^{3}He D-state effects in the ^{1}H($\vec{d},\gamma$)^{3}He reaction

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The tensor analyzing powers of the ^{1}H($\vec{d},\gamma$)^{3}He reaction initiated by a polarized beam are studied using the Sasakawa wave function for the three-body bound state and neglecting initial state interactions. Good agreement is obtained with recent A_{yy} data taken at $E_\gamma = 14.66$ MeV. It is shown that at low energy the tensor analyzing powers are sensitive to the asymptotic region of the bound state wave function and can be used to determine the asymptotic D/S state ratio, η, in ^{3}He.

The radiative proton-deuteron capture and its inverse, photodisintegration of ^{3}He, have been studied in some detail both experimentally and theoretically. The cross section experimental data have been compiled in recent reviews by Tomusiak[1] and by Berman.[2] Skopik, Weller, Roberson, and Wender[3] have measured the angular distribution of the vector analyzing power iT_{11} over the energy region of $E_\gamma = 7$–15 MeV using a polarized proton beam and obtained values close to zero showing that the reaction proceeds mainly through $E1$ and $E2$ transitions. More recently, Baumgartner *et al.*[4] have measured A_{yy} at 14.66 MeV using a tensor polarized deuteron beam.

Recent theoretical work on the radiative p-d capture and its inverse has focused on the problem of determining the importance of contributions to the cross section from the D-state components in the bound-state wave functions. Using plane wave continuum states and model wave functions for ^{3}He, Gibson and O'Connell[5] have shown that in the low-energy region $E_\gamma \leq 35$ MeV the cross section should not be very sensitive to D-state effects. Aufleger and Drechsel[6] investigated the process using more realistic bound-state wave functions generated with the Reid soft-core potential and confirmed that the D-state effects in the cross section are small. They found that at the peak of the $\theta = 90°$ photodisintegration cross section the S-D interference terms increase the cross section from 60 to 70 μb/sr without, however, changing its shape. More recently King, Roberson, Weller, and Tilley[7] have shown that the a_2 parameter in a Legendre polynomial expansion of the cross section angular distributions at $9.82 \leq E_\gamma \leq 16.16$ MeV indicates a sensitivity to the D state of ^{3}He.

In this paper we consider the D-state effects on the vector and tensor analyzing powers of the radiative capture reaction. The main motivation for this study is to determine the sensitivity of the polarization observables at low energy to the D-state components of the ^{3}He wave function and, in particular, to the asymptotic D/S state ratio η of ^{3}He. This quantity is an important parameter of the three-nucleon bound system which, to a good approximation, is related to the D_2 parameter[8] by $D_2 = \eta/\alpha^2$, where α is the wave number corresponding to the deuteron separation energy from ^{3}He. η has only been estimated through the determination of D_2 from measurements of the tensor analyzing powers in ($\vec{d}$,^{3}He) reactions.[9] However, D_2 for ^{3}He is presently not a very well determined quantity with values ranging from -0.37 to -0.22 fm^2.[10]

We describe the $p+d \leftrightarrow {}^3\mathrm{He}+\gamma$ process in terms of a first order electromagnetic transition with the interaction Hamiltonian

$$H = -\sum_{i=1}^{3}\left(\frac{e_i}{mc}\vec{A}(\vec{r}_i)\cdot\vec{p}_i + \vec{\mu}_i\cdot\nabla\times\vec{A}(\vec{r}_i)\right) , \qquad (1)$$

where $\vec{A}$ is the vector potential. The transition amplitude for the radiative capture is then

$$H_{fi} = \langle \psi_{^3\mathrm{He}};\vec{k}n | H | \psi_{\mathrm{pd}};0\rangle . \qquad (2)$$

The initial state $|\psi_{\mathrm{pd}};0\rangle$ represents the proton-deuteron scattering state and the vacuum for the photon field. The final state $|\psi_{^3\mathrm{He}};\vec{k}n\rangle$ consists of the three-nucleon bound state $\psi_{^3\mathrm{He}}$ and a photon with momentum $\vec{k}$ and polarization described by the polarization vector $\vec{\epsilon}_n$.

Upon introducing the usual plane-wave expansion of the vector potential we obtain in the coordinate space representation

$$H_{fi} = -2\pi i\delta(E_f - E_i + E_\gamma)\frac{ie\hbar}{m}\left(\frac{\hbar}{\omega V}\right)^{1/2}\int d\vec{r}_1\, d\vec{r}_2\, d\vec{r}_3\, \psi^*_{^3\mathrm{He}}(\vec{r}_1,\vec{r}_2,\vec{r}_3)$$
$$\times\sum_{j=1}^{3} e^{-i\vec{k}\cdot\vec{r}_j}(e_j\vec{\epsilon}^{\,*}_n\nabla_j + \tfrac{1}{2}\mu_j\vec{k}\times\vec{\epsilon}^{\,*}_n\cdot\vec{\sigma}_j)\psi_{\mathrm{pd}}(\vec{r}_1,\vec{r}_2,\vec{r}_3) , \qquad (3)$$

where V is the quantization volume and

$$e_j = \tfrac{1}{2}[1+\tau_z(j)] ,$$
$$\mu_j = \tfrac{1}{2}(\mu_p+\mu_n) + \tfrac{1}{2}(\mu_p-\mu_n)\tau_z(j) , \qquad (4)$$

where μ_p (μ_n) is the proton (neutron) magnetic moment and $\tau_z(j)$ is the z component of the isospin operator for the jth nucleon.

