Vector analyzing powers of ^{1}H(d, γ) and ^{2}H(p, γ) reactions at $E_x = 6$ MeV

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(Received 15 June 1984)

The vector analyzing powers have been measured for the $^1\text{H}(\vec{d},\gamma)^3\text{He}$ and the $^2\text{H}(\vec{p},\gamma)^3\text{He}$ reactions at $E_x = 6$ MeV. The results indicate the presence of channel spin $\frac{3}{2}$ capture strength. An $M1$ strength amounting to between 1 and 8% of the cross section is able to explain the observations if a significant $s = \frac{3}{2}$ component is included.

The photodisintegration of ^{3}He has been studied previously in the energy region just above threshold as a function of energy and angle via both capture and photonuclear reaction measurements.[1–3] Polarized capture (or the inverse) reaction measurements have, however, only been studied at higher energies. Skopik, Weller, Roberson, and Wender[4] have measured the angular distribution of the vector analyzing power over the energy region of $E_\gamma = 7$–15 MeV using a polarized proton beam.

The mixed-symmetry S'-state and the D-state admixtures in the ground state of ^{3}H are of great importance in the thermal ($M1$) n-d capture problem. Meson-exchange corrections have been shown to be essential in order to calculate the thermal n-d capture cross section.[5] Since $M1$ strength at threshold is so sensitive to meson-exchange effects and the details of the three-body wave function, $M1$ strength above threshold should also reflect details of these quantities. The cross section just above threshold is expected to be governed by a mixture of $M1$ and $E1$ radiation. Therefore, the analyzing powers of the n-d capture reaction, which arise from interference efects, should be sensitive to the presence of these two radiatons. Similar effects are expected in ^{3}He as observed in the p-d capture channel. The present paper is a report of analyzing-power measurements for both proton capture on deuterons and deuteron capture on protons at an excitation energy of 6 MeV in ^{3}He, just 0.5 MeV above threshold. The sensitivity of these results to the presence of channel spin $\frac{3}{2}$ capture strength will be described. A model calculation will be employed to estimate the $s = \frac{3}{2}$ $M1$ strength necessary to account for the data.

The $^2\text{H}(\vec{p},\gamma)^3\text{He}$ reaction was measured at the University of Giessen at a proton center-of-target energy of 0.77 MeV. Analyzing powers were obtained at 10 angles over the range of 35° to 150° with a mean statistical error of about 10%. The target consisted of a 200 Torr gas cell which was 43 mm long. The entrance foil was a 0.5 μm thick Ni foil. The energy loss was 80 keV in the foil and another 80 keV in the gas. Gamma rays were measured with four 100 cm^3 GeLi detectors, two 15.2×15.2 cm, and one 7.6×7.6 cm NaI detector.

The differential cross section for the $^2\text{H}(\vec{p},\gamma)^3\text{He}$ reaction can be written as[7]

$$\sigma_{\text{p}}(\theta) = \sigma_{\text{p}u}(\theta)[1 + PA_{\text{p}}(\theta)] \ . \tag{1}$$

The unpolarized cross section $\sigma_{\text{p}u}(\theta)$ can be expanded in terms of Legendre polynomials:

$$\sigma_{\text{p}u}(\theta) = A_0\left[1 + \sum_k a_k P_k(\cos\theta)\right] \ . \tag{2}$$

The analyzing powers of the $^2\text{H}(\vec{p},\gamma)^3\text{He}$ reaction were obtained from

$$A_{\text{p}}(\theta) = \frac{1}{P}\left[\frac{N_+ Q_0}{N_0 Q_+} - 1\right] \ , \tag{3}$$

where $N_+(N_0)$ represents the number of counts obtained in the polarization "on" ("off") configuration, $Q_+(Q_0)$ are the corresponding integrated target currents, and P is the beam polarization. The beam polarization of the Lamb-shift source was switched (60 Hz) between "on" and "off" in order to avoid instrumental asymmetries. The product of the cross section times the analyzing powers was expanded in terms of associated Legendre polynomials using

$$A_{\text{p}}(\theta)\sigma_{\text{p}u}(\theta) = A_0\left[\sum_{k=1} b_k P_k^1(\theta)\right] \ . \tag{4}$$

