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Probing α-particle wave functions by (d,α) tensor analyzing powers

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Components of α-particle wave functions corresponding to d-d configurations are used to predict analyzing powers in the (d,α) reaction. Tensor analyzing powers, especially A_{xx}, are shown to clearly distinguish between wave functions generated by different realistic nucleon-nucleon interactions. Data for the ^{58}Ni$(d,\alpha)^{56}$Co reaction to the 7^+ stretch-nucleon-orbital state at 2.283-MeV excitation in ^{56}Co, measured with 22-MeV deuterons, are compared to predictions from the Argonne and Urbana interactions. Similar comparisons are made to data for the lowest $J^\pi=7^+$ state in ^{48}Sc populated by the ^{50}Ti$(d,\alpha)^{48}$Sc reaction at 16 MeV.

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Among the very light nuclei the α particle is of special importance because of its large binding energy, indicative of strong short-range attractions when the total angular momenta among the four nucleons are coupled to zero. With recent advances in computational techniques, realistic *ab initio* wave functions for the α particle are becoming available [1-3]. They are being used to predict such observables as electromagnetic form factors, structure functions, and $(e,e'p)$ spectra [4,5], which will be of particular interest at the new electronuclear facilities such as CEBAF. The simplest nonspherical relative motion in the α particle is a D-state motion between two deuteron clusters (d-d). In very light nuclei D states are sensitive to details of the nucleon-nucleon tensor interaction. Recent reviews of such states are given in Refs. [6,7].

In this paper we demonstrate for the first time the sensitivity of the tensor analyzing power A_{xx} in (d,α) reactions to the effective nucleon-nucleon interactions used to model the α-particle wave function, ψ_α. Previous (d,α) studies (e.g., Refs. [8,9]) used only schematic wave functions, such as those generated by Woods-Saxon d-d interaction potentials. To illustrate this sensitivity, we compare the effects on the tensor analyzing powers in (d,α) of the d-d components in ψ_α calculated by Schiavilla, Pandharipande, and Wiringa from the Argonne [10] and Urbana [11] interactions—AV14 and UV14—and the predictions with data. We find that the sensitivity of tensor analyzing powers in (d,α) to the choice of α-particle wave functions is much greater than for α-particle properties studied in electron scattering [4,5]. In the ^{2}H$(d,\gamma)^4$He reaction the tensor analyzing powers are also sensitive to D-state components, but there is considerable theoretical uncertainty in their interpretation [7]. In the following, we summarize relevant aspects of ψ_α, of (d,α) tensor analyzing powers, of our experiments, and of comparison of the predictions with data.

Figure 1 compares the S- and D-state radial components of ψ_α in terms of the d-d relative coordinate, r, for AV14 and UV14 interactions. These interactions when used for $A>2$ include a three-nucleon force [1] (model VII) which is the same for the two interactions. We obtain the radial components, $R_S(r)$ and $R_D(r)$, by Fourier transforming from the momentum-space representations tabulated by Schiavilla, Pandharipande, and Wiringa [1]. Interestingly, AV14 has a 7% stronger one-pion-exchange potential than has UV14, and it produces a larger D-state probability in the deuteron, $P_D(\text{AV14},d)=6.1\%$, whereas $P_D(\text{UV14},d)=5.2\%$. The predicted D_2 parameter for the d-d component in ψ_α, which gauges the behavior of $R_D(r)$ relative to $R_S(r)$ at large r, has $D_2(\text{AV14})=-0.16$ fm^2, whereas $D_2(\text{UV14})=-0.24$ fm^2. Such a difference in D_2 is suggested by the behaviors of R_S and R_D as a function of r in Fig. 1 for the two interactions. The 7% increase of the πNN coupling constant from UV14 to AV14 would tend to increase the magnitude of D_2, but the additional short-range tensor components in AV14 enhance the D-state component mainly at small r and give rise to a smaller D_2, as suggested by Fig. 1 and discussed in Refs. [1,10]. Thus, D-state effects in the α particle are very sensitive to the short-range behavior of the nucleon-nucleon tensor force, because the two deuteron clusters must be in close proximity in order to be tightly bound in the α particle. Although P_D is not an observable, D_2 is directly related to the transition matrix element $\langle\alpha|V_{dd}|dd\rangle$ at low d-d relative momentum. The distorted-wave Born approximation (DWBA) analysis below uses the transition matrix element computed for either AV14 or UV14.

