Tensor-Polarized–Deuteron Capture on Deuterium and the D State of ^{4}He

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The tensor analyzing power $T_{20}(\theta)$ of the reaction ^{2}H$(d,\gamma)^4$He has been measured at six angles at $E_d=9.7$ MeV. The result is found to be isotropic with a value of $T_{20}=-0.22\pm0.014$. This analyzing power arises from the interference of $S=0$ and $S=2$ capture amplitudes. Since the reaction proceeds predominantly via $E2$ radiation, the $S=2$ capture strength can be attributed to $S=2$, $L=2$ ground-state admixtures. A heuristic model calculation has been used to show that a 4.8% D-state admixture in the two-deuteron wave function describing ^{4}He can account for the observed T_{20}.

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The previous experimental work on the reaction ^{2}H$(d,\gamma)^4$He consists of measurements of the differential cross section as a function of energy and angle.[1–4] These angular distribution measurements indicate that at low energies the reaction proceeds via an $E2$ transition from the $^0D_2$ scattering state to the $^0S_0$ ground-state component of the ^{4}He wave function (where the notation is ^SL_J with $\vec{L}+\vec{S}=\vec{J}$). One aspect of this reaction, which to date has been neglected, is the possible effect of a small D-state admixture in the ^{4}He ground-state wave function. The tensor analyzing powers obtained with a tensor-polarized deuteron beam should be sensitive to the presence of D-state admixtures ($^2D_0$) in the ground state. This Letter reports the first measurement of a tensor analyzing power in the reaction ^{2}H$(d,\gamma)^4$He. We have measured the differential cross section and the tensor analzying power, $T_{20}(\theta)$, at six angles for the reaction ^{2}H$(d,\gamma)^4$He with a deuteron bombarding energy of 9.7 MeV.

Mandl and Flowers[5] have pointed out that, to the extent that the magnetic multipole operator depends only upon the spin coordinates and the electric operators only upon the spatial coordinates of the nucleon, the reaction ^{2}H$(d,\gamma)^4$He should be dominated by $E2$ radiation. Furthermore, because the incident deuterons are identical bosons, only scattering states with $L+S$ even are allowed. In the case of $E1$ radiation, this requirement is met only by $(L=1,\ S=1)1^-$ [i.e., the $^1P_1(E1)$ transition matrix element]. Besides being inhibited by the isospin selection rule in self-conjugate nuclei ($\Delta T=\pm1$), $E1$ transitions to the ground state ($S=0$ or $S=2$) will be further diminished because they have $\Delta S=1$.

There is only one possible $M1$ capture amplitude: $^2D_1(M1)$. This term will be nonzero only for $M1$ transitions which lead to the small $L=2$, $S=2$ ground-state component. Furthermore, isospin selection rules should give a considerable inhibition for these $\Delta T=0$ $M1$ transitions.[6] Hence, as discussed in Ref. 1, $M1$ strength is not expected to be present in this reaction at the energy being considered.

In the case of $M2$ radiation there are two possible capture amplitudes: $^1P_2(M2)$ and $^1F_2(M2)$. The form of the angular distribution observed for the reaction ^{2}H$(d,\gamma)^4$He clearly rules out the possibility that $M2$ strength is present at more than the few percent level.[1] In fact, the present measurement indicates that $M2$ radiation is negligibly small since it would show up as an asymmetric term (an odd-order Legendre function) in $T_{20}(\theta)$ as a result of interference with the dominant $E2$ radiation. As will be seen below, no indication of such terms is found in the data.

Since the spin-dependent part of the $E2$ operator is negligibly small at these energies,[7] S cannot change in an $E2$ transition. With the ground state of ^{4}He being predominantly $^0S_0$ with a small $^2D_0$ admixture, we therefore have four $E2$ transition matrix elements which have $L+S$ even:

$$^0D_2(E2)\rightarrow {}^0S_0,\quad {}^2S_2(E2)\rightarrow {}^2D_0,$$

$$^2D_2(E2)\rightarrow {}^2D_0,\quad {}^2G_2(E2)\rightarrow {}^2D_0.$$

Equations (11) and (23)–(25) of Seyler and Weller[8] allow us to write the observables $T_{kq}(\theta)$ in terms of the amplitudes and phases of these transition matrix elements. To simplify the resulting expressions for the T_{kq}, the quantities A, B, and C are defined as:

