Singlet deuteron production in the ^{4}He($d,p\alpha$)n reaction at 7 MeV

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The cross section and transverse tensor analyzing power $^TT_{20}$ have been measured in kinematically complete geometry for the ^{4}He($d,p\alpha$)n reaction at 7 MeV. Kinematic conditions were chosen to correspond to production of the singlet deuteron (d^*) near a c.m. angle of 100°. The data show clear evidence for production of the d^*. A comparison of the measured cross sections and analyzing powers with the results of three-body calculations shows good agreement in the kinematic region away from that in which the d^* is produced, but this agreement worsens as the region in which $E_{np}=0$ is approached. In this region, the data are reproduced qualitatively by a calculation which includes the singlet n-p interaction as well as an improved approximation to the p-α Coulomb interaction, but the magnitude of the cross section is underpredicted in this calculation.

I. INTRODUCTION

The breakup of deuterons in $d+\alpha$ collisions has been studied experimentally and theoretically for several decades. Much of the interest in this reaction results from the simple nature of the d-α system, since for c.m. energies less than about 20 MeV, the alpha particle can to a good approximation be treated as an inert spinless particle. Whereas the results of most of the early work on this reaction were analyzed with the impulse approximation or some type of final-state-interaction (FSI) formalism, the theoretical approach most commonly used within the last decade has been based on the three-body method of Faddeev. In these calculations the nucleon-nucleon and nucleon-alpha interactions are represented by separable potentials in each of the partial waves, which permits a realistic calculation of the alpha $+\,d$ system and the breakup of the deuteron on the alpha particle. In the analysis of the data, the calculations have been marked by a progressive refinement in the interactions used in the two-body channels. This is particularly true of the experiments in which measurements of polarization observables have provided more stringent tests of the calculations. The most serious limitation of these calculations, at least at low energies, is that no straightforward procedure has been found for treating the p-alpha Coulomb interaction in a satisfactory way.

Two papers by Y. Koike[1,2] contained the first application of the three-body technique to the $d+\alpha$ breakup reaction. The first contains calculations for the kinematically complete reaction ^{2}H($\alpha,\alpha p$)n over the range $E_\alpha=15-42$ MeV. In a subsequent paper,[2] these calculations were extended to cross sections and polarization observables for the ^{4}He(d,p)^{4}He$\,n$ and ^{2}H(α,n)^{4}He$\,p$ reactions. The calculations in these papers are in impressive agreement with the data in most of the cases considered. These first calculations included only the central triplet S-wave interaction in the n-p channel. The tensor interaction was later introduced in a report by Ishikawa *et al.*,[3] which included measurements of tensor analyzing powers. The cross-section and vector-analyzing-power data were well reproduced by their calculation using only the central n-p triplet force, but the tensor-analyzing-power data required the inclusion of the n-p tensor force for even a qualitative fit.

