Effects of the ^{3}He D State in the Reaction ^{2}H(p, γ)^{3}He

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Angular distributions of the reaction ^{2}H(p,γ)^{3}He have been measured for E_p from 6.5 to 16 MeV. A comparison of the extracted a_2 coefficients with an effective two-body direct calculation indicates a sensitivity to the inclusion of D-state components in the ^{3}He wave function. These calculations use ^{3}He bound-state wave functions generated from Faddeev-type equations. The theoretical three-body ^{3}He ground-state wave functions having D-state probabilities of 5%–9% ($D_2 = -0.224$ to -0.236) are consistent with the present data.

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One of the goals of the investigations of photodisintegration of ^{3}He and its inverse reaction (p-d capture) is to test theoretical calculations of the ^{3}He wave function. Since the electromagnetic operators are, in principle, known, the photonuclear reaction should provide a means for this test. Of particular interest are the D-state components of the ^{3}He wave function. Recent tensor-polarized ($d_{\rm pol}$, ^{3}He) and ($d_{\rm pol}$, t) experiments[1] have extracted the parameter D_2 which is approximately proportional to the ratio of the asymptotic normalization constants of the D and S state wave functions,[2,3]

A problem with studying D-state effects in ^{3}He is that the D-state probability, P_D(^{3}He), cannot be measured directly but depends upon the dynamical model chosen.[4] Although different models will give a range of results, the experimental information can be interpreted within a given dynamical framework. This Letter reports the energy dependence of the a_2 coefficient extracted from a Legendre-polynomial expansion of the angular distribution and comparison with effective two-body direct radiative-capture calculations. The results indicate that, contrary to previous claims,[5–7] precision a_2 values measured as a function of energy are sensitive to the D-state component of the ^{3}He wave function.

The Triangle Universities Nuclear Laboratory tandem Van de Graaff accelerator was used to measure angular distributions in the reaction ^{2}H(p, γ)^{3}He for 11 to 13 angles from 30° to 150° at the proton energies 6.5, 8.0, 11.0, 15.0, and 16.0 MeV. A gas-target system gave an order of magnitude increase in count rate and substantially reduced the background in the γ-ray spectra compared to previous solid-CH_2-target studies.[8] It also enabled measurements over a much larger energy range than was possible with the solid targets. The gas target consisted of a 23-cm-long, 15-cm-diam thin-walled brass target chamber filled with 34.4 to 83.1 kPa of high-purity (>99.99%) deuterium gas. The gas-cell entrance foil was an 0.6-μm-thick nickel foil mounted over a 0.317-cm aperture in a tantalum collimator, and the exit foil was a 2.5-μm-thick, 1.3-cm-diam Havar foil. All parts of the setup exposed to the beam were lined with tantalum to reduce background γ rays. The target was defined by sets of tungsten and lead collimators. As a result, the target thickness varied as a function of detector angle. A typical target thickness was 255 μg/cm^2 at 90°. The angular distribution data were corrected by means of a Monte Carlo calculation which included the effects of the finite beam size and position, gas-cell length, detector size, and collimator geometry, as well as the attenuation of γ rays in the collimator edges. The correction factors obtained with this calculation were found to be within a few percent of the first-order approximation of $1/\sin(\theta)$ for all energies and angles.

The γ rays were detected with two 25.4- by 25.4-cm cylindrical NaI spectrometers as described previously by Weller and Roberson.[9] In order to reduce the neutron-induced and cosmic-ray backgrounds, the proton beam was pulsed at 2 MHz. Time-of-flight spectra were used to accept only the events corresponding to prompt γ rays. Background spectra were measured by plugging the NaI detector collimators with 15 cm of lead. This background (a ~5% effect) included target-related neutron-induced background. The background-corrected spectra were fitted with our standard γ-ray response function.[9] A solid-state detector was employed as a monitor utilizing the reaction $^2H(p,p)$. The data were normalized to both the beam current integration and the monitor sums; the two results agreed to within ±2%.

The center-of-mass and finite-geometry-corrected data were fitted with the Legendre-polynomial expansion

$$\sigma(\theta) = A_0 \left[1 + \sum_{k=1}^{4} a_k P_k(\cos\theta)\right],$$

where $k > 4$ was not statistically justified. The large difference in the a_2 coefficient for capture to the S and D components of the bound-state wave function was expected to provide a sensitive test for observing D-state effects on the basis of preliminary phenomenological direct capture calculations. An angular distribution was measured at 15-MeV proton energy, in order to compare to measurements of Belt *et al.*[10] and Skopik *et al.*[11] Although the absolute cross sections of the two capture experiments agreed within error (~10%), the electrodisintegration results (Ref. 11) were about 20% higher. The three angular distributions, normalized through A_0, are shown in Fig. 1. The a_i coefficients given in the figure are for the combined data. The agreement between the three measurements is excellent. It is important to realize that these measurements were made by three totally different experimental techniques. Belt detected recoil ^3He nuclei from deuteron capture on hydrogen, Skopik used the reaction $^3He(e, d)e'p$ and detected the outgoing deuterons, while in the present experiment we measured proton capture and detected the outgoing γ rays.

