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^{2}H($\vec{d}$,γ)^{4}He reaction at $E_d = 1.2$ MeV

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The ^{2}H($\vec{d}$,γ)^{4}He reaction observables $\sigma(\theta)$, $A_y(\theta)$, and $A_{yy}(\theta)$ have been measured at six angles at $\langle E_d(\text{lab})\rangle = 1.2$ MeV. The data have been compared to a microscopic multichannel resonating group model calculation. According to this calculation, the cross section consists of nearly equal contributions from $E2$, $E1$, and $M2$ radiation, and the tensor analyzing power arises primarily as a consequence of the large $E1/M2$ strength.

The sensitivity of the ^{2}H($\vec{d}$,γ)^{4}He reaction to the D state of ^{4}He was first demonstrated by measurements of the tensor analyzing power for this reaction using 10 MeV beams of tensor polarized deuterons.[1,2] Since the reaction is dominated by $E2$ radiation at this energy, the tensor analyzing power arises from d-wave capture ($S=0$) leading to the $L=S=0$ component of the 0^+ ^{4}He ground state interfering with s-, d-, and g-wave capture ($S=2$) leading to the $L=S=2$ ground-state component (the D state). The presence of s-wave capture implied that the effects of the D state of ^{4}He could be more readily observed at lower deuteron beam energies, since the angular momentum barrier should suppress the d-wave capture to the S state relative to the s-wave capture to the D state. Measurements at E_d(lab) below 3 MeV have been interpreted using this idea, together with the assumption of pure (or at least dominant) $E2$ radiation.[3] This s-wave capture to the D state has also been used to explain the behavior and magnitude of the capture cross section at very low energies.[4] It should be mentioned, however, that s-wave capture to the ^{4}He S state is also possible as a result of the existence of the deuteron D state, which has been neglected in most of the presently available treatments of the ^{2}H(d,γ)^{4}He reaction (the exception is Ref. 23).

The published reports[2,5] of a nonvanishing vector analyzing power A_y at $E_d(\text{lab}) = 10$ MeV determined that non-$E2$ radiation is present at about the 7% level in this reaction at this energy. Recent Triangle Universities Nuclear Laboratory (TUNL) measurements[6,7] of the vector analyzing power A_y as a function of E_d(lab) have also revealed the presence of non-$E2$ radiation at low energies, especially below 3 MeV. The data suggest substantial contributions of $E1$ and/or $M2$ strength at these lower energies.

In this paper, we present measurements of $\sigma(\theta)$, $A_y(\theta)$, and $A_{yy}(\theta)$ at $\langle E_d(\text{lab})\rangle = 1.2$ MeV. The data are compared to the results of a new microscopic calculation[8] which includes coupling to n-^{3}He and p-^{3}H channels, as well as $E2$, $E1$, $M2$, and $M1$ radiation. This calculation indicates that at this energy, significant contributions ($\sim 55\%$) to the capture cross section arise from $E1/M2$ strength. The model provides a good description of the data, especially the tensor analyzing power $A_{yy}(\theta)$, and suggests that the presence of the odd-parity multipoles is crucial in order to reproduce the measured $A_{yy}(\theta)$.

The experiments were performed at TUNL using polarized deuterons from a Lamb-shift source equipped with a spin filter.[9] The target was a 1.27-cm-long tantalum-lined gas cell, filled with deuterium gas at 896 kPa at room temperature and terminated by a 1.0 mm tantalum disk to stop the beam. The desired beam energy was achieved by passing a 3.3 MeV deuteron beam through a 0.019-mm-thick Havar degrading foil, as described in earlier work.[3,7] In this manner, the actual beam energy in the gas target was 1.6–0.6 MeV due to energy loss, with a center-of-target energy of $\langle E_d\rangle = 1.2$ MeV. Combining the beam energy spread ($\sim$100 keV) due to the degrading foil and the intrinsic uncertainty in the mean energy due to accelerator regulation and energy loss in the foil ($\pm$50 keV), the net uncertainty in the actual beam energy on the gas target was estimated to be $\sim$140 keV.

