Measurement of T_{20} for the Reaction $^1H(d_{pol},\gamma)^3He$ and D-State Effects in ^3He

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The tensor analyzing power T_{20} for the radiative capture reaction $^1H(d_{pol},\gamma)^3He$ has been measured in order to test new three-body wave functions. This observable arises from the D state of ^3He. An effective two-body direct-capture calculation, which was previously shown to fit the a_2 coefficient of a Legendre-polynomial expansion of the differential cross section, is found to give a good description of the present data. A value for the asymptotic D/S ratio is extracted from the data although it is found to be model dependent.

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Recent theoretical calculations of few-body wave functions have stimulated interest in new measurements on very light nuclei. In particular several related reactions have been used to study the ground state of ^3He. Among these are photodisintegration[1,2] and electrodisintegration[3] of ^3He and radiative capture of protons by deuterons[4–6] and of deuterons by protons.[7] The a_2 coefficient of a Legendre-polynomial expansion of the differential cross section for γ-ray emission following capture of protons by deuterons has been found sensitive to the D-state component of the ^3He ground-state wave function.[5] As pointed out by Seyler and Weller,[8] the tensor analyzing powers of the reaction $^1H(d_{pol},\gamma)^3He$ are expected to be more sensitive to D-state effects. In fact they are identically zero if the $S=\frac{3}{2}$ capture amplitude, which arises from the D state, is absent. Of the previous work only Ref. 6 involves a polarized beam, the incident particles being protons. Therefore, it is important that experiments be done with a polarized deuteron beam. Measurements of T_{20}, with good statistical accuracy, have been performed for the reaction $^1H(d_{pol},\gamma)^3He$ and are reported in this Letter. An effective two-body radiative-capture calculation, similar to the one used in Ref. 5 to describe the differential cross section, fits the present data well. In addition, an upper limit of 0.050 for the asymptotic D/S state ratio η is implied by the data.

The deuteron beam used in this reaction produces a high neutron flux which makes it difficult to detect the γ rays. To avoid this problem the recoiling ^3He nuclei were detected instead with an Enge split-pole spectrograph. A one-to-one relationship exists between the energy of the ^3He and the angle of the γ ray (Fig. 1). However, for the beam energy used, the ^3He nuclei are confined to a cone about the beam axis with a maximum angle of 2.6°; the beam particles are therefore in the way. An appropriate magnetic field was chosen such that the beam was collected in a Faraday cup at a large radius of curvature R in the spectrograph, while the ^3He particles were separated magnetically and focused at low R. The McMaster University Lamb-shift polarized-ion source was used to produce polarized deuterons alternatively in the $m=1$ and $m=0$ substates relative to the beam direction. An energy of 19.8 MeV was used. The target was a polyethylene (CH_2) film approximately 100 $\mu g/cm^2$ thick. The ^3He particles were detected with two solid-state position-sensitive counters with an active length of 47 mm each. The detectors were repositioned halfway through the experiment in order to collect the full energy range of the ^3He (12–14.3 MeV). A monitor detector was mounted in the target chamber and the reaction $^1H(d_{pol},d)^1H$ was used to normalize the data. An angle of 21° was chosen for the monitor because the analyzing power of this reaction is very small ($T_{20}\leq 0.01$) and constant with angle in this region. Finally a third position-sensitive detector was located on the focal plane to monitor the polarization of the

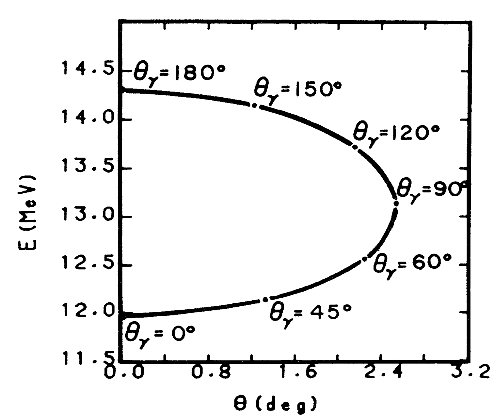

FIG. 1. Kinematics for the reaction $^1H(d_{pol},\gamma)^3He$ at 19.8 MeV. The axes correspond to the energy and angle of the ^3He particles in the laboratory frame.

beam. The known analyzing power at zero degrees for the reaction $^{12}C(d_{pol},\alpha)$ leading to the 3.59-MeV natural-parity 2^+ excited state of ^{10}B was used for this purpose.[9]

