}Ca(d,\alpha)^{38}K$(g.s.) which is an $L=4$, $J=3$ transfer and the (bottom) reaction $^{28}Si(d,\alpha)^{26}Al$(g.s.) which is predominantly $L=4$, $J=5$. The latter distribution is the average of 11 separate distributions taken in 0.1 MeV steps from 16.0 to 17.0 MeV. Errors represent standard deviations from the mean. The DWBA predictions were made using parameters in Table I.

TABLE I. Optical-potential parameters used in the analysis of (d,α) reactions. The deuteron potentials, from Ref. 11, have a surface-absorption potential. The α potentials, from Ref. 12, have volume absorption. Changes of $\leq 5\%$ were sometimes made in the strength of the real central potential.

Target		V (MeV)	r_R (fm)	a_R (fm)	W (MeV)	r_r (fm)	a_r (fm)	$V_{s.o.}$ (MeV fm^2)	$a_{s.o.}$ (fm)	$a_{s.o.}$ (fm)
^{28}Si	d	101.2	1.05	0.86	16.6	1.41	0.594	7.0	0.75	0.50
	α	200.8	1.425	0.557	16.5	1.425	0.557			
^{32}S	d	98.0	1.05	0.86	16.6	1.41	0.61	7.0	0.75	0.50
	α	205.0	1.349	0.592	17.0	1.349	0.592			
^{40}Ca	d	104.0	1.05	0.86	16.15	1.41	0.64	7.0	0.75	0.50
	α	211.6	1.14	0.79	28.8	1.14	0.75			

(1.97 MeV in ^{30}P and 0.42 MeV in ^{26}Al). The L values can be determined from the differential cross section.[14] The data show distinctly different oscillatory patterns for different J transfers, but similar patterns for the same J transfers, and agree reasonably well with the appropriate DWBA calculations for the reaction ^{32}S$(d,\alpha)^{30}$P. Figure 2(c) contains results for $L=4$ tranfers. The reaction ^{28}Si$(d,\alpha)^{26}$Al(g.s.) corresponds to an $L=4$, $J=5$ transfer as mentioned previously. The reaction ^{40}Ca$(d,\alpha)^{38}$K(g.s.) involves the pick-up of a pair of $1d_{3/2}$ particles from ^{40}Ca to provide an $L=4, J=3$ transfer. The DWBA calculations for these transfers again predict the trends of the data.

In conclusion, the VAP angular distributions show pronounced differences for different J values transferred, and are in reasonable agreement with DWBA calculations. States populated by the transfer of the same L and J have similar patterns even though they may occur in different nuclei. Thus, with a vector polarized beam both L and J values can be determined and nuclear structure calculations may be tested in this mass region. Additional (d,α) reaction calculations have been made for lighter and heavier target nuclei, for reactions with widely varying Q values, and for different deuteron bombarding energies. All of these calculations reveal significant differences in the VAP distributions depending on the J for a unique L transfer. Further VAP measurements could be made with other nuclei to test these predicted differences and to see if VAP data involving multiple L values can be compared to DWBA calculations to extract relative contributions to these reactions.

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