^{4}He D-state effects in the ^{2}H(d,γ)^{4}He reaction at low energies

H. R. Weller, P. Colby,* J. Langenbrunner, and Z. D. Huang†
Duke University and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706

D. R. Tilley
North Carolina State University, Raleigh, North Carolina 27695 and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706

F. D. Santos‡
Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27514

A. Arriaga and A. M. Eiró
Centro de Fisica Nuclear da Universidade de Lisboa, 1699 Lisboa Codex, Portugal

(Received 12 December 1985)

The ^{2}H(d, γ)^{4}He cross section was measured for deuteron laboratory energies between 0.7 and 4.5 MeV. Angular distributions were obtained at laboratory energies of $E_d = 1.38$, 2.05, 9.6, and 15.0 MeV. These data indicate that the D state of ^{4}He, which can be populated via S-wave capture in this reaction, has a large effect on the energy and angle dependence of this low energy capture cross section. The data are shown to imply an asymptotic D-to-S state ratio $\rho = -0.2 \pm 0.05$. The implication of this observation for the absolute cross section below 1.0 MeV is discussed.

I. INTRODUCTION

The energy dependence of the cross section of the ^{2}H(d,γ)^{4}He reaction and its inverse have been studied previously in the energy range 3.0 MeV $< E_d <$ 60 MeV.[1–4] More recently, polarized capture reaction measurements have been performed by Weller *et al.*[5] and by Mellema *et al.*[6] at deuteron energies of 9.6 MeV and 10.0 MeV, respectively. The theoretical analysis[7] of the tensor analyzing power data indicates a strong sensitivity to the D-state component of ^{4}He.

The identity of the colliding particles (bosons) in the entrance channel restricts the scattering states $^{2S+1}L_J$ to those for which the channel spin S has the same parity as the orbital angular momentum L. With multipoles of order $L \leq 2$ the allowed transitions are therefore[7] ($E1$;$^3P_1$), ($M1$;$^5D_1$), ($E2$;$^1D_2$), ($E2$;$^5S_2$), ($E2$;$^5D_2$), ($E2$;$^5G_2$), ($M2$;$^3P_2$), and ($M2$;$^3F_2$). Conservation of isospin in a self-conjugate nucleus implies that (in the long wavelength approximation) the $E1$ transition is forbidden and that the $M1$ transition is suppressed between states with the same isospin.[8] The $E2$ transition is therefore expected to be dominant. In fact, down to an energy of $E_d = 10$ MeV the differential cross section has a distinct $\sin^2 2\theta$ shape characteristic of an $E2$ transition from the $^1D_2$ scattering state to the $^1S_0$ component of the ^{4}He ground state. The $^5D_0$ component of ^{4}He, although it has a much smaller probability, can be populated via $E2$ transitions from the initial states $^5S_2$, $^5D_2$, and $^5G_2$, all with channel spin 2. As the deuteron incident energy is decreased, the centrifugal barrier will suppress scattering states with L different from zero relative to the $L = 0$ scattering state ($^5S_2$). Thus we expect the effect of the ^{4}He D state to increase noticeably at low energy. The present paper reports on cross section measurements at various scattering angles in the energy range $0.7 < E_d < 15.0$ MeV. The sensitivity of these results to the ^{4}He D state will be discussed and the value of the asymptotic D state to S state ratio ρ is estimated.

II. EXPERIMENTAL

The data to be reported in this paper were obtained using the TUNL FN tandem Van de Graaff accelerator to provide beams of deuterons between 2.5 and 15 MeV. The γ rays were detected using our two anticoincidence shielded 25.4 cm$\times$25.4 cm detectors,[9] positioned so that their solid angle of acceptance was 45 msr. Typical spectra, along with "standard" line-shape fits[9] are shown for two different energies in Fig. 1.

The targets used in the present work were of two types. In the case of the 10 and 15 MeV beams, the target consisted of a liquid nitrogen cooled gas cell having a diameter of 1.9 cm. Entrance and exit windows consisted of 0.0064 mm thick tantalum foils. A suppressed Faraday cup positioned 7 cm in back of the target was used to integrate the beam. This cooled gas cell was operated at a pressure of 414 kPa.