The experimental procedures we used are summarized as follows. In order to reduce ambiguities in describing the reaction mechanism, we selected the ^{58}Ni$(d,\alpha)^{56}$Co reaction to a state in ^{56}Co with stretched nucleon angular

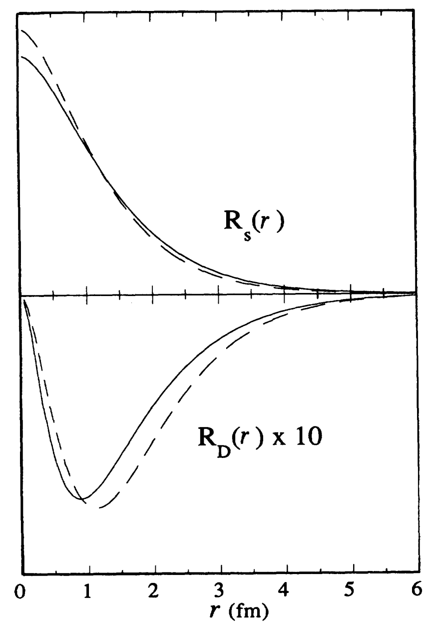

FIG. 1. Radial wave functions, $R_S(r)$ and $10\times R_D(r)$, as a function of d-d separation r for the S- and D-state components of the α-particle wave function in the d-d configuration, derived from the momentum-space wave functions of Ref. [1]. The solid curves are for the Argonne-V14 nucleon-nucleon interaction and the dashed curves are for the Urbana-V14 interaction. For the α particle both interactions include the model-VII three-nucleon force.

momenta, the 2.283-MeV $J^\pi=7^+$ state, which achieves a unique target-cluster configuration. This transition also has orbital angular momentum transfer $L=J-1$, which enhances D-state effects on tensor analyzing powers [6]. The differential cross section, $\sigma(\theta)$, the vector analyzing power, $A_y(\theta)$, and the tensor analyzing powers, $A_{xx}(\theta)$ and $A_{yy}(\theta)$, were measured at a laboratory bombarding energy of 22 MeV at the Munich MP tandem accelerator laboratory, using methods described elsewhere [9]. Thin targets of enriched ^{58}Ni were bombarded by vector- and tensor-polarized deuteron beams. The α particles were detected using a magnetic spectrometer with a focal-plane detector system that allows kinematic correction [12] to achieve resolution of 12 keV full width at half maximum (FWHM) at the full spectrometer acceptance of 11 msr, to produce the data shown in Fig. 2. The (d,α) reaction observables in Figs. 2 and 3 were predicted in a full-finite-range DWBA model, assuming a one-step d-cluster-transfer mechanism, by using the computer code TWOFNR [13]. Both nucleon orbitals are from the $f_{7/2}$ shell and will therefore have maximal overlap, which gives rise to 7^+ transition cross sections which are at least an order of magnitude larger than transitions to nearby states at these bombarding energies.

The transition to the 7^+ state may also take place by two-step processes such as $(d,t),(t,\alpha)$ and $(d,{}^3\mathrm{He})$, $({}^3\mathrm{He},\alpha)$, in addition to direct pickup. It has been pointed out that two-step processes can strongly influence the reaction yield even in cases of large direct amplitudes [14]. Therefore, we estimated the strength of two-step processes, despite the lack of pertinent input data; the reactions forming the second step are not measurable since the necessary target nuclei are unstable. By using average spectroscopic amplitudes from pickup reactions on nearby nuclei [15] for each step of both reactions, we find that the predicted maximum $(d,{}^3\mathrm{He}),({}^3\mathrm{He},\alpha)$ cross section is about 5% of the maximum measured cross section, while the $(d,t),(t,\alpha)$ cross section is about 2% of this value. Calculations combining maximum estimates for two-step amplitudes with one-step amplitudes exhibit changes in tensor analyzing powers which are comparable to those resulting from uncertainties in optical-model potentials, that is, essentially unchanged for A_{xx} with slightly larger changes possible for A_y and A_{yy}.

