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Effects of the Triton D State in (d,t) Reactions

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Measurements of the tensor analyzing powers for (d,t) reactions on ^{118}Sn and ^{208}Pb are presented. It is shown that the measured quantities are sensitive to the D-state components in the triton wave function. The magnitudes of the observed analyzing powers are in good agreement with predictions obtained from a triton D-state wave function calculated in first-order perturbation theory.

It is well known that the deuteron D state can produce marked effects in (d,p) reactions.[1,2] The D state has very little influence on the reaction cross section, but can produce large changes in the observables for reactions induced with a polarized beam. In particular, the deuteron D state is primarily responsible for the large tensor analyzing powers[3] which are observed in (d,p) reactions on intermediate and heavy nuclei.

In this Letter, we argue that similar effects should be present in (d,t) reactions. In this case, however, the effects arise primarily from the D-state components in the triton wave function,[4] rather than from the deuteron D state. Measurements of the tensor analyzing powers for (d,t) reactions on ^{118}Sn and ^{208}Pb are presented, and the measurements are compared with the results of distorted-wave calculations.[5] A simple triton wave function, in which the D-state components are calculated from first-order perturbation theory, is used to predict the magnitude of the effects of the triton D state.

The reaction calculations presented in this Letter are based on the distorted-wave Born approximation[5] (DWBA). In DWBA, the transition amplitude for a (d, t) reaction depends on the internal structure of the deuteron and triton through the overlap integral[6]

$$R(\vec{r}) = \langle \chi_{1/2}{}^{\sigma_n} \varphi_d{}^{\sigma_d}(\vec{\rho}) | \varphi_t{}^{\sigma_t}(\vec{r}, \vec{\rho}) \rangle. \quad (1)$$

Here $\varphi_d{}^{\sigma_d}$ and $\varphi_t{}^{\sigma_t}$ are the internal wave functions of the deuteron and triton, respectively, and $\chi_{1/2}{}^{\sigma_n}$ is the spin wave function of the transferred neutron. The quantity $\vec{\rho}$ is the internal coordinate of the deuteron, and $\vec{r}$ is the separation of the transferred neutron from the deuteron center of mass. According to Eq. (1), one projects out that part of the triton wave function which looks like a deuteron plus a neutron, and the motion of the neutron relative to the deuteron center of mass is described by the quantity $R(\vec{r})$.

From general angular momentum and parity selection rules, it is clear that $R(\vec{r})$ can contain only S- and D-state terms. Specifically we may write

$$R(\vec{r}) = \sum_{L=0,2} \sum_{\Lambda,\sigma} u_L(r) Y_L{}^{\Lambda}(\hat{r}) \langle L\Lambda, s\sigma | \tfrac{1}{2}\sigma_t \rangle \times \langle 1\sigma_d, \tfrac{1}{2}\sigma_n | s\sigma \rangle, \quad (2)$$

where $s = \frac{3}{2}$ for $L = 2$ and $s = \frac{1}{2}$ for $L = 0$. The quantities u_0 and u_2 are radial functions which depend on the internal structure of the triton and deuteron. In all previous distorted-wave calculations for (d, t) reactions, the effects of the $L = 2$ term in Eq. (2) have been ignored.

In terms of its angular momentum structure, the expression given in Eq. (2) is identical to that which appears in the transition amplitude for (d, p) reactions.[6] In particular, the $L = 0$ and $L = 2$ terms in Eq. (2) enter into the (d, t) calculations in precisely the same manner as the deuteron S- and D-state wave functions enter the calculations for (d, p) reactions. By analogy, it follows that the tensor analyzing powers for (d, t) reactions will be sensitive to the D-state term in Eq. (2).

The deuteron beam from the University of Wisconsin polarized-ion source was used to measure angular distributions of the three tensor analyzing powers[7] (T_{20}, T_{21}, and T_{22}) for the reactions ^{118}Sn$(d, t)^{117}$Sn at 12.0 MeV and ^{208}Pb$(d, t)^{207}$Pb at 12.3 MeV. The measurement techniques have previously been described by Rohrig and Haeberli.[8] A complete report on the experiment will be published separately.[9] The measured analyzing powers for three strong transitions are shown in Fig. 1. It is interesting that the (d, t) analyzing powers are similar in shape and magnitude to the analyzing powers for low-energy (d, p) reactions,[1] but have the opposite sign.