A second target arrangement was employed for the lower energy 130° (θ_{lab}) yield curve ($E_d < 5$ MeV) and the low energy angular distributions. This was necessary in order to achieve accurate beam current integration. This target consisted of a thin walled tantalum lined gas cell having an entrance window of 5.65 mg/cm^2 Havar. In this case the gas cell was 2.5 cm long and the beam was stopped in the cell on a thick 1 mm Ta disc. The entire cell, which was isolated from the beam pipe and was suppressed, served as the Faraday cup.

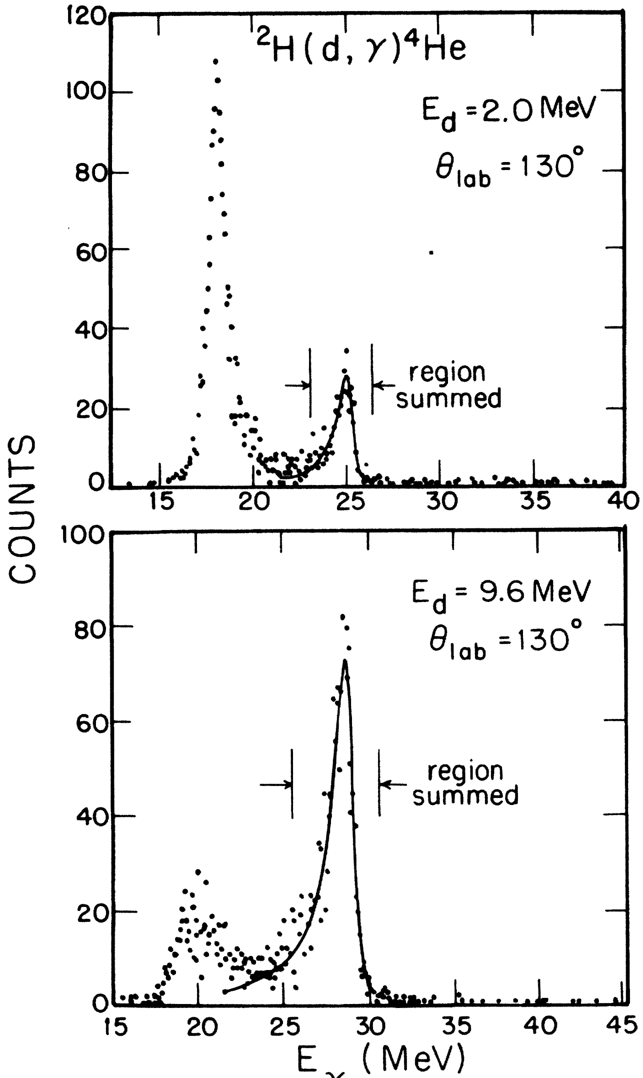

FIG. 1. Spectra at $E_d=2.0$ and 9.6 MeV at $\theta_{lab}=130°$ along with the line-shape fits. Summing regions are indicated.

The lower energy measurements were performed using degrading foils to reduce the beam energy. The energy loss in the foils as well as that in the gas was measured in a separate experiment. In this work the direct deuteron beam was incident on a thin gold foil and the elastically scattered deuterons were detected in a solid state detector. This detector was contained in a small chamber which had a foil entrance window and to which deuterium gas could be added. The energy of the scattered deuterons was calculated from the known beam energy and kinematics and measured without foil and without gas with a calibrated solid state detector. Measurements were then made with foil(s) and gas of varying amounts in the chamber. It was found, for example, that if a 3.0 MeV beam were incident on a 5.65 mg/cm^2 Havar foil, a 2.4 MeV beam emerged. This beam was further reduced to 1.7 MeV by the addition of deuterium gas having a pressure of 193 kPa. Therefore, the mean energy was 2.05 MeV with a spread of from 1.7 to 2.4 MeV. Table I shows the experimental conditions and the mean energies used for these measurements. The 10 MeV data corresponded to a center-of-target energy of 9.6 MeV.