We minimized an ambiguity in earlier studies of tensor analyzing powers in (d,α), namely, the effects of transitions of mixed L for a given J ($L=J\pm1$ for an unnatural-parity transition), by choosing a stretched state with unique $L=l_p+l_n=6$. The other allowed L value,

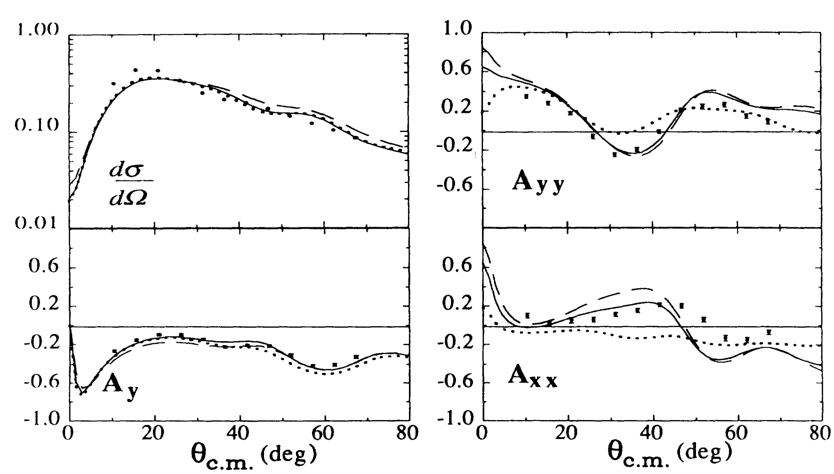

FIG. 2. Angular distributions of the cross section (arbitrarily normalized), A_y, A_{xx}, and A_{yy} at 22-MeV deuteron energy for $^{58}\mathrm{Ni}(d,\alpha)^{56}\mathrm{Co}$ to the lowest 7^+ state in ^{56}Co. Solid curves are predictions for AV14, dashed curves are for UV14, and dotted curves are for both when only the S state of d-d relative motion is included.

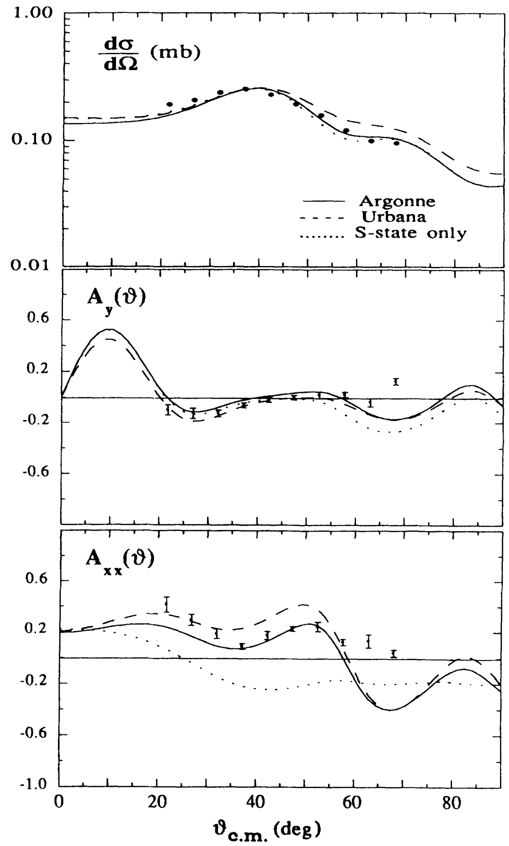

FIG. 3. Angular distribution of the cross section (arbitrarily normalized), A_y and A_{xx} at 16-MeV deuteron energy for ^{50}Ti$(d,\alpha)^{48}$Sc to the 1.07 MeV ($J^\pi=7^+$) state in ^{48}Sc. The solid curves are predictions for AV14, dashed curves for UV 14, and dotted curves for the S state of d-d relative motion only.