A point of considerable interest in $d+\alpha$ breakup has been the extent to which the singlet deuteron (d^*) is produced in the reaction. In a paper on the kinematically complete ^{2}H($\alpha,p\alpha$)n reaction, Rausch *et al.*[4] reported evidence for d^* production in the shapes of their energy-sharing distributions in the kinematic region where the n-p relative kinetic energy in the final state is zero ($E_{np}=0$). On the basis of an analysis of the maximum in the cross section in this region using the Watson-Migdal[5,6] formalism, these authors concluded that the data could not be adequately described without including the n-p singlet interaction in the final state. In a similar experiment, Bruno *et al.*[7] analyzed their data in the kinematic region appropriate to d^* production employing both a modified impulse approximation and a three-body calculation. In the impulse-approximation calculation, the data could be reproduced only if the single n-p interaction was included. The three-body calculation did not include the $^1S_0$ interaction, and did not reproduce the observed enhancement in the cross section. This was taken to be evidence of isospin-breaking effects resulting in d^* production. In a later investigation, however, Bruno *et al.*[8] commented that the above interpretation is open to question since the region of the maximum is close to those in which strong N-α FSI peaks occur. Recently, Bruno *et al.*[9] have published ^{2}H($\alpha,\alpha p$)n cross-section measurements at $E_\alpha=11.3$ MeV for kinematic conditions corresponding to d^* c.m. emission angles between 33° and 47.5°, and 97°. From a comparison of their data with three-body calculations[10] which include an improved treatment of the p-α Coulomb interaction as well as the $^1S_0 n$-p interaction, they concluded that d^* production is much greater for θ_d^* between 33° and 47.5° than it is at $\theta_d^*=97°$. This conclusion was based on the fact that cross-section maxima occurring at a point on the kinematic locus where the n-α ($E_{n\alpha}\approx 0.9$ MeV) and the n-p ($E_{np}\approx 0$) FSI are both present are generally larger than predicted by calculations which omit the $^1S_0$ interaction, whereas calculations which include this interaction predict much stronger maxima. For the case in which $\theta_{d^*}=97°$, no significant maximum was observed. Not all searches for d^* production have yielded positive results. DeVries *et al.*[11] and Bruno *et al.*[12] reported experiments in which no evidence for singlet deuteron production was found.

Since the production of the d^* can be considered a two-body reaction having the spin structure $1^+ + 0^+ \rightarrow 0^+ + 0^+$, angular momentum and parity conservation[13] require that the total angular momentum be related to the orbital angular momentum in the entrance and exit channels by $J=L=L'$. This implies that the only deuterons which can initiate d^* production are those in the $m=0$ substate relative to a spin-quantization axis normal to the scattering plane. The corresponding transverse analyzing power $^TT_{20}$ (defined in Sec. III) for this reaction has the maximum possible negative value, $-\sqrt{2}$. Thus if a maximum in the cross section is to be interpreted as evidence for d^* production, it must also be accompanied by a corresponding minimum in $^TT_{20}$, provided, of course, that the d^* maximum does not coincide with any N-α FSI peaks with which it might interfere. Steigenhöfer and von Witsch[14] exploited this property of the reaction in an experiment in which they employed a tensor-polarized deuteron beam to initiate the ^{4}He$(d,p\alpha)n$ reaction. The dependence on beam polarization of the magnitude of an enhancement in the cross section at $E_{np}=0$ was measured. Within the uncertainties in the measurements, the dependence found corresponds to what would be expected if the enhancement were due to d^* production.

A theoretical treatment of d^* production in $d+\alpha$ breakup was reported in 1981 by Werntz and Cannata.[15] These authors used an impulse-approximation calculation including second-order terms in the N-α scattering. They also investigated isospin mixing between adjacent 2^+ states in ^{6}Li as a possible cause of d^* production and concluded that it does not play a significant role. Their calculations predict enhanced d^* production at low deuteron bombarding energies for d^* c.m. angles in a broad range around 90°.

The published reports claiming evidence for d^* production in the breakup reaction are susceptible to some criticism. In a comprehensive and critical review[16] of experimental and theoretical work on this question, C. Heinrich has raised a number of objections to the claims that convincing evidence for d^* production has been found. For example, in the case of Watson-Migdal analyses of maxima in the cross section near $E_{np}=0$, the background contributions from amplitudes corresponding to N-α FSI and their interference with each other and with the n-p FSI amplitudes are largely unknown away from the N-α FSI peaks. Consequently, any analysis which oversimplifies these amplitudes and neglects their coherence is open to some question. The fact that some Faddeev-type calculations[17] which include *no* n-p singlet interaction can predict a maximum in the cross section at the point where $E_{np}=0$ shows that the simple presence of a peak in the spectrum at this relative energy is not sufficient evidence for the production of the d^*. With regard to the tensor analyzing powers, the calculations of Ref. 3 and those in the present report predict in some cases a large negative $^TT_{20}$ in the general region where $E_{np}=0$, even when no singlet n-p interaction is used in the calculations.