Each spectrum was fitted by our standard line shape to determine a centroid and a width. A sum was then obtained by integrating the data from a point two widths below the centroid to a point one width above it. The summing regions are indicated in Fig. 1. A correction for cosmic ray background not rejected by the shield was made by summing the flat region above the peak and, after normalizing this sum to correspond to the number of channels included in summing the data, subtracting this from the data sum. In all cases this amounted to less than a 10% correction.

III. THEORY AND RESULTS

In the analysis of the present data it is assumed that the transition is dominated by $E2$ radiation. This is likely to be a very good approximation at energies sufficiently low so that the d-d fusion in relative $P,D,\ldots$ states is strongly suppressed by centrifugal barrier effects relative to fusion in an S state. The $E1$ transition is expected to be very weak because it is forbidden by isospin selection rules and also because it requires an initial $^3P_1$ state. The $M1$ transition requires an initial $^5D_1$ state and therefore is strongly inhibited as the energy goes below 2 or 3 MeV.

The initial states $^1D_2$, $^5S_2$, $^5D_2$, and $^5G_2$ for the $E2$ transition can be mixed by the tensor force part of the nuclear interaction since they all have $J=2$. However, the mixing of these $J=2$ states should become negligible at energies close to the Coulomb barrier since at these ener-

TABLE I. Energy conditions for various target configurations.

E_{beam} (MeV)	No. of 0.0064 mm Havar foils	Gas pressure (kPa)	E_{min} (MeV)	E_{max} (MeV)	$\bar{E}$ (MeV)
2.5	2	145	0.4	1.0	0.7
2.5	1	193	0.9	1.9	1.4
3.0	1	193	1.7	2.4	2.05
3.85	1	290	3.1	3.5	3.3
5.0	1	290	4.4	4.6	4.5
10.0	Ta foil (0.0064 mm)	414 cooled	9.3	9.9	9.6
15.0	Ta foil (0.0064 mm)	414 cooled	14.7	15.0	14.85

gies nuclear distortions are small. Although we neglect $J=2$ mixing in the present calculations, this effect may be important at higher energies.

Under the above assumptions the differential cross section for the radiative capture reaction is, apart from numerical and statistical factors, given by

$$\sigma(\theta) \propto \frac{E_\gamma^5}{p} T(\theta), \tag{1a}$$

where E_γ is the energy of the γ ray and p is the incident deuteron center of mass momentum. The angular dependence is contained in

$$\begin{aligned} T(\theta) = {} & \tfrac{3}{4}(|A|^2 + \tfrac{2}{7}|C|^2)\sin^2 2\theta + 2\left|B - \frac{C}{2\sqrt{14}}(3\cos^2\theta - 1)\right|^2 + \tfrac{9}{28}|C|^2(1-\cos^4\theta) \\ & + \frac{|D|^2}{126}(17 + 60\cos^2\theta - 45\cos^4\theta) + \frac{2}{3\sqrt{14}}\mathrm{Re}(BD^*)(-35\cos^4\theta + 30\cos^2\theta - 3) \\ & + \tfrac{2}{21}\mathrm{Re}(CD^*)(25\cos^4\theta - 24\cos^2\theta + 3), \end{aligned} \tag{1b}$$

where in the notation of Ref. 7, A, B, C, and D are the $E2$ amplitudes corresponding to the initial states ${}^1D_2$, ${}^5S_2$, ${}^5D_2$, and ${}^5G_2$, respectively. In the absence of ^{4}He D-state effects $B=C=D=0$, and Eqs. (1) give the well-known $\sin^2 2\theta$ angular dependence for $\sigma(\theta)$. The amplitudes A, B, C, and D were calculated as in Ref. 7 using scattering wave functions generated with separable potentials constrained to give the energy dependence of the phase shifts of the wave functions obtained by Chwieroth, Tang, and Thompson[10] using the resonating group method. Previous calculations included only nuclear distortion. However, at the energies of the present experiments, the Coulomb repulsion between the deuterons in the entrance channel must be taken into account. This effect was estimated using an energy dependent Coulomb penetration factor P_C for each $E2$ amplitude. P_C was assumed to be given as the square of the ratio between the $E2$ amplitude calculated with a distorted wave generated by representing each deuteron as a uniform charge distribution with a radius equal to the deuteron rms radius, and the $E2$ amplitude calculated with a plane wave of the same energy. A point deuteron approximation for the $E2$ operator was used, as in Ref. 7. With this approximation the $E2$ amplitudes depend on the ^{4}He internal structure through the overlap with the two deuteron bound state wave functions $\langle \phi_d \phi_d | \phi_\alpha \rangle$. The S- and D-state radial wave functions $u_{L'}(r)$ of the overlap can be written as