$L=8$, would require both nucleon orbitals to be from the same higher major shell, $g_{9/2}$ or greater, which is energetically very unfavored and so is not considered. The relative wave function in the target system, therefore, has $L=6$, $J=7$, and is generated by a Woods-Saxon potential.

In our DWBA predictions the remaining ingredients are the optical-model potentials for the deuteron and α-particle channels. We used the same deuteron optical potential (OMP) as in the previous parameterization of (d,α) at 16 MeV by Haller *et al.* [8], except that the real-well depth was reduced by 2% to improve the description of the (d,α) vector analyzing powers. The potential has the same geometric parameters as in the global parameterization of Daehnick, Childs, and Vrcelj [16]. For the α channel we obtained OMP parameters by fitting angular distribution data measured at Triangle Universities Nuclear Laboratory (TUNL) for ^{59}Co$(\alpha,\alpha)^{59}$Co and ^{58}Ni$(\alpha,\alpha)^{58}$Ni at 18.5, 22.5, and 24 MeV.

As discussed above, the ψ_α of Schiavilla, Pandharipande, and Wiringa obtained from variational Monte Carlo calculations using either AV14 or UV14 then projected onto the d-d configuration [1] was used directly to calculate the transition matrix elements. The DWBA calculations for $\sigma(\theta)$ and for the tensor analyzing powers shown in Fig. 2 and 3 are predictions using potentials slightly modified in strength, rather than best fits.

The most striking aspect in Fig. 2 is the strong sensitivity of A_{xx} to effects on the d-d configuration in ψ_α resulting from differences between the AV14 and UV14 parametrizations of the nucleon-nucleon interaction. The differences are comparable to the effects of completely ignoring the D-state components of ψ_α, and are relatively insensitive to the choice of optical-model potential and the presence of small two-step contributions. Comparisons of predictions for A_{yy} data are expected to be less meaningful, since the latter are more sensitive to two-step contributions and depend strongly on the spin-dependent parts of the (d,d) potentials employed, which are still not well determined.

Similar effects can be observed in the A_{xx} calculations shown in Fig. 3 where they are compared to measurements for the lowest $J^\pi=7^+$ state populated in the ^{50}Ti$(d,\alpha)^{48}$Sc reaction taken at 16 MeV at TUNL using techniques described previously [8]. This transition is similar to the ^{58}Ni$(d,\alpha)^{56}$Co transition described previously in that both nucleons are picked up from a $f_{7/2}$ shell in a stretched configuration resulting in a unique $L=6$ transfer. The calculations for this reaction were made using Argonne and Urbana interactions combined with the deuteron OMP parameters of Daehnick, Childs, and Vrcelj [16] and alpha potentials identical to those used for the ^{58}Ni data except for adjustments of the real- and imaginary-well depths to fit ^{48}Ti$(\alpha,\alpha)^{48}$Ti data taken at 20 MeV. Improved comparisons to A_{xx} data can be obtained by further variation of these parameters. The very sensitivity of tensor analyzing power calculations to OMP parameters at this energy, however, makes these data less useful than the aforementioned 22-MeV data for distinguishing between parametrizations of the N-N interaction. The ^{50}Ti$(d,\alpha)^{48}$Sc reaction data and calculations show, however, that similar A_{xx} dependences on the choice of N-N interaction also occur at different deuteron bombarding energies and with other target nuclei.

In conclusion, from this analysis we have shown for the first time that A_{xx} tensor analyzing powers in (d,α) reactions provide very sensitive tests of realistic α-particle wave functions. For the future, if A_{xx} data could be obtained at energies in the 100- to 200-MeV range, the momentum components in ψ_α that can be sensitively probed by this technique would be comparable to those reached in electron-scattering studies [4,5]. Such hadronic-probe data will additionally be very sensitive to D-state components of the α-particle wave function, especially to its short-range behavior.

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