It would clearly be useful to have three-body calculations which include both triplet and singlet n-p interactions and to have both cross-section and tensor-analyzing-power measurements so that the corresponding effects could be cleanly identified and distinguished. The present experiment was undertaken in order to provide such data. Measurements on ^{4}He$(d,p\alpha)n$ initiated by tensor-polarized deuterons were made at the lowest practical energy of 7 MeV for a d^* c.m. angle near 90°. We concentrated on one set of angles in order to ensure adequate statistical accuracy. Our choice of bombarding energy and c.m. angle was guided by the calculations of Werntz and Cannata[15] who predicted an enhanced d^* production at low energy for $\theta_d^* \sim 90°$. Although the results of Ref. 9 indicate a relatively low d^* production cross section near $\theta_d^* \approx 100°$, the present measurements have been made at a higher equivalent bombarding energy, and in addition, we considered it important to look for d^* production in a kinematic region free of other FSI peaks. Three-body calculations, including those incorporating the $^1S_0 n$-p interaction, are also presented.

II. EXPERIMENTAL DETAILS

The measurements were carried out with tensor-polarized deuterons produced in the Notre Dame Lamb-shift polarized ion source and accelerated through the FN tandem accelerator. Beam polarization was monitored with a tensor polarimeter mounted at the beam exit port of the scattering chamber. The polarimeter, which also served as a Faraday cup for charge integration, utilized the ^{3}He$(d,p)^4$He reaction.[18] Typical values for the polarization relative to the spin-symmetry axis of the beam were $\tau_{20}=-0.45$ with a vector polarization of $\tau_{10}=0.10$. The measurements were made at a deuteron bombarding energy of 7.0 MeV. Alpha particles emitted at a laboratory angle of 32° were detected in coincidence with protons emitted at a laboratory angle of 62° on the opposite side of the beam line. The corresponding d^* c.m. emission angle is $\sim 98°$. Four silicon surface-barrier detectors arranged in symmetric pairs on opposite sides of the beam served to detect the protons and alpha particles. All detectors were in the horizontal plane at a distance of 67.5 mm from the center of the scattering chamber. The detectors had identical collimating slits consisting of a vertical front slit 1.5 mm wide $\times 8.4$ mm high at a distance of 21 mm from the target center, and a rear slit 3 mm wide $\times$ 8 mm high placed 1 mm in front of the dector face.

The target consisted of ^{4}He gas at a pressure of 0.1 atm. absolute, filling the entire scattering chamber so as to avoid the energy loss associated with the use of target-cell windows. The gas was separated from the beam line vacuum at beam entrance and exit ports by 4-μm-thick stainless steel foil. Pulses from the detectors were preamplified at the scattering chamber and sent to conventional fast-coincidence circuitry in the accelerator control room. Coincidence events in both pairs of detectors were digitized and stored in four-parameter (alpha particle energy, proton energy, time-of-flight difference, and a number indicating in which detector pair the event occurred) form on magnetic tape.

The polarized beam current on target was typically of the order of 50 nA. Measurements were made with the beam alternately unpolarized and tensor polarized with the quantization axis normal to the scattering plane. Individual runs in each mode lasted several hours. On-line analysis of the data events permitted display of two-parameter coincidence spectra showing events distributed along the kinematic locus in the E_α-E_p plane. In addition to the breakup events, these spectra contained horizontal and vertical bands of random coincidence events in which one of the pulses corresponded to either an elastically scattered deuteron or an elastic recoil alpha particle. These groups, along with the locus of breakup events, served for energy calibration of the spectra. Since the group of elastic recoil alpha-particle pulses from the proton detector in random coincidence with pulses from the alpha detector overlapped the locus of breakup events, a 0.75-μm-thick Ni foil was inserted in front of the proton detectors to stop the recoil alpha particles without excessive reduction in the energy of the breakup protons.