$$A \equiv {}^0D_2\,{}^2D_2 \cos\Phi({}^0D_2 - {}^2D_2), \tag{1}$$

$$B \equiv {}^0D_2\,{}^2G_2 \cos\Phi({}^0D_2 - {}^2G_2), \tag{2}$$

$$C \equiv {}^0D_2\,{}^2S_2 \cos\Phi({}^0D_2 - {}^2S_2). \tag{3}$$

In the above expressions, the absolute magnitude of the transition matrix elements are denoted by the quantum numbers of the scattering states ${}^SL_J$, and $\Phi({}^SL_J - {}^{S'}L'_{J'})$ denotes the phase difference between the ${}^SL_J$ and ${}^{S'}L'_{J'}$ capture amplitudes. Since the $S=2$ terms are expected to account for only a few percent of the cross section, we neglect terms which are products of two $S=2$ matrix elements. With this approximation, the $T_{kq}(\theta)$ analyzing powers written in terms of A, B, and C are

$$iT_{11}(\theta) = 0, \tag{4}$$

$$T_{20}(\theta) = -0.594A + 0.797B + 0.497C, \tag{5}$$

$$T_{21}(\theta) = (0.087A + 0.155B - 0.145C) \times (2.8 - 5.6\cos^2\theta)/\sin 2\theta, \tag{6}$$

$$T_{22}(\theta) = -0.242A - 0.055B - 0.203C, \tag{7}$$

where the amplitudes are normalized such that $\frac{5}{9}\sum({}^SL_J)^2 = 1.0$. It is apparent from these equations that the T_{kq} are proportional to the amplitudes of the $S=2$ transition matrix elements which, in turn, are proportional to the amplitude of the D-state admixture in the ground state of ${}^4\mathrm{He}({}^2D_0)$. We also see that the assumption of pure-$E2$ radiation leads to the result that $T_{20}(\theta)$ and $T_{22}(\theta)$ will be *isotropic*.

The present measurements were performed by bombarding a 1.9-cm-diam gas cell containing deuterium gas with a 10-MeV deuteron beam. A target thickness of 1.7 mg/cm^2 was obtained by operating the gas cell at a pressure of 270 kPa absolute and cooling the cell to liquid nitrogen temperatures. Tantalum foil having a thickness of 2.5×10^{-3} mm was chosen for the deuteron-beam entrance and exit windows on the gas cell, as this material was found to contribute negligible γ-ray background above a γ-ray energy of 20 MeV. The beam energy at the center of the target was calculated to be 9.7 MeV. The 28-MeV γ rays produced in the reaction ${}^2\mathrm{H}(d,\gamma){}^4\mathrm{He}$ were detected with two 25.4×25.4-cm γ-ray spectrometers.[9] Both detector systems subtended 23 msr with an acceptance angle of $\pm4.8°$. The resulting spectrum obtained in a single detector at a given angle is shown in Fig. 1. The high Q-value (23.84 MeV) of the reaction makes it relatively easy to produce rather clean spectra. The nature of the background was tested at each scattering angle by taking spectra with no gas cell, an empty gas cell, and the cell filled with deuterium. By comparing the γ-ray yields amongst these, we conclude that (a) the γ-ray yield below 20 MeV in Fig. 1 is due to the presence of the cell windows, (b) the flat background above the ${}^2\mathrm{H}(d,\gamma)$ peak is due to cosmic-ray events and, (c) with target gas present the γ-ray yield above 20 MeV is consistent with the known response function of the γ-ray spectrometer with a flat cosmic-ray background added.