The $^1\text{H}(\vec{d},\gamma)^3\text{He}$ reaction was studied at TUNL (Triangle Universities Nuclear Laboratory) at a center-of-target energy of 1.62 MeV. A gas cell having a radius of 10.2 cm was used as the target with the detectors[4,6] collimated so as to see only a region of the cell approximately 1.9 cm long when the detectors were at 90°. This geometry was necessary in order to reduce the backgrounds generated from the interaction of the deuteron beam with the entrance and exit foils. The gas cell was maintained at a pressure of 83.1 kPa.

Ultrahigh purity hydrogen was flowed through the cell at 6 cm^3/sec to maintain a clean gas sample. This arrangement produced an energy spread slightly less than 200 keV for the events observed at the extreme angles where the target thickness is the greatest. The γ-ray detectors consisted of two 25.4×25.4 cm NaI spectrometers which have been described elsewhere.[6] Analyzing powers were obtained at five angles between 50° and 135° by switching the vector polarization of the deuteron beam between spin-up and spin-down configurations, with the two detectors placed at symmetric angles on the left (L) and right (R) sides of the beam direction. The vector analyzing powers were then computed from

$$A_d(\theta)=\frac{2}{3}\frac{1}{P}\frac{r-1}{r+1} \ , \tag{5}$$

where

$$r^2=L_+R_-/L_-R_+ \ . \tag{6}$$

The quantities $L_+(L_-)$ represent the number of counts in the left detector for spin-up (down) measurements and $R_+(R_-)$ the same for the right detector. The quantity P is the beam polarization. This equation eliminates the need for normalizations resulting from differences in the detector efficiencies as well as normalizations between runs.

In the case of the $^1H(\vec{d},\gamma)^3He$ reaction, the cross section for a reaction initiated by vector polarized particles can be written as[7]

$$\sigma_d(\theta)=\sigma_{du}(\theta)[1+\tfrac{3}{2}PA_d(\theta)] \ . \tag{7}$$

In this case we make the same expansion of the unpolarized cross section

$$\sigma_{du}(\theta)=A_0\left[1+\sum_k a_kP_k(\cos\theta)\right] \ , \tag{8}$$

while the product of the unpolarized cross section and the analyzing power $A_d(\theta)$ is expanded in terms of associated Legendre polynomials

$$\tfrac{3}{2}A_d(\theta)\sigma_{du}(\theta)=A_0\left[\sum_{k=1} b_kP_k^1(\theta)\right] \ . \tag{9}$$

The unpolarized cross-section data used in the present analysis of both the $^1H(\vec{d},\gamma)^3He$ and $^2H(\vec{p},\gamma)^3He$ data were obtained using the $^1H(d,\gamma)^3He$ reaction at $E_d=1.62$ MeV. These data were fitted by an expansion in terms of Legendre polynominals following Eq. (8). However, since previous work had more accurately evaluated the isotropic component[8] (assuming no fore-aft asymmetry), and the fore-aft asymmetry[9] in this cross section, the expansion through $P_3(\cos\theta)$ was performed subject to the two constraints

$$-(1+\tfrac{3}{2}b)a_2-(1+\tfrac{5}{8}b)a_4=1.0 \ ,$$

with $b=0.029\pm0.005$, as obtained by interpolating the results of Table I of Ref. 8, and

$$a_1-0.67a_3=0.09\pm0.01$$

obtained from the curve of Ref. 9 (Fig. 2), which extrapolates the data of Ref. 9 to the present energy. The angular distribution data and the fit obtained using this procedure are shown in Fig. 1(a) as a function of $\theta_{c.m.}(p,\gamma)$. The a_k parameters obtained from this fit are presented in Table I.