The curves in Fig. 1 show the results of DWBA calculations.[10] These calculations were carried out using the local-energy approximation.[6,11] This approximation method is known to work reasonably well for calculations of the D-state effects in low-energy (d, p) reactions.[1] In the local-energy approximation, the magnitude of the D-state effect depends only on the value of a single parameter, D_2. The value of this parameter is related to the functions u_0 and u_2 according to

$$D_2 = \tfrac{1}{15} \int_0^\infty u_2(r) r^4 \, dr \Big/ \int_0^\infty u_0(r) r^2 \, dr. \quad (3)$$

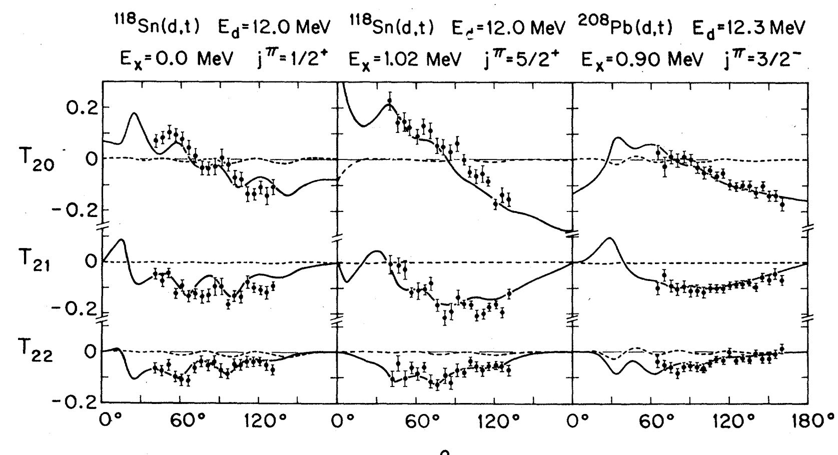

FIG. 1. Angular distributions of the tensor analyzing powers for (d,t) reactions on ^{118}Sn and ^{208}Pb. The dashed curves are DWBA calculations in which the D-state effects were neglected. The solid curves are DWBA calculations which include the D-state effects with $D_2 = -0.24$ fm^2.

To a good approximation, the calculated tensor analyzing powers scale linearly with D_2.

The dashed curves in Fig. 1 show the results of standard DWBA calculations, in which the D-state term is neglected. As one can see, these calculations greatly underestimate the magnitude of the tensor analyzing powers. In order to include the D-state effects in the DWBA calculations, we treated D_2 as an adjustable parameter, since the correct value of D_2 was not known from previous work. The value $D_2 = -0.24$ fm^2 provided the best fit to the measurements, and this value was used for the calculations which produced the solid curves. From these results it is clear that the D-state term in Eq. (2) is primarily responsible for the observed tensor analyzing powers.

It is interesting to compare the experimentally determined value of D_2 with the value calculated from particular triton and deuteron wave functions. The first question in such a calculation is to determine which components in the triton and deuteron wave functions are likely to give the major contributions of the overlap D state. In general, the $L=2$ term in Eq. (2) can be nonzero if either the deuteron or the triton wave function contains a D-state term. From the deuteron D state one obtains terms proportional to $Y_2^m(\hat{\rho})$. In taking the overlap we integrate over the coordinate $\vec{\rho}$ and thus this term will integrate to zero unless the triton wave function depends on the angular coordinates of $\vec{\rho}$.[12] Thus one expects that the contribution from the deuteron D state will be small. From the triton D-state wave functions[4] one can obtain terms proportional to either $Y_2^m(\hat{\rho})$ or $Y_2^m(\hat{r})$. In this latter case the spherical harmonic can be taken outside the integral and one directly obtains an $L=2$ term in the overlap. Thus the D-state term in Eq. (2) arises primarily from the triton configuration in which the transferred neutron has $L=2$ relative to the remaining nucleons.