As in Ref. 11 we have neglected initial state interactions between the proton and the deuteron. It is difficult to predict the effect of final state interactions on the T_{2q}. However, we note that these effects in the unpolarized cross section are larger[11,12] (of the order of 20% to 25%) for photon energies near the peak at about $E_\gamma = 11$ MeV. The initial state wave function with deuteron and proton spin projections m_d and m_p is given by

$$\langle \vec{\xi}\vec{\rho}|\psi_{pd}\rangle = \sqrt{2}e^{i\vec{p}\cdot\vec{\rho}}\psi_d^{m_d}(\vec{\xi})\chi_p^{m_p} \tag{5}$$

in the familiar Jacobi coordinates

$$\vec{\xi}=\vec{r}_1-\vec{r}_2;\ \ \vec{\rho}=\tfrac{1}{2}(\vec{r}_1+\vec{r}_2)-\vec{r}_3\ . \tag{6}$$

A totally antisymmetrized wave function for the final state and a symmetrical transition operator for the single particle currents are used. The factor $\sqrt{2}$ in Eq. (5) results from antisymmetrization between the single proton and the proton in the deuteron. In the multipole operators it is assumed[5] that the position vectors of the nucleons in the deuteron are proportional to $\vec{\rho}$. With this approximation we take into account the contributions from the main components of the ^{3}He and deuteron internal wave functions.

By decomposing the operator in Eq. (3) into electric and magnetic multipole operators we obtain the following expressions for the EL transitions:

$$(EL)_{fi}=-i\left[\frac{L+1}{L}\right]^{1/2}\frac{mk^{L-1}\omega}{(2L+1)!!}\times\sum_{j=1,2}\int e^{i\vec{p}\cdot\vec{\rho}}(C_j\rho)^L Y_{LM}^*(\vec{\rho})\langle\psi_{^3\mathrm{He}}|\psi_d\chi_p\rangle\,d\vec{\rho}\ , \tag{7}$$

where $C_1=\frac{1}{3}$ and $C_2=-\frac{2}{3}$. Equation (7) shows that the EL matrix elements are essentially determined by the overlap integral $\langle ^3\mathrm{He}|\mathrm{dp}\rangle$. It is well known[8] that this overlap is the superposition of an S and a D state. The D-state part has a contribution of the order of 90% from the ^{3}He D state.[13] To calculate $\langle ^3\mathrm{He}|\mathrm{dp}\rangle$ we have used the ^{3}H wave function of Sasakawa[14] generated from the Reid soft-core potential using Faddeev equations. Although this wave function is for ^{3}H rather than ^{3}He it is known that the Coulomb interaction has a very small effect on the bound state wave function changing only the binding energy.[10] For the deuteron we used the Reid soft-core wave function.[15] The $M1$ transitions are expected to be small except at forward and backward angles[6] and therefore were not taken into account. The contributions from mesonic degrees of freedom were not included in the present calculations. However, according to Siegert's theorem, such contributions to the electric multipole moments are small at low energies.

Calculations, including the $E1$ and $E2$ transitions, were performed for the angular distributions of the cross section and analyzing powers iT_{11}, T_{20}, T_{21}, and T_{22} for an energy range of $6\leq E_\gamma\leq 26$ MeV. We find that the effect of the D state of the $\langle ^3\mathrm{He}|\mathrm{dp}\rangle$ overlap in the cross section is very small, of the order of 1%. In our model iT_{11} is identically zero. However, the tensor analyzing powers T_{2q} become nonvanishing when the D-state part of the overlap is included. The T_{2q} are essentially a manifestation of the interference between the overlap S and D states and at low energy they are very sensitive to the asymptotic part of the wave functions.

The full curve in Fig. 1 shows the results of calculations for

$$A_{yy}=-\sqrt{3}\left[T_{22}+\frac{1}{\sqrt{6}}T_{20}\right]$$

at $E_\gamma=14.66$ MeV. Good agreement is obtained with the data of Ref. 4. The nearly flat angular distribution around $\theta=90°$ in Fig. 1 can be understood as a characteristic signature of D-state effects in A_{yy}.[16] The angular distribution of T_{21}, shown in Fig. 2, is quite different from that of A_{yy} with two distinct peaks in the forward and backward hemispheres. The contributions from $E1$ and $E2$ transitions to T_{21} tend to interfere destructively for $\theta<90°$ and constructively for $\theta>90°$. T_{22} is very small, of the order of 0.001, in the present range of energies.