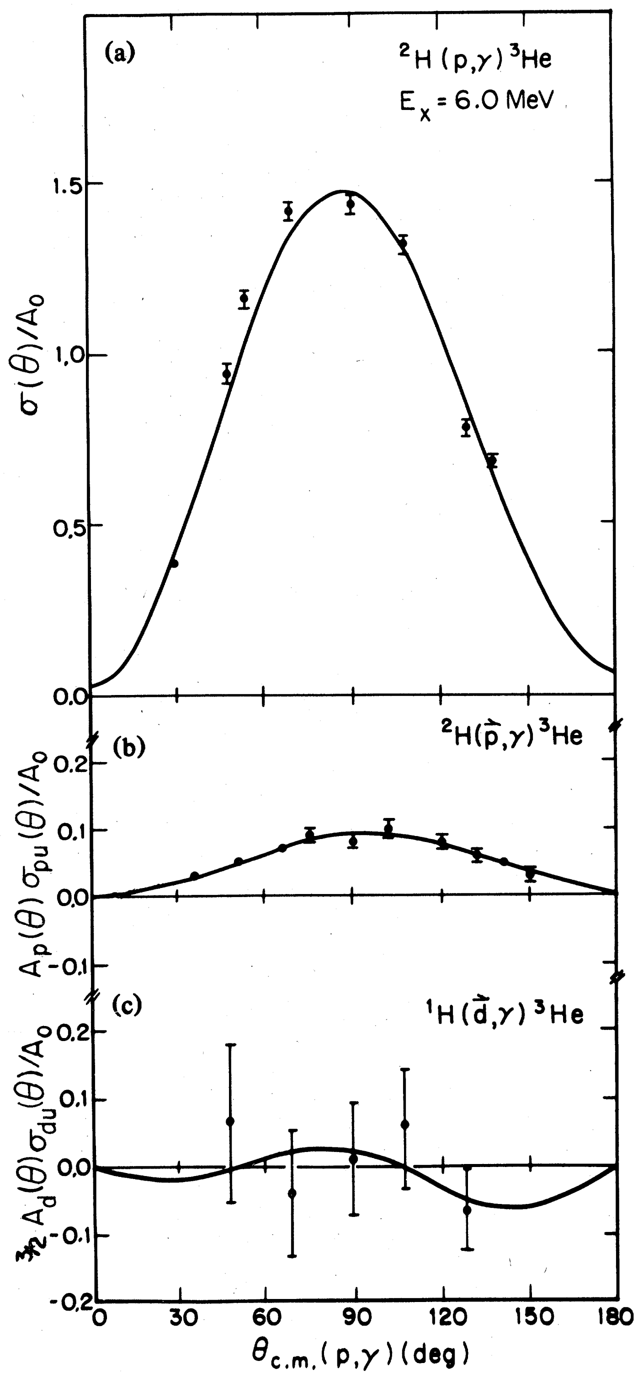

FIG. 1. Cross sections and analyzing powers for the $^2H(\vec{p},\gamma)^3He$ reaction at $E_x=6.0$ MeV. (a) Cross section data from $^1H(d,\gamma)^3He$ measurements. (b) Analyzing powers times cross sections for $^1H(\vec{p},\gamma)^3He$. (c) Same as (b) but for $^1H(\vec{d},\gamma)^3He$. Error bars represent statistical uncertainties only. The solid lines are the result of polynomial fits to the data (see text). Note that the (p,γ) angles have been used in all cases.

The product function $A_d(\theta)\sigma_{du}(\theta)$ was generated from the measured $A_d(\theta)$ and $\sigma_{du}(\theta)$ for the d-on-p case. Equation (9) was then used to fit these data by expanding them in terms of associated Legendre polynomials. The resulting fit is shown in Fig. 1(c); the b_k coefficients are presented in

TABLE I. Expansion coefficients for the ^{1}H(d, γ) and ^{2}H(p, γ) reaction at $E_x = 6.0$ MeV.