III. ANALYSIS OF THE DATA

The two-parameter (alpha energy and proton energy) spectra were corrected for energy loss in the target gas and, for the protons, in the Ni foils in front of the detectors. Three-body breakup events, distributed in a band along the kinematics locus for the reaction, were projected onto the locus by summing events lying within a band of width ± 350 keV, which was sufficient to contain all coincidence events, and within 150-keV-wide energy bins along the locus. Events within each interval were assigned to the energy corresponding to the midpoint of that interval. We estimate the uncertainty in these energies arising from uncertainty in the energy calibration and from the effect of finite solid angles subtended by the detectors to be no greater than 100 keV. A gate approximately 50 nsec wide was set on the peak in the time-of-flight difference spectrum and only those events whose time pulses were within the gate were included in the data used. Accidental background events were obtained using a gate of the same width in the region of the time spectrum containing only accidental counts. The accidental coincidence rate amounted to about 5% or less of the total coincidence rate over most of the spectrum. In the kinematic region of interest for d^* production, the accidental coincidence rate averaged about 16% of the total coincidence rate. Since the data had been accumulated in a series of measurements, each of which lasted several days, results of all of the measurements were combined to obtain cross sections using polarized and unpolarized beams for each pair of detectors as a function of the energy, S, measured along the kinematic locus. We have followed the practice of previous authors in taking S to be 0 at the point of minimum proton energy on the kinematic locus. The combined coincidence spectrum obtained using unpolarized deuterons is shown by the data of Fig. 1. The data have been corrected for energy loss of the detected particles and for accidental coincidence events, and have been normalized so as to give the laboratory cross section $d^3\sigma/d\Omega_p d\Omega_\alpha dS$.

For coincidence measurements with a gas target the calculation of cross section from the measured yield involves a geometrical G factor which was calculated following the procedure of Ref. 19. The breakup cross section and the tensor analyzing power ${}^T T_{20}$ were calculated as a function of arc length S along the kinematic locus. The relation[20] between the charge-normalized yields using polarized (I) and unpolarized (I_0) beams is given by

$$I = I_0[1+\sqrt{2}\tau_{10}(iT_{11})\sin\beta\cos\phi+\tfrac{1}{2}\tau_{20}T_{20}(3\cos^2\beta-1) + \sqrt{6}\tau_{20}T_{21}\sin\beta\cos\beta\sin\phi - \sqrt{\tfrac{3}{2}}\tau_{20}T_{22}\sin^2\beta\cos2\phi] , \quad (1)$$

where τ_{10} and τ_{20} are the vector and tensor polarizations, respectively, of the beam, β and ϕ are the polar and azimuthal angles, respectively, defining the orientation of its spin quantization axis, and the T_{kq} are the analyzing powers. By using the average of the measured ratios $(I/I_0)_A$ and $(I/I_0)_B$ for the two symmetric pairs of detectors, the iT_{11} and T_{21} terms in (1) drop out and we are left with

$$R = \tfrac{1}{2}[(I/I_0)_A + (I/I_0)_B] = 1+\tfrac{1}{2}\tau_{20}T_{20}(3\cos^2\beta-1) - \sqrt{\tfrac{3}{2}}\tau_{20}T_{22}\sin^2\beta\cos2\phi . \quad (2)$$

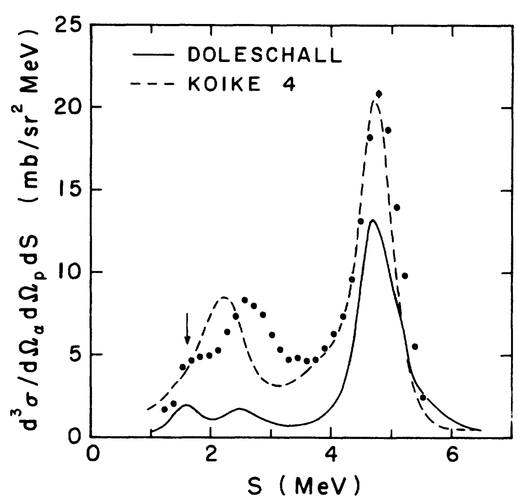

FIG. 1. Laboratory cross section for the ^{4}He$(d,p\alpha)n$ reaction for $\theta_p = 62°$, $\theta_\alpha = 32°$ as a function of S, the laboratory energy along the kinematic locus. Solid circles: measurements; solid line: Doleschall calculation ($M2$ model) including the $^1S_0$ interaction; dashed line: Koike calculation without the $^1S_0$ interaction, 4% deuteron D state.