Several runs were done for $m=1$ and $m=0$. The spectra were added, normalized, and corrected for background. The tensor analyzing power was calculated from the following equation:

$$T_{20}=\sigma_1-\sigma_0/P(\sigma_0/\sqrt{2}+\sqrt{2}\sigma_1),$$

where σ_1 and σ_0 are the yields for $m=1$ and $m=0$, respectively, and P is the polarization of the beam, which was approximately 60%. The ^{3}He energy spectrum was divided into 25 regions corresponding to approximately 6° bins for the differential cross section. The results are shown in Fig. 2. Points below 25° and above 155° are less reliable because the cross section at extreme angles is very small. However, T_{20} is found to approach 0 for extreme angles in two separate experiments. One can therefore have some confidence in this behavior. This does not agree with theory as will be discussed later.

An effective two-body direct-capture calculation, similar to that used by King *et al.*,[5] was performed. In the long-wavelength approximation, the radial transition matrix elements can be written $R\sim\langle\psi|q_{\text{eff}}r^L|\phi\rangle$, where ψ is the final bound state and ϕ is the initial continuum wave function. The wave functions ψ are the same as those used in Ref. 5. These are two-body $p+d$ wave functions projected from the three-body wave functions of Gibson and Lehman.[10] The latter are generated from a Faddeev calculation using $^1S_0$ and $^3S_1$-$^3D_1$ separable potentials adjusted to fit two-body properties. The wave functions ϕ were obtained from a distorted wave calculation for the entrance channel. As in Ref. 5, the optical model parameters used were those of Guss. The equations relating these matrix elements to the tensor analyzing powers are given by Seyler and Weller.[8] $E1$, $E2$, and $E3$ transitions are included in this calculation although $E3$ is found to make only a small contribution. The calculated T_{20} is shown in Fig. 2 as the solid line. Although the D-state admixture is not a direct observable, a determination of P_D can be made within the context of our model. These calculations were done with a wave function generated by a potential which gives rise to a 7% probability for the deuteron D state. This gives a 9.12% probability for the D state in ^{3}He. The calculations were repeated for the wave functions corresponding to 2%, 4%, and 9% deuteron D state (2.16%, 5.08%, and 11.52% ^{3}He D state). The results for 4% and 7% are almost identical. This can be understood by examination of the projected two-body wave functions. The D-state component of the ground state is shown in Fig. 3. King *et al.* found that 70% of the $E1$ transition amplitude occurs between 2.5 fm and 6.5 fm. These wave functions are almost identical in this region. The situation is the same for the S state. Hence the radial matrix elements are almost equal, and the same follows for T_{20}. Therefore, a precise determination of the D-state admixture is difficult. However, results for the 2% and 9% wave functions do not fit the data as well as the 4% and 7% results (see Fig. 2). Therefore, limiting values for $P_D(^3\text{He})$ of 5%

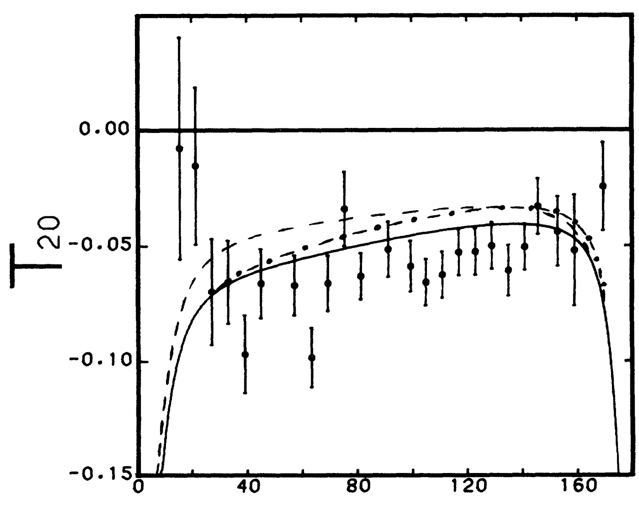

FIG. 2. T_{20} for the reaction $^1H(d_{pol},\gamma)^3He$. The solid line, the dashed line, and the dot-dashed line correspond to 7%, 2%, and 9% deuteron D state, respectively.