(a) Angular distribution (using p-on-d angles)	
	$a_1 = +0.04 \pm 0.02$
	$a_2 = -0.96 \pm 0.02$
	$a_3 = -0.07 \pm 0.02$
(b) ^{2}H($\vec{\mathrm{p}}$, γ)^{3}He analyzing powers	
	$b_1 = +0.08 \pm 0.007$
	$b_2 = -0.005 \pm 0.006$
	$b_3 = -0.006 \pm 0.006$
	$b_4 = -0.001 \pm 0.006$
(c) ^{1}H($\vec{\mathrm{d}}$, γ)^{3}He analyzing powers (using p-on-d angles)	
	$b_1 = -0.006 \pm 0.045$
	$b_2 = +0.018 \pm 0.036$
	$b_3 = -0.018 \pm 0.036$

Table I. In the case of the p-on-d data, the angular distribution coefficients of the $\sigma_{du}(\theta)$ data were used to construct the product function $A_p(\theta)\sigma_{pu}(\theta)$ using $\sigma_{pu}(\theta) = \sigma_{du}(180° - \theta)$. In terms of the a_k coefficients, this transformation is equivalent to changing the signs of a_1 and a_3. The resulting product function $A_p(\theta)\sigma_{pu}(\theta)$ for the p-on-d case is shown in Fig. 1(b) along with the fit obtained using Eq. (4). For the b_k coefficients, the angle transformation given above is equivalent to changing the signs of b_2 and b_4 when going from d-on-p to p-on-d angles. All data shown and all coefficients reported are for the same (p-on-d) angle variable.

A comparison of the b_k coefficients obtained in the ^{2}H($\vec{\mathrm{p}}$, γ)^{3}He reaction with those obtained in the ^{1}H($\vec{\mathrm{d}}$, γ)^{3}He reaction is particularly sensitive to the presence of $s = 3/2$ terms, where s is the channel spin for the capture reaction ($\frac{1}{2}$ or $\frac{3}{2}$). Following Eq. (21) of Ref. 7, the ratio of the b_k coefficients for the ^{1}H(d, γ)^{3}He reaction to those for the ^{2}H(p,γ)^{3}He reaction for a particular choice of s and s' is

$$\frac{b_k(\mathrm{d},\gamma)}{b_k(\mathrm{p},\gamma)} = -\frac{3}{2}\frac{W[1s1s';(1/2)1]}{W[(1/2)s(1/2)s';11]} .$$

This ratio can be explicitly evaluated for the three possible types of terms which can appear in Eq. (21) of Ref. 7.

(1) $s = s' = \frac{1}{2}$ (pure doublet terms),

$$\frac{b_k(\mathrm{d},\gamma)}{b_k(\mathrm{p},\gamma)} = -3.0 .$$

(2) $s = \frac{1}{2}$, $s' = \frac{3}{2}$; or $s = \frac{3}{2}$, $s' = \frac{1}{2}$ (doublet-quartet terms),

$$\frac{b_k(\mathrm{d},\gamma)}{b_k(\mathrm{p},\gamma)} = \frac{3}{4} .$$

(3) $s = s' = \frac{3}{2}$ (quartet-quartet terms),

$$\frac{b_k(\mathrm{d},\gamma)}{b_k(\mathrm{p},\gamma)} = \frac{3}{2} .$$

Hence, if the reaction proceeds via pure $s = \frac{1}{2}$ terms, then the b_k's obtained in the d-on-p experiment should be a factor of -3.0 times the b_k's obtained in the p-on-d experiment. Any $s = \frac{3}{2}$ contribution would cause this ratio to deviate from the factor of -3.0. The measurement of both sets of b_k's is therefore a sensitive means for investigating the presence of $s = \frac{3}{2}$ strength in these reactions.

Since the b_k's for the p-on-d case were obtained from Eq. (4) and those for the d-on-p case from Eq. (9), we see that

$$\frac{(3/2)A_d(\theta)}{A_p(\theta)} = \left[\sum b_k(\mathrm{d},\gamma)P_k^1(\theta)\right] \Big/ \left[\sum b_k(\mathrm{p},\gamma)P_k^1(\theta)\right] ,$$

where θ is the same angle variable throughout. So, for example, for $s = s' = \frac{1}{2}$,

$$\frac{A_d(\theta)}{A_p(\theta)} = -2 .$$

Figure 2 shows the measured analyzing powers from both reactions plotted as a function of the proton center-of-mass angle. The analyzing power expected in the (d, γ) case obtained from the previously described fits to the (p, γ) data (the a_k and b_k of Table I) and the relation above ($s = s' = \frac{1}{2}$) is also shown.