The a_2 coefficients obtained in the present work are shown along with previous values in Fig. 2 and in Table I. For all energies except $E_p = 6.5$ MeV, the values of a_2 are between −0.87 and −0.93 with statistical uncertainties of less than ±0.02 for the present work.

Since a complete three-body calculation of the capture reaction $^2H(p,\gamma)^3He$ is not yet available, we have performed an effective two-body direct capture calculation using the best available wave functions for the initial continuum state and the final bound state of ^3He. The radial transition matrix elements for electric transitions were written, in the long-wavelength approximation, as

$$T_{lj}{}^L \propto \langle u_{l',j'}(r) | q_{\rm eff} r^L | \varphi_{l,j} \rangle,$$

where $u_{l',j'}(r)$ represents the final bound state of the captured single particle while $\varphi_{l,j}$ is the initial continuum wave function with orbital and total angular momentum l and j, respectively.

Gibson and Lehman[3] generated momentum-space three-body ^3He ground-state wave functions

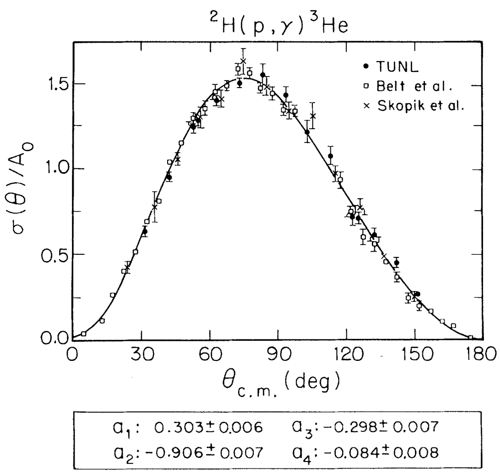

FIG. 1. Angular distributions at a proton energy of 15 MeV of the present work (circles) and Refs. 10 (squares) and 11 (crosses) shown along with the statistical error bars. The curve is the Legendre-polynomial fit to the data with the coefficients given in the figure.

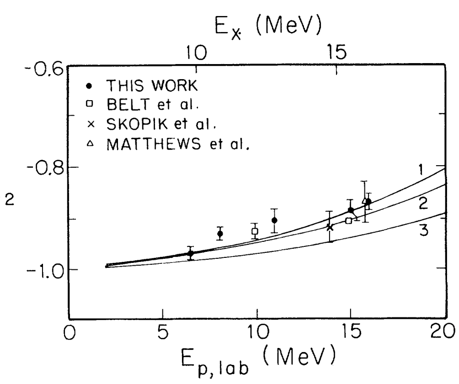

FIG. 2. The a_2 angular distribution coefficients of Table I shown as a function of proton bombarding and excitation energies. Data from the present work (circles) and Refs. 10 (squares), 11 (cross), and 12 (triangle) are shown with statistical error bars. The curves are the results of the direct capture calculations including $E1$, $E2$, and $E3$ radiation and using Lehman and Gibson's ^3He wave functions as described in the text. Curves 1, 2, and 3 assume 7%, 4%, and 0% deuteron D-state probability, respectively, in the calculation of the ^3He bound state.

TABLE I. a_2 angular distribution coefficients.

Experiment	E_p (MeV)	E_x (MeV)	a_2
This work	6.50	9.83	-0.97 ± 0.01
	8.00	10.83	-0.93 ± 0.01
	10.93	12.78	-0.91 ± 0.02
	14.96	15.47	-0.89 ± 0.02
	15.94	16.12	-0.87 ± 0.01
Belt *et al.*[a]	9.9	12.09	-0.93 ± 0.01
	14.87	15.41	-0.91 ± 0.01
Skopik *et al.*[b]	13.89	14.75	-0.92 ± 0.03
Matthews *et al.*[c]	15.76	16.0	-0.87 ± 0.04

[a]Ref. 10.
[b]Ref. 11.
[c]Ref. 12.

TABLE II. Calculated D-state parameters in ^{3}He for different values of $P_D(d)$.