Capture γ rays were detected in two anticoincidence-shielded 25.4×25.4-cm NaI(Tl) spectrometers[10] located on either side of the beam axis. Each detector was surrounded by 10 cm of passive Pb shielding, as well as 20 cm of lithium-carbonated paraffin to moderate neutrons [primarily from the ^{2}H$(d,n)^3$He reaction]. Spectra observed in the present experiment were comparable to those measured previously at $E_d = 2.0$ MeV (Ref. 3). Data were analyzed by fitting the γ_0 transition with the empirically determined NaI-detector response function. Measured yields were obtained by summing over a γ-ray energy region corresponding to one line-shape width below the peak centroid energy up to one width above it. The final results included corrections for unrejected cosmic-ray background and accidental rejection of good γ-ray events.

Vector and tensor analyzing powers (A_y and A_{yy}) were determined from the measured yields by the following:

$$A_y(\theta) = \frac{1}{P}\frac{Y_1 - Y_3}{Y_1 + Y_2 + Y_3}\,,$$

$$A_{yy}(\theta) = \frac{1}{P}\frac{Y_1 + Y_3 - 2Y_2}{Y_1 + Y_2 + Y_3}\,,$$

where P is the beam polarization (obtained by the quench ratio method[11]) and Y_i are the normalized yields corresponding to the deuteron spin states ($i = 1,2,3$ refers to $m = 1, 0, -1$, respectively) as defined with respect to a spin-symmetry axis given by $\mathbf{k}_{\rm in} \times \mathbf{k}_{\rm out}$. In the Madison convention,[12] this corresponds to $\beta = 90°$ and $\phi = 0°$, where β designates the angle between the spin axis and the beam-momentum axis and ϕ is the angle between the spin axis and the normal to the reaction plane.

Calculations were performed in the framework of the microscopic multichannel resonating group model, as described by Wachter, Mertelmeier and Hofmann.[8] A nucleon-nucleon force, consisting of Coulomb, central, spin-orbit, and tensor forces, was used to determine the full scattering and bound-state wave functions (containing p-^{3}H, n-^{3}He, and d-d components). While the fragments were treated as having finite extent (i.e., not pointlike), the internal wave functions consisted only of S states. Within this model space, the bound-state wave function was chosen to give the most deeply bound 0^+ ground state, which corresponds to a D-state probability of 2.2% in the ^{4}He ground state. This D-state fraction is comparatively lower than other estimates based on more sophisticated calculations[13–15] which utilize more realistic nucleon-nucleon interactions.

The theoretical treatment includes the following transitions: $E2$ ($^1D_2$; $^5S_2$; $^5D_2$), $E1$ ($^3P_1$), $M2$ ($^3P_2$), and $M1$ ($^5D_1$), where the notation $^{2S+1}L_J$ refers to the scattering state. These calculations have been shown[8] to reproduce the 10 MeV data of Mellema, Wang, and Haeberli[2] quite well, with 86% of the cross section coming from the $^1D_2\,E2$ transition to the S state of ^{4}He, 10% from the $^5S_2$ and $^5D_2\,E2$ transitions to the D state and the remaining 4% due to $E1$, $M2$, and $M1$ strength.

In Fig. 1, we present the experimental results for $\sigma(\theta)$, $A_y(\theta)$, and $A_{yy}(\theta)$ at $\langle E_d(\text{lab})\rangle = 1.2$ MeV. The solid curves show the results of the calculation including all multipoles $L \leq 2$. Both the relative cross section $\sigma(\theta)$ and tensor analyzing power $A_{yy}(\theta)$ are well described by this prescription. The vector analyzing power $A_y(\theta)$ shows some deviation for the back angles. The variation in the calculated polarization observables over the energy thickness of the target (1.6–0.6 MeV) was investigated, and the results were found to be relatively insensitive to this effect. The principal contributions to the total cross section, as given by this microscopic model, are listed in Table I. Roughly 55% of the observed yield arises from p-wave capture ($E1/M2$ strength), whereas less than 1% of the cross section is due to s-wave capture ($E2$ strength) to the D state. This small s-wave contribution, which is an artifact of the present calculation,[8] results from an accidental cancellation caused by the multichannel nature of the scattering wave function.