The data represented in Fig. 2 and Table I establish the presence of $s = \frac{3}{2}$ strength in the two-body photodisintegration of ^{3}He at $E_x = 6.0$ MeV. Furthermore, since the b_1 coefficient (see Table I) observed in the p-on-d data is nonzero, the presence of non-$E1$ radiation is also established by these data. The two most likely candidates for this radiation are $E2$ and $M1$.

In order to investigate the presence of this non-$E1$ strength, we can attempt to analyze the data in terms of the amplitudes and phases of the contributing T-matrix elements. If we consider only $E1$, $E2$, and $M1$ transition matrix elements, there are 16 real amplitudes and 15 relative phases in this problem. This number of unknowns prohibits a model independent analysis. It was therefore necessary to employ the results of the model calculation described in Ref. 10. In this model the ground state wave function of ^{3}He is generated from Faddeev-type equations using separable interactions, while the continuum wave function was

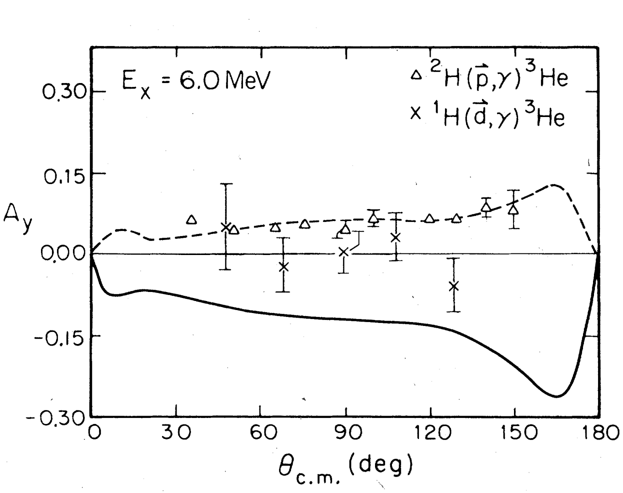

FIG. 2. The analyzing powers measured in the ^{2}H($\vec{\mathrm{p}}$, γ)^{3}He and the ^{1}H($\vec{\mathrm{d}}$, γ)^{3}He reactions. The dotted curve is the result of the fit to the ^{2}H(p, γ) data (see Fig. 1). The solid curve is the predicted ^{1}H($\vec{\mathrm{d}}$, γ)^{3}He result based on the observed ^{2}H($\vec{\mathrm{p}}$, γ)^{3}He data with the assumption of $s = \frac{1}{2}$ terms only.

generated from an optical-model potential which describes the elastic scattering of protons from deuterons. This model, which includes the D-state component in the ground state of ^{3}He, has successfully described the a_2 coefficients observed in the ^{2}H$(p,\gamma)^3$He reaction for proton energies between 6.5 and 16 MeV. It was used in the present case to compute the $E1$ and $E2$ amplitudes and phases at $E_x=6$ MeV. The $E1+E2$ model predicted a b_1 coefficient which was essentially equal to zero at this energy. It was found, however, that a satisfactory fit (90% confidence limit) to the present data could be obtained by adding as little as 1% (and less than 8%) $M1$ strength to the $E1+E2$ model result. The minimum $M1$ strength was found to be predominantly $s=\frac{3}{2}$ type strength. This analysis indicates the sensitivity of the present *polarized* capture measurements to the presence of small $s=\frac{3}{2}$ admixtures.

The results shown in Fig. 4 of Ref. 11 indicate that the calculated $M1$ strength near $E_x=6$ MeV accounts for about 2.3% of the cross section. This calculated $M1$ strength is "dominated by the $s=\frac{1}{2}$ contribution" and therefore is probably unable to account for the present result. However, more recent calculations which include D-state and meson exchange current corrections obtain a significant $s=\frac{3}{2}$ $M1$ strength at threshold.[12] A full three-body calculation which computes the observables of the present experimental work is needed to properly evaluate these results.

This work was partially supported by the U.S. Department of Energy under Contract No. DE-AC05-76ER01067.

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