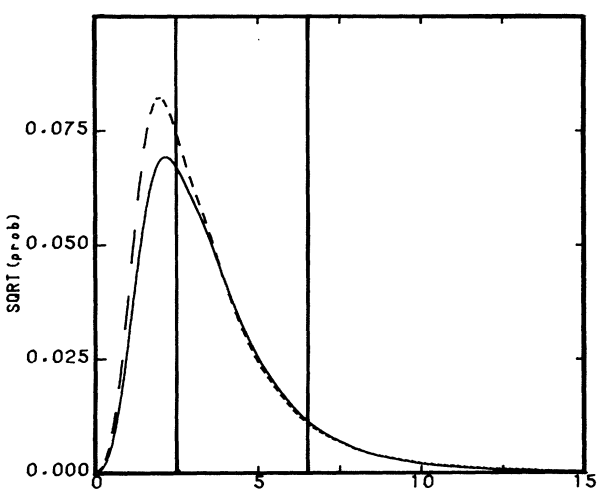

FIG. 3. D-state components of the two-body wave functions used in the calculation. The region of interest is marked by the vertical lines. The dashed line is for the 9.12% D-state wave function, while the solid line corresponds to 5.08% D state.

and 9%, corresponding to a D-state probability in the deuteron of between 4% and 7%, are consistent with our results.

At extreme angles T_{20} is predicted to be large and negative. As mentioned above, this does not agree with experiment since T_{20} tends to 0 in this region. This may be due to the omission of $M1$ radiation whose contribution, although small, may be significant at extreme forward and backward angles. These matrix elements are difficult to calculate because two different methods were used to obtain the initial and final states resulting in nonorthogonal wave functions.[11] However, a calculation treating the $M1$ matrix elements as parameters has shown that less than 3% $M1$ amplitude is sufficient to account for extreme-angle discrepancies.[12]

As pointed out by Arriaga and Santos,[13] the low-energy 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. Following their suggestion, we have studied this problem using the asymptotic forms of the bound-state wave functions:

$$u_S = C_S(\mu/2\pi)^{1/2}\exp(-\mu r)/r, \quad u_D = c_D(\mu/2\pi)^{1/2}[\exp(-\mu r)/r](1+3/\mu r+3/\mu^2 r^2),$$

where μ is the wave number corresponding to the deuteron separation energy in ^{3}He ($\mu = 0.42\ \mathrm{fm}^{-1}$), and C_S and C_D are the asymptotic normalization constants for the S and D states, respectively. η is defined as C_D/C_S. It was found that, with these functions, the contribution from the interior of the nucleus is emphasized (e.g., 43% of the $E1$ transition amplitude to the D state occurs inside 2.0 fm). This contribution is abnormally high when compared to the similar amplitude from realistic wave functions (9%). We conclude that, for a given η, the D/S state ratio in the interior is greatly overestimated, resulting in a value of T_{20} that is too large. This is because, as previously stated, most of the capture amplitude occurs between 2.5 fm and 6.0 fm; at this beam energy, we are not probing the asymptotic part of the wave function.

However, a calculation was carried out using the asymptotic wave functions for r greater than 2.5 fm. This is done because the tail of the realistic wave functions is reasonably well reproduced by the asymptotic forms. As was found in Ref. 13, T_{20} is proportional to η. If we fit the data to within the range of the statistical error bars, η is found to be 0.035 ± 0.01. This is consistent with the result of Ref. 13, as well as with the range of η calculated for the realistic wave functions of Gibson and Lehman[10] ($0.038 \leq \eta \leq 0.050$ for P_D between 4% and 7%). However, one must be careful in interpreting these results. Calculations done for differing cutoff radii show a sensitivity to this parameter. The value of η quoted is therefore model dependent. The additional uncertainty introduced in η by this fact is approximately 0.01.

In conclusion, the method of detecting the recoiling ^{3}He particles rather than the γ rays has allowed us to measure T_{20} for the reaction $^1\mathrm{H}(d_{\mathrm{pol}},\gamma)^3\mathrm{He}$ with a high degree of statistical accuracy. These results are consistent, within our model, with a D-state admixture of between 4% and 7% for the deuteron, corresponding to between 5% and 9% for ^{3}He. These results are also significant in that they are predicted by the same model, with no changes in parameters, as the one used to fit the differential cross section at several energies.[5] This is a strong confirmation for the validity of the effective two-body direct-capture model for this reaction as well as for the three-body wave functions of Gibson and Lehman. Furthermore, a value for the asymptotic D/S state ratio of 0.035 is consistent with our data.

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