The vector analyzing power arises from products of transition matrix elements that satisfy the triangle rela-

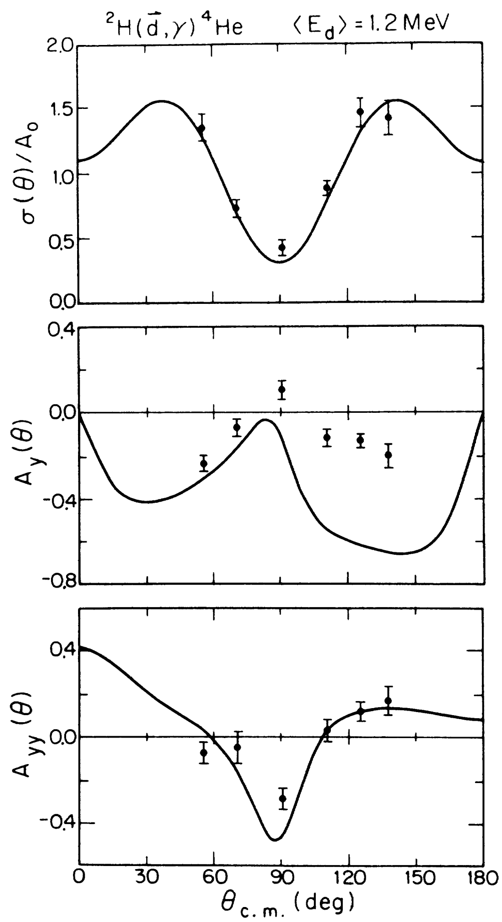

FIG. 1. Relative differential cross section, vector and tensor analyzing powers measured in the present work for the ^{2}H$(\vec{d},\gamma)^4$He reaction at $\langle E_d(\text{lab})\rangle = 1.2$ MeV, plotted as a function of center-of-mass angle. The error bars represent the statistical uncertainty associated with the data points. The solid curves are the results of the full microscopic calculation discussed in the text, including all multipoles $L \leq 2$.

TABLE I. Theoretical percentage contributions of each multipole to the total cross section for the $^2H(\vec{d},\gamma)^4He$ reaction at $\langle E_d(\text{lab})\rangle = 1.2$ MeV. The notation $^{2S+1}L_J$ is used to identify the different partial waves.

Partial wave	Multipolarity	Cross section (%)
$^1D_2$	$E2$	43.1
$^5S_2$	$E2$	0.9
$^5D_2$	$E2$	1.0
$^3P_1$	$E1$	29.5
$^3P_2$	$M2$	25.3
$^5D_1$	$M1$	0.1

tion $\mathbf{S}+\mathbf{S}'=1$. In the present model, the nonvanishing A_y is primarily due to interference of the odd-parity $(S=1)$ multipoles with the strong $E2$ capture amplitude $(S'=0)$ to the S-state component of the ^{4}He ground state. While D-state terms $(S'=2)$ also contribute to A_y through interference with the odd-parity multipoles, the magnitude of this effect is considerably smaller than the one mentioned above.

The calculation indicates that these odd-parity multipoles play a crucial role in describing the magnitude and angular dependence of A_{yy} as well. In Fig. 2, the A_y and A_{yy} data are shown compared to two variations of the above calculation: (1) the $E2$ transitions to the ^{4}He D state ($^5S_2$ and $^5D_2$) have not been included (solid curves), and (2) the $E1$ ($^3P_1$) and $M2$ ($^3P_2$) transitions have not been included (dashed curves). Clearly, the case with no $E1$ or $M2$ strength fails most dramatically to reproduce the data, whereas the effect of eliminating the D-state terms is minimal.