$$u_{L'}(r) = \sqrt{P_{L'}}\, u_{L'}^N(r), \tag{2}$$

where $P_{L'}$ are the corresponding probabilities and N denotes that the functions $u_{L'}^N(r)$ are normalized to unit probability. The total probability for finding two isospin-zero pairs in ^{4}He simultaneously in deuteron states can be written as

$$P = P_S + P_D . \tag{3}$$

By calculating the $E2$ amplitudes with the radial bound state wave functions $u_{L'}(r)$, it is clear that upon substituting into Eq. (1) the dominant probability P_S factorizes and may therefore be determined from a comparison between experimental and theoretical cross sections. The spin-isospin configuration of the ${}^1S_0$ component of the ^{4}He ground state wave function implies that the probability of two spin-zero isospin-one n-p pairs is $\frac{1}{6}$, while the probability of two spin-one isospin-zero n-p pairs is $\frac{1}{2}$. Note also that the probability of two spin-zero isospin-one clusters of identical nucleons is $\frac{1}{3}$. Therefore the total number of deuterons in ^{4}He is, to a good approximation, $3P$.

Asymptotically

$$u_{L'}(r) \underset{r\to\infty}{\longrightarrow} -N_{L'} i^{L'} h_{L'}(i\alpha r), \tag{4}$$

where $\alpha = 1.072$ fm^{-1} is the wave number corresponding to the separation of two deuterons from ^{4}He. The asymptotic D state to S state ratio is defined as

$$\rho = \frac{N_2}{N_0} . \tag{5}$$

The ratio of the asymptotic amplitudes of the *normalized* radial wave functions $u_{L'}^N(r)$ is

$$\rho' = \frac{\sqrt{P_S}}{\sqrt{P_D}}\rho . \tag{6}$$

In the present calculations the $u_{L'}(r)$ were generated in a Woods-Saxon potential ($r_0 = 1.5$ fm, $a = 0.5$ fm) with a well depth constrained to give the same separation energy for the S and D states. It should be emphasized that in a low energy experiment we are more likely to obtain a reliable estimate of ρ than of P_D. This is because at low energies the D-state effects are almost entirely determined by the asymptotic behavior of $u_{L'}(r)$ and therefore by ρ and α. Equation (6) shows that to estimate P_D we also need to know ρ', which depends on the unknown short range behavior of the model dependent wave functions $u_{L'}^N(r)$.

Figure 2 shows the measured angular distributions at $E_d = 2.05$ and 9.6 MeV along with calculations for different values of ρ. The calculated curves shown here were corrected for the finite geometry effects of the experiment by performing the appropriate integrations on the point geometry calculated angular distributions. The cross section at the lower energy deviates considerably from the $\sin^2 2\theta$ shape at $\theta = \pi/2$. As the deuteron energy is