To obtain a numerical estimate of D_2 we make use of the deuteron wave function of Reid,[13] and for the dominant triton S state we adopt the wave function of Jackson, Lande, and Sauer.[14] For the triton D state we use a wave function obtained from first-order perturbation theory, since the inclusion of a complete D state would be quite laborious. In momentum space this wave function is given by[15]

$$\langle \vec{\mathfrak{p}},\vec{\mathfrak{q}}|D\rangle = N(B_t - \hbar^2p^2/M - 3\hbar^2q^2/4M)^{-1} \times \langle \vec{\mathfrak{p}},\vec{\mathfrak{q}}|V_T^{13}+V_T^{23}+V_T^{12}|S\rangle, \quad (4)$$

where $\vec{\mathfrak{p}}$ and $\vec{\mathfrak{q}}$ are the momenta conjugate to $\vec{\rho}$ and $\vec{r}$ respectively. Here B_t is the triton binding energy, V_T^{ij} is the tensor potential between nucleons i and j (the Reid soft-core potential), and N is a normalization constant which is adjusted to reproduce the desired D-state probability. This approximate D-state wave function predicts a charge form factor for ^{3}He which is in good agreement[16] with results obtained from the exact D-state wave function of Ref. 14.

The major contribution to the $L=2$ term in Eq. (2) arises from the overlap integral involving the deuteron S state and the triton D state. In Eq. (4), the tensor force between the pairs 13 and 23 gives rise to a triton D state in the coordinate $\vec{r}$ (we take particle 3 to be the transferred neutron), which in turn produces a substantial $L=2$ term in the overlap. The contributions which arise from V_T^{12} and from the overlap integral involving the deuteron D state and the triton S state are small and have been neglected in our calculation. A complete description of the calculation will be published elsewhere.[17]

Since the triton D-state wave function depends on the normalization constant N, our final result for D_2 is a function of the triton D-state probability P_D. We obtain

$$D_2 = -0.648[P_D/(1-P_D)]^{1/2}\ \mathrm{fm}^2. \quad (5)$$

For $P_D = 8.8\%$ (as predicted from a complete solution of the Faddeev equations[18]), Eq. (5) gives $D_2 = -0.20$ fm^2. In view of the approximations used in calculating D_2 and the uncertainties involved in extracting D_2 from the measured tensor analyzing powers, the agreement between the calculated value and the experimental value (-0.24 fm^2) is as good as one would expect to obtain.

The fact that the tensor analyzing powers have opposite signs for (d,p) and (d,t) reactions is easily understood. In the deuteron the nucleon spin vectors $\vec{\sigma}_1$ and $\vec{\sigma}_2$ are parallel, and as a result the tensor force is attractive when $\vec{\rho}$ is parallel or antiparallel to $\vec{\sigma}_i$.[19] Thus the effect of the tensor potential is to increase the magnitude of the deuteron wave function when $\vec{\rho}$ is parallel to $\vec{\sigma}_i$ and to decrease the wave function when $\vec{\rho}$ and $\vec{\sigma}_i$ are perpendicular. For a deuteron in the $m=1$ state we write[19]

$$\langle \chi_{1/2}^{1/2}(p)\chi_{1/2}^{1/2}(n)|\varphi_d^{\,1}(\vec{\mathfrak{p}})\rangle = \frac{u(\rho)}{\rho}Y_0^0(\hat{\rho}) + \left(\frac{1}{10}\right)^{1/2}\frac{w(\rho)}{\rho}Y_2^0(\hat{\rho}). \quad (6)$$

From this expression one can see that the radial wave functions u and w must have the same sign, and it follows that D_2 for (d,p) reactions must be positive. We now consider the (d,t) reaction. In this case, for an $m=1$ deuteron we have from Eq. (2)

$$\langle \chi_{1/2}^{-1/2}\varphi_d^{1}|\varphi_t^{1/2}\rangle = (\tfrac{2}{3})^{1/2}[u_0(r)Y_0^{0}(\hat{r}) + (\tfrac{1}{10})^{1/2}u_2(r)\,Y_2^{0}(\hat{r})]. \qquad (7)$$

As we have seen, the $L=2$ term in Eq. (7) arises primarily from the tensor forces between the pairs 13 and 23. Since $\vec{\sigma}_3$ is antiparallel to $\vec{\sigma}_1$ and $\vec{\sigma}_2$ in configuration (7), the relevant tensor potentials are repulsive when $\vec{r}$ is parallel or antiparallel to $\vec{\sigma}_i$. Thus it turns out that u_0 and u_2 have opposite signs, and D_2 must be negative for (d,t) reactions.

The results reported in this note show that tensor analyzing-power measurements for (d,t) reactions are sensitive to the D-state components in the triton wave function. However, at this point it is not clear whether the measurements can be used to obtain quantitative information about the D-state wave function which is not available from other sources. Further experiments and more refined theoretical calculations will be required to elucidate this point.

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