The transition matrix elements that contribute to the tensor analyzing power must satisfy the relation $\mathbf{S}+\mathbf{S}'=2$. At higher deuteron energies [$E_d(\text{lab}) \geq 10$ MeV], where the reaction is dominated by $E2$ radiation, the important terms in the tensor analyzing power arise from products of $S=0$ and $S'=2$ $E2$ matrix elements.[16,17] However, in the calculations at $\langle E_d(\text{lab})\rangle = 1.2$ MeV, the most significant contributions to A_{yy} arise from products of two $S=1$ terms ($E1$-$E1$, $M2$-$M2$, or $E1$-$M2$), as can be inferred from Fig. 2. In fact, the A_{yy} data can be reproduced fairly well without any $E2$ amplitudes at all in the calculation.

It is difficult to determine which of the $E1$ or $M2$ multipoles is more important to give the proper form of the tensor analyzing power, since either one of them alone gives a calculated A_{yy} similar to the one given by the full calculation. Measurements of the full set of independent vector and tensor analyzing powers might help clarify this issue. However, it is clear from Fig. 2 that according to this model *at least one* odd-parity multipole is required to correctly describe the A_{yy} data. This conclusion is quite different from the earlier results for polarized deuteron capture at $E_d = 10$ MeV,[1,2,18,19] where simple models were used to conclude that the D state of the ^{4}He ground state was largely responsible for the observed A_{yy}.

In summary, we have shown that a new microscopic coupled channel calculation can successfully describe many features of the observables $\sigma(\theta)$, $A_y(\theta)$, and $A_{yy}(\theta)$ for the $^2H(\vec{d},\gamma)^4He$ reaction at $\langle E_d(\text{lab})\rangle = 1.2$ MeV, with the exception of the back-angle behavior of $A_y(\theta)$. This failure may reflect the fact that, as stated in Ref. 8, the calculated d-d threshold is too low in energy so that the nearby 1^- and 2^- resonances contribute more than in reality. It is the presence of these broad, experimentally observed[20,21] p-wave resonances which is, in fact, responsible for the large $E1$ and $M2$ strengths at these low energies. This model also implies that these odd-parity multipoles largely account for the measured tensor analyzing power $A_{yy}(\theta)$ at this energy. It is clear that these low-energy resonance structures require further study. However, we believe that the present work establishes the existence of sizable odd-parity multipole strength in the $^2H(d,\gamma)^4He$ reaction at this energy, and, based on this comparison of data and theory, it seems clear that previous analyses of the low-energy data for this reaction [$E_d(\text{lab}) < 3$ MeV] which assumed pure $E2$ radiation[3,4,22,23] must be carefully reexamined.

New calculations which employ more realistic nucleon-nucleon forces and include D states in all of the fragments are currently in progress. These improvements will hopefully give a more realistic prediction of the position of the low-lying p-wave resonances and a more reliable estimate of the ^{4}He D-state probability.

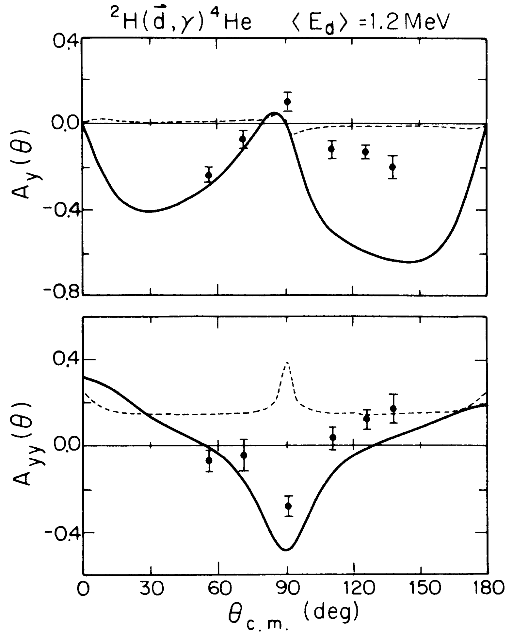

FIG. 2. The same data for the vector and tensor analyzing powers as in Fig. 1, compared to two variations of the theory. The dashed curves show the results of the calculation without the odd-parity multipoles ($E1$ and $M2$) included. The solid curves show the results of the calculation without the $E2$ amplitudes for capture to the D state.

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