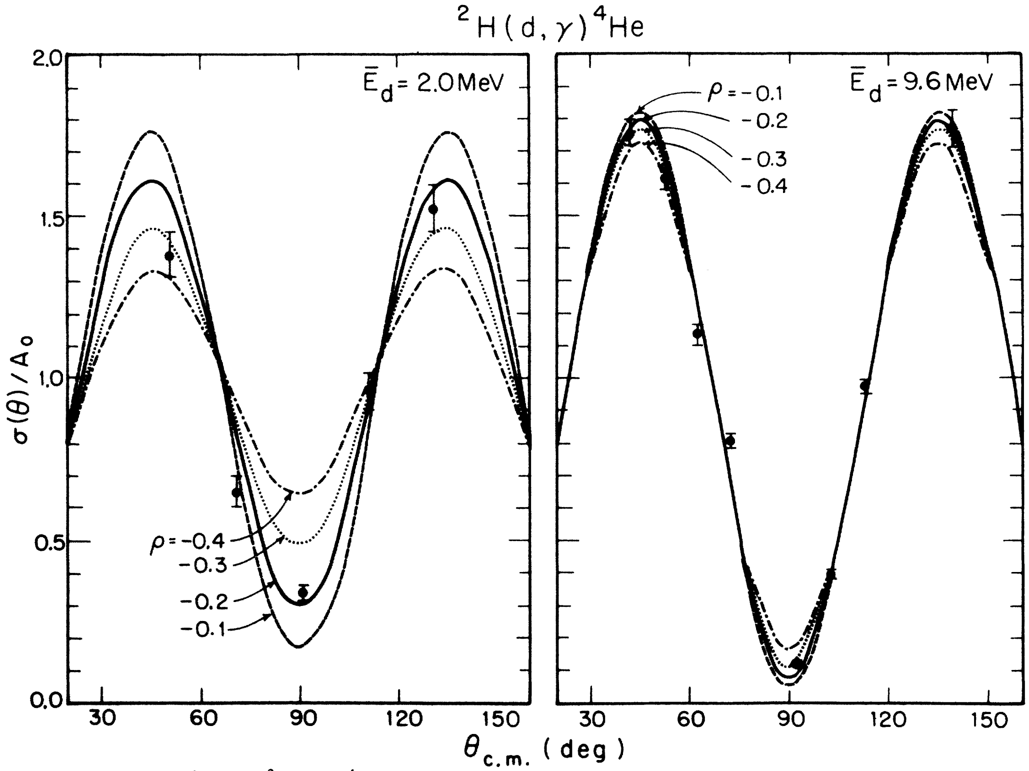

FIG. 2. Angular distributions for the ^{2}H(d,γ)^{4}He reaction at $E_d = 2.05$ and 9.6 MeV. Cross sections are in the center-of-mass frame. The solid curves are the result of the calculations described in the text. Statistical uncertainties are indicated. (Note the existence of the data point at $\theta_{c.m.} = 92°$ for $E_d = 9.6$ MeV.)

lowered, the cross section ratio $R = \sigma(\pi/2)/\sigma(3\pi/4)$ is expected to increase. Figure 3 shows a comparison between our experimental data at several deuteron energies and calculations for various values of ρ. The experimental values were obtained from our measured angular distributions (see Fig. 2) along with the results of previous work.[4] Although the precise center of mass angles were not measured (90°, 135°), the nearby data points at $\theta_{c.m.} = 92°$, 131° were extrapolated to these angles using the results of a Legendre polynomial fit to the data. The best fit to experiment is obtained for $-0.25 < \rho < -0.15$. The corresponding D-state probability P_D implied by our model calculation if we assume that $P = 1$ was between 5% and 13%. The sign of ρ has been established from calculations of the functions[11–13] $u_{L'}(r)$, and confirmed by the analysis of tensor polarization measurements in the ^{2}H(d,γ)^{4}He reaction[5,7] and in the (d,α) reaction.[14,15] The calculated values of R shown in Fig. 3 were corrected for finite geometry effects as mentioned above. The need for a higher value of ρ was observed in the analysis[7] of the tensor analyzing powers at $E_d = 9.7$ MeV. The discrepancy might be due to the point deuteron approximation in the $E2$ operator, mixing of $J = 2$ states, or the contribution from other multipoles, especially $M1$ and $M2$, at the higher energies. Calculations including these effects are in progress.

The increase in the calculated angle integrated cross section with respect to a pure S-state ^{4}He calculation at low energies, as shown in Fig. 4, is due to the presence of the $^5S_2$ amplitude B. The effect becomes increasingly pronounced as the energy is lowered. The data shown in Fig. 4 for the present work were obtained from the $\sigma(131°)$ data using the calculated angular distributions. Previous works include those of Ref. 16 (see below) which were converted from branching ratios to σ_T values using the cross sections for the ^{2}H(d,p)^{3}H reaction from Ref. 17, as well as the data from Refs. 1–3. As can be seen in Fig.