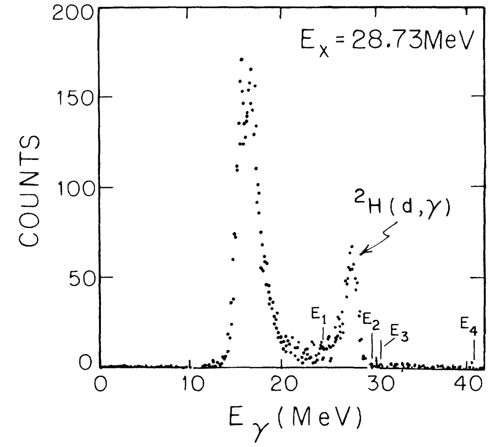

FIG. 1. The spectrum obtained at $E_d = 9.7$ MeV for the reaction ${}^2\mathrm{H}(d,\gamma){}^4\mathrm{He}$ at $\theta_{\mathrm{lab}} = 130°$. The yields used to calculate T_{20} were obtained by summing the events between E_1 and E_2 and then subtracting a cosmic-ray background based on the number of events between E_3 and E_4.

The differential cross section for a spin-one polarized beam can be written[8] in terms of the tensor moments, t_{kq}, which describe the beam polarization and the analyzing power tensors $T_{kq}(\theta)$ as

$$\sigma(\theta,\Phi) = \sigma_u(\theta)[1 + 2it_{11}iT_{11}(\theta) + t_{20}T_{20}(\theta) + 2\,\mathrm{Re}\,t_{21}T_{21}(\theta) + 2\,\mathrm{Re}\,t_{22}T_{22}(\theta)]. \tag{8}$$

Polarized deuterium ions were produced by use of a Lamb-shift polarized-ion source equipped with a spin filter.[10] Data were taken using the beam polarizations $t_{20}^{(1)} = P_Q/\sqrt{2}$ and $t_{20}^{(0)} = -2P_Q/\sqrt{2}$ where P_Q, as defined in Trainor, Clegg, and Lisowski,[11] represents the percentage beam polarization. P_Q was determined by means of the quench-ratio method.[11] The spin symmetry axis was chosen along the beam momentum so that the effect of it_{11}, t_{21}, and t_{22} on the measured $T_{20}(\theta)$ was negligibly small. With use of expression (8), $T_{20}(\theta)$ is given by

$$T_{20}(\theta)=\frac{\sqrt{2}}{P}\frac{Y_2(\theta)-Y_0(\theta)}{2Y_1(\theta)+Y_0(\theta)}, \qquad (9)$$

where $Y_1(\theta)$ and $Y_0(\theta)$ are the γ-ray yields at angle θ for the same incident flux and for deuteron polarizations $t_{20}^{(1)}$ and $t_{20}^{(0)}$, respectively.

To test for count-rate asymmetries from the possible presence of spurious it_{11} and t_{21} beam moments, data were collected with both spectrometers at the same scattering angles, but on opposite sides of the beam direction. In addition, the sign of it_{11} was periodically reversed by taking data with the spin symmetry axis both parallel and antiparallel to the beam momentum. The effects due to it_{11} and t_{21} were observed to be consistent with zero, as expected for the present choice of spin symmetry axis.

Measurements of $\sigma(\theta)$ and $T_{20}(\theta)$ were obtained at $E_d=9.7$ MeV ($E_x=28.7$ MeV in ^{4}He) at six angles as shown in Fig. 2. The $T_{20}(\theta)$ shown are the result of averaging the measurements made with both spectrometers. The absolute cross section shown here was obtained by normalizing our data to the results of Ref. 2. The curve drawn through the $\sigma(\theta)$ data has the form $\sin^2(\theta)\cos^2(\theta)$, as expected for the dominant $^0D_2(E2)\rightarrow {}^0S_0$ capture amplitude. The solid curve shown on the $T_{20}(\theta)$ data is the result of fitting the data with a constant. An attempt to include higher-order Legendre polynomials indicated that such terms were not statistically significant. This result is in excellent agreement with what is expected if the reaction proceeds via pure $E2$ radiation.

The isotropic $T_{20}(\theta)$ data shown in Fig. 2 lead to a value of T_{20} of -0.220 ± 0.014 when fit to a constant. This large T_{20} value may, at first sight, appear to be unreasonably large if due to a few percent D-state admixture in the ground state of ^{4}He. We can, however, get some perspective on this value of T_{20} if we assume that the $S=2$ strength arises entirely from the $L=2$ continuum partial wave [$^2D_2(E2)\rightarrow {}^2D_0$] and that the phases of the transition matrix elements do not depend on S. We can then use the experimental value of T_{20} in Eq. (5) along with the normalization condition on the amplitude of the matrix elements to find the $S=2$ capture strength. The result indicates that a T_{20} value of -0.22 is equivalent to having 3% of the cross section arising from $S=2$ capture strength.