$P_D(d)$ (%)	$P_D(^3\text{He})$ (%)	$P_D(p+d)$ (%)	D_2 (fm^2)
0	0	0	0.0
4	5.08	1.2	-0.236
7	9.12	1.5	-0.224

from Faddeev-type equations using $^1S_0$ and $^3S_1$-$^3D_1$ separable interactions which fitted the low-energy two-nucleon properties. The three-body wave functions have s-wave asymptotic normalizations which agree with experimental results.[3] The two-body $(n+d)$ wave functions needed for the present calculation were projected out of these three-body wave functions by Lehman[13] by evaluating the overlap integral between the triton wave function and the product of the deuteron wave function plus a neutron. The resulting wave functions were then Fourier transformed to obtain configuration-space results. Although these wave functions are for the $n+d$ system rather than the $p+d$ system, it is known that the Coulomb interaction has an insignificant effect on the bound-state wave function, changing only the binding energy.[14] The D-state contribution in these wave functions is put into the model in the form of the D-state probability contained in the deuteron. The three-body wave functions were obtained for three deuteron D-state probabilities, $P_D(d)$, of 0%, 4%, and 7%. Table II gives the ^{3}He three-body D-state probability, the $p+d$ projected wave-function probability, and the asymptotic parameter D_2 obtained in these three calculations. For comparison, the empirical value of D_2 for ^{3}H quoted in Ref. 1 is -0.275 fm^2.

The initial continuum wave function was obtained from the optical-model potential which describes elastic scattering of protons (neutrons) from deuterons. The optical-model parameters used were those of Guss[15] for $^2\text{H}(n,n)^2\text{H}$ scattering. The Coulomb term, added for the present case, did not change the wave functions significantly. The optical-model potential parameters of Devries, Perrenoud, and Slaus[16] were also used giving essentially the same results. The electromagnetic operator is $q_{\text{eff}}r^L$, where L is the multipolarity of the interaction and q_{eff} is the kinematic effective charge. The use of the long-wavelength approximation in the energy region of this experiment was shown to be valid, introducing less than 0.6% effects on the a_2 coefficients in comparison with the "exact" form of the operator obtained using Siegert's theorem.[17] Terms corresponding to $E1$, $E2$, and $E3$ capture were included in the present calculations.

The results of the direct capture calculations adequately described (to within experimental errors) the cross section and the a_1, a_3, and a_4 coefficients. The calculations predicted a pure D-state contribution to the 90° cross section of about 0.35 μb/sr at an excitation energy of 11 MeV, a value too small to be observed in A_0. This result is similar to that of Ref. 5 but quite different from that of Ref. 6 (which obtained 8 μb/sr). It was also found that the D-state effects in the a_1, a_3, and a_4 coefficients were smaller than the experimental uncertainties in these coefficients.

Figure 2 shows that the a_2 coefficient is not accounted for if D state is absent from the ground state of ^{3}He. The results of the calculation which assume $P_D(d)$ values of 0%, 4%, and 7% are shown here. The use of the optical-model wave functions increases the D-state effect on a_2 by a factor of 3 compared to the use of plane waves as in Refs. 5 and 6. The solutions including the deuteron D-state are in good agreement with the experimental a_2 coefficients. Previous analyses[8] have implicitly attributed the discrepancy in a_2 with respect to the 0% D-state prediction to the presence of $E2$ radiation and have produced anomalously large $E2$ cross section. However, the present calculations have shown that the D-state component in ^{3}He is able to account for the observed a_2 values. D-state presence would correspond to including $S=\frac{3}{2}$, $E1$ amplitudes in the analysis of Ref. 8. It should be noted that since different-channel spin amplitudes do not interfere, the D-state effects appear in a_2 incoherently.

The present results have shown that, contrary to previous theoretical claims,[5] high-quality angular distribution data taken over a reasonable range of energies *are* sensitive to the D-state presence in ^{3}He. Within the context of the model used we find that a D-state probability of 5%–9% in the ^{3}He three-body wave function [or D_2 parameter of about -0.23 (see Table II)] explains the magnitude and energy dependence of the a_2 coefficients. Furthermore, our calculations indicate that the present radiative-capture study provide a means of probing the ^{3}He wave function between 2.5 and 6.5 fm since 70% of the $E1$ D-state transition amplitude strength occurs in this region. The study of tensor-polarized ^{1}H($d_{\rm pol}$, γ)^{3}He capture should provide an even more sensitive measure of the D-state presence in ^{3}He since $S=\frac{3}{2}$ capture amplitudes are necessary to produce a tensor analyzing power. A full three-body calculation is needed for a more thorough understanding of these observables.

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