To determine the sensitivity of the tensor analyzing powers to the asymptotic region we represent the $\langle ^3\mathrm{He}|\mathrm{pd}\rangle$ overlap by an asymptotic wave function with radial part $N_L h_L(i\alpha\rho)$, where $L=0,2$. The tensor analyzing powers calculated with the same asymptotic D/S state ratio $\eta=N_2/N_0$ as for the Sasakawa wave function, and represented by broken curves in Figs. 1 and 2, show that at low energies the reaction is mainly determined by the tail of the wave functions. Since the dominant contribution arises from the interference between the S and D states the T_{2q}

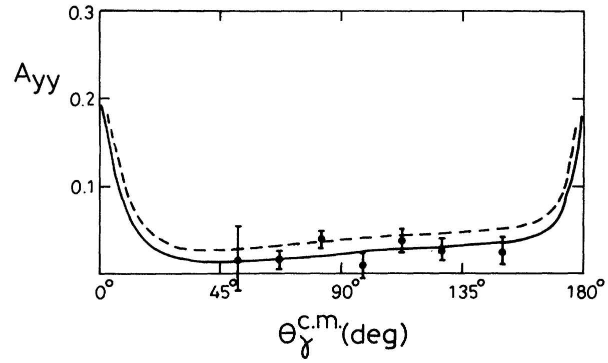

FIG. 1. The full and broken lines represent A_{yy} angular distributions for the $^1\mathrm{H}(\vec{d},\gamma)^3\mathrm{He}$ reaction at $E_\gamma=14.66$ MeV calculated using, respectively, the Sasakawa wave function and the asymptotic approximation with the same $\eta=-0.029$. The data points are from Ref. 4.

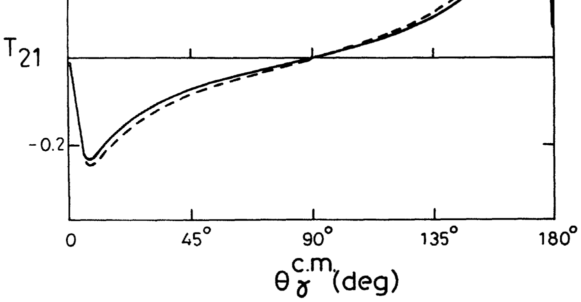

FIG. 2. The full and broken lines represent T_{21} angular distributions and have the same meaning as in Fig. 1.

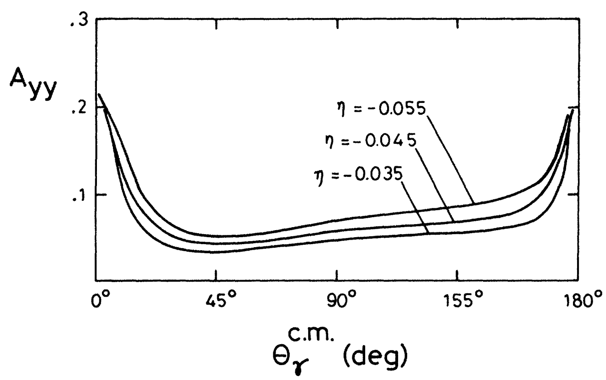

FIG. 3. The three curves represent A_{yy} angular distributions for the same reaction and energy as in Fig. 1, calculated using the asymptotic approximation with different values of η.

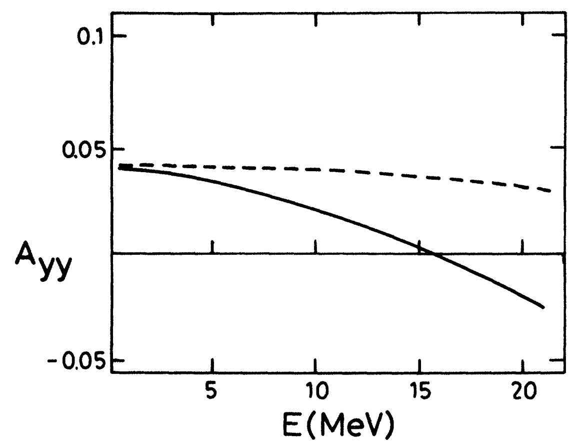

FIG. 4. The full and broken lines represent A_{yy}, at $\theta_\gamma^{c.m.}=90°$, as a function of the deuteron incident energy in the center of mass system and have the same meaning as in Fig. 1.

have an almost linear dependence on η. This is shown in Fig. 3 where A_{yy} was calculated using different values of η.

Figure 4 shows the dependence on energy of A_{yy} at $\theta_\gamma = 90°$. The separation between the two curves with increasing energy results from the importance of the contributions from small distances at the higher energies.

In conclusion, we have shown that the tensor analyzing powers of the ^{1}H($\vec{d}$,γ)^{2}He are very sensitive to the D-state component of the ^{3}He bound state wave function and, in particular, to the η parameter. Furthermore, the good agreement with the data of Ref. 4 indicates, then, that the reaction can be used to determine η in ^{3}He. The present calculations show that measurements of T_{21} would be more appropriate than measurements of A_{yy} for a determination of η, since it has larger D-state effects. To estimate the accuracy of this determination a complete three-body calculation for the bound and scattering states including initial state interactions is in progress.

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