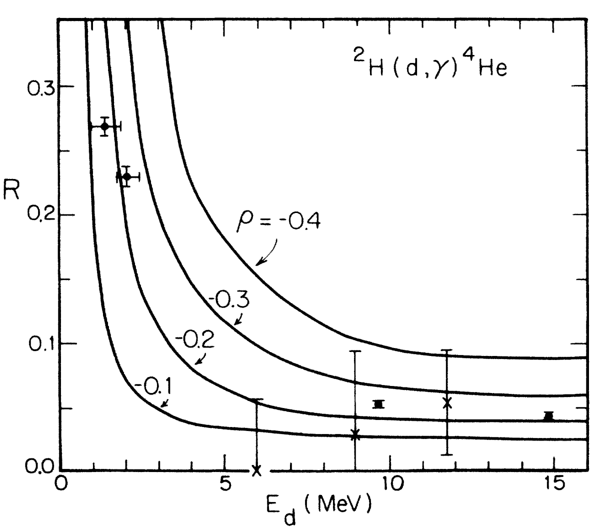

FIG. 3. The ratio $R = \sigma(90°)_{c.m.}/\sigma(135°)_{c.m.}$ as a function of E_d(lab). Theoretical predictions of R are shown for various values of ρ. The calculations have been corrected for experimental finite geometry and energy averaging effects. Dots represent present results; ×'s are from Ref. 4. Statistical uncertainties are indicated.

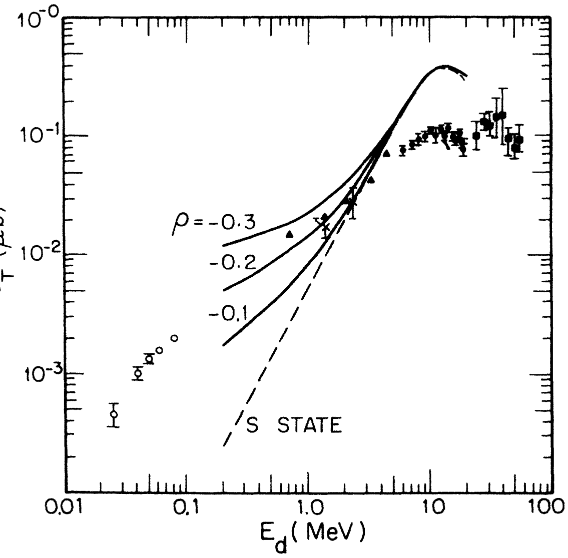

FIG. 4. The angle integrated ^{2}H(d,γ)^{4}He cross sections are shown as a function of energy for the present work (▲), the data of Ref. 1 (×), the data of Ref. 2 (●), the data of Ref. 3 (■), and the data of Ref. 16 (○). Statistical uncertainties are indicated. Absolute cross sections are uncertain to $\pm 15\%$ for the present work. Theoretical predictions are for a pure S-state ^{4}He (broken curve) and for the asymptotic D state to S state parameter ρ equal to -0.3, -0.2, and -0.1 (full curves).

4, σ_T is quite sensitive to the value of ρ, especially for deuteron energies below 2 MeV. Calculations of the angle integrated cross section were performed in the deuteron energy range $0.2 < E_d < 20$ MeV and normalized so that the result with $\rho = -0.2$ best fit the data in the $1 < E_d < 4$ MeV region. The discrepancy between theory and experiment for deuteron energies above 4 MeV is probably due to contributions from other multipoles besides $E2$ and also from the 2^+ resonance[2] in ^{4}He.

Wilkinson and Cecil[16] have reported measurements of the Γ_γ/Γ_p branching ratio for the d + d reaction for deuteron bombarding energies ranging from 50 to 150 keV. They find that the branching ratio Γ_γ/Γ_p is surprisingly large and almost independent of energy for deuteron energies below 2 MeV. This result was interpreted as an indication of a strong $M1$ transition.[16] However, it is more likely that at these low energies both the ^{2}H(d,p)^{3}H and the ^{2}H(d,γ)^{4}He reactions proceed predominantly from an initial continuum S state. For the radiative capture reaction this means that the transition is $E2$ from an initial $^5S_2$ state going to the D state in ^{4}He.