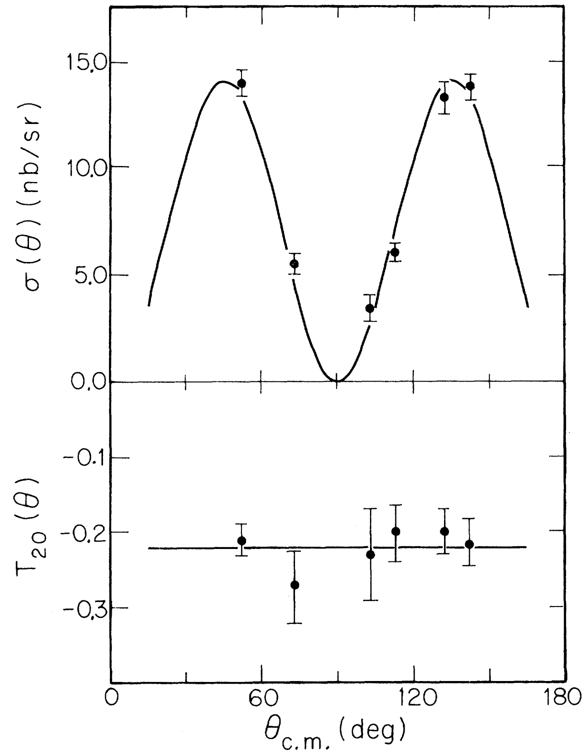

FIG. 2. The $\sigma(\theta)$ and $T_{20}(\theta)$ data obtained at $E_d=9.7$ MeV for the reaction ^{2}H$(d,\gamma)^4$He. The solid curve in the $\sigma(\theta)$ case is of the form $\sin^2\theta\cos^2\theta$. The solid curve shown for the $T_{20}(\theta)$ data is the result of fitting the data with a constant. Errors shown are statistical only.

A heuristic model calculation has been performed to investigate the sensitivity of T_{20} to the D-state present in ^{4}He. Since the reaction ^{2}H$(d,\gamma)^4$He at these energies has been shown to be primarily direct, the $E2$ transition matrix elements were calculated using the direct-capture formalism.[12] The ground-state wave function was constructed from two Wood-Saxon potentials which bound the two point deuterons at 23.84 MeV with $L=0$ ($V_0=54.61$ MeV, $r_0=2.0$ fm, $a=1.0$ fm), and $L=2$ ($V_0=120.8$ MeV, $r_0=2.0$ fm, $a=1.0$ fm), respectively. The scattering wave functions were generated from these same potentials. These wave functions were used to calculate the four complex $E2$ transition matrix elements discussed above using Siergert's form of the $E2$ operator but not making the long-wavelength approximation. It was found that a 4.8% admixture of $L=2$ strength in the ground state of ^{4}He was required to reproduce the observed T_{20} value.

This simple two-body model calculation indicates the sensitivity of T_{20} to D-state admixture in the ground state of ^{4}He. Of course a complete fourbody calculation of this problem must treat tensor-force effects in a consistent manner which includes effects such as channel-spin mixing in the entrance channel. However, these effects are expected to be small since the tensor analyzing powers observed in the *d*-*d* elastic scattering problem are very small, being less than 3%.[13]

Recent calculations have demonstrated that the total *D*-state admixture in the ground state of ^{4}He is quite sensitive to the form of the potential used to describe the *N*-*N* interactions.[14,15] In Ref. 14, the *D* state of ^{4}He was calculated for several nucleon-nucleon potentials using a method based on hyperspherical harmonics. The resulting *D*-state admixtures range from 7.8% to around 13%. More recently, Goldhammer,[15] using a variational method, found that the Paris potential resulted in a *D*-state admixture of 5.36%. The present experimental result, being a relatively easy observable to calculate, should be extremely useful for testing these various model wave functions. It seems clear that the results of the present measurements provide an important new observable which should be of tremendous value in the study of tensor force effects in ^{4}He.

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