When the quantization axis is perpendicular to the reaction plane, $\beta=\pi/2$ and $\phi=0$, so that

$$R=1-\tfrac{1}{2}\tau_{20}T_{20}-\sqrt{\tfrac{3}{2}}\tau_{20}T_{22}=1+\tau_{20}{}^{T}T_{20}\ , \tag{3}$$

where ${}^{T}T_{20}=-\frac{1}{2}T_{20}-\sqrt{\frac{3}{2}}T_{22}$ is referred to the "transverse" coordinate system in which the z axis is normal to the reaction plane. For the present measurements, the average values of β and ϕ were $95°\pm2.5°$ and $12°\pm2°$, respectively, so it was necessary to correct for the deviation of these angles from the nominal values. The correction was made by rewriting Eq. (2) as

$$R=1+\tau_{20}{}^{T}T_{20}\sin^2\beta\cos2\phi$$
$$+\tfrac{1}{2}\tau_{20}T_{20}(3\cos^2\beta+\sin^2\beta\cos2\phi-1)\ . \tag{4}$$

The third term is the correction term and has the value $0.0162T_{20}$. Since T_{20} was not determined by our measurements, the values predicted by the calculations of Koike were used to evaluate the correction term at each value of the energy, S. Because of the smallness of the correction term, a conservative estimate of uncertainty of ±0.4 in the calculated values of T_{20} generally produce a negligible contribution to the uncertainty in the ${}^{T}T_{20}$ determined from the data using Eq. (4).

Since the singlet deuteron can only be produced in the breakup reaction when the spin substate of the incident deuteron is $m=0$ relative to a quantization axis normal to the reaction plane, a separation of the cross section into $m=0$ and $m=\pm1$ components is desirable. If we denote by σ_+, σ_0, and σ_- the partial breakup cross sections corresponding to incident deuterons in the $m=1$, 0, and -1 substates of the transverse system, respectively, these cross sections are given by

$$\sigma_0=\sigma_u(1-\sqrt{2}\,{}^{T}T_{20})\ , \tag{5}$$

and

$$\sigma_\pm=\sigma_++\sigma_-=3\sigma_u-\sigma_0\ . \tag{6}$$

In Eqs. (5) and (6), ${}^{T}T_{20}$ and σ_u are the measured tensor-analyzing power and unpolarized cross section, respectively. These equations were used to obtain values of σ_0 and $\sigma_\pm$ from the measured σ_u and ${}^{T}T_{20}$.

IV. RESULTS AND DISCUSSION

The results of the measurements are presented in Figs. 1–8. In each of the figures, the solid circles represent measured points. Error bars include statistical uncertaintes in the measured yields, and for the cross sections do not include an estimated uncertainty of $\pm15\%$ in the absolute normalization. No error bars are given if the uncertainties do not exceed the size of the points. In all cases, the data are given as a function of S, the laboratory energy measured along the kinematic locus. The arrow indicates where $E_{np}=0$.

Figure 1 shows the cross section for an unpolarized beam. Predictions using the three-body program of Koike[2] including a n-p tensor force corresponding to a deuteron D-state probability of 4% but no ${}^1S_0$ n-p interaction are given by the dashed curve. The solid curve shows a calculation of Doleschall.[9,10] using his $M2$ model and including the ${}^1S_0$ n-p interaction. Figure 2 compares the same data to Koike calculations corresponding to D-state probabilities of 0% and 