The $M1$ transition should not be important at these very low energies since it requires an initial $^5D_1$ state. The experimental results of Ref. 16, converted to σ_T using Ref. 17, are shown in Fig. 4. Although the present model calculations have not been extended to the energy region of these results, it seems likely that $E2$ capture to the D state of ^{4}He is a key to understanding this low energy cross section. For deuteron energies below 0.2 MeV, effects such as those which could arise from including an extended deuteron form in the $E2$ operator and deuteron polarizability in the Coulomb field should be taken into account before quantitative comparisons with experiment are attempted.

The present results indicate the presence of large ^{4}He D-state effects in the ^{2}H(d,γ)^{4}He reaction at low energies. The analysis of the data gives an asymptotic D state to S state ratio ρ in the range $-0.25 < \rho < -0.15$. These results indicate that the D state of ^{4}He can enhance the calculated cross section for the ^{2}H(d,γ)^{4}He reaction by an order of magnitude near $E_d = 1.0$ MeV. Although it may be expected that these low energy data provide a rather reliable estimate of ρ, further efforts should be made to improve the theory describing the reaction.

The data reported in this paper have been deposited with the Physics Auxiliary Publication Service of AIP.[18]

This work was supported by the U.S. Department of Energy, Office of High Energy and Nuclear Physics, under Contract No. De-AC05-76ER01067.

---

*Present address: Lockheed Corporation, Palo Alto, CA 94304.
†Permanent address: Institute of Atomic Energy, Beijing, China.
‡Permanent address: Centro de Fisica Nuclear da Universidade de Lisboa, Av. Gama Pinto 2, 1699, Lisbon Codex, Portugal.

[1]R. Zurmuhle, W. Stephens, and H. Straub, Phys. Rev. **132**, 751 (1963).
[2]W. E. Meyerhof, W. Feldman, S. Gilbert, and W. O'Connell, Nucl. Phys. **A131**, 489 (1969).
[3]D. M. Skopik and W. R. Dodge, Phys. Rev. C **6**, 43 (1972).
[4]J. M. Poutissou and W. Del Bianco, Nucl. Phys. **A199**, 517 (1973).
[5]H. R. Weller, P. Colby, N. R. Roberson, and D. R. Tilley, Phys. Rev. Lett. **53**, 1325 (1984).
[6]S. Mellema, T. R. Wang, and W. Haeberli, Bull. Am. Phys. Soc. **30**, 1268 (1985); Phys. Lett. **166B**, 282 (1986).
[7]F. D. Santos, A. Arriaga, A. M. Eiró, and J. A. Tostevin, Phys. Rev. C **31**, 707 (1985).
[8]E. K. Warburton and J. Weneser, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), p. 185.
[9]H. R. Weller and N. R. Roberson, IEEE Trans. Nucl. Sci. **NS-28**, No. 2, 1268 (1981).
[10]F. S. Chwieroth, Y. C. Tang, and D. R. Thompson, Nucl. Phys. **A189**, 1 (1972).
[11]F. D. Santos, S. A. Tonsfelt, T. B. Clegg, E. J. Ludwig, Y. Tagishi, and J. F. Wilkerson, Phys. Rev. C **25**, 3243 (1982).
[12]F. D. Santos and A. M. Eiró, Port. Phys. **15**, 65 (1984).
[13]J. A. Tostevin, J. Phys. G **11**, L211 (1985).
[14]B. C. Karp, E. J. Ludwig, W. J. Thompson, and F. D. Santos, Phys. Rev. Lett. **53**, 1619 (1984).
[15]J. A. Tostevin, J. M. Nelson, O. Karban, A. K. Basak, and S. Roman, Phys. Lett. **149B**, 9 (1984).
[16]J. F. Wilkinson III and F. E. Cecil, Phys. Rev. C **31**, 2036 (1985).
[17]Nelson Jarmie and Ronald E. Brown, Nucl. Instrum. Methods

Phys. Res. **B10/11**, 405 (1985); and F. E. Cecil, private communication.

[18]See AIP document no. PAPS PRVCA-34-32-2 for two pages of tabulated data. Order by PAPS number and Journal reference from American Institute of Physics, Physics Auxiliary Publication Service, 335 East 45th Street, New York, NY 10017. The price is $1.50 for each microfiche or $5.00 for photocopies. Airmail additional. Make checks payable to the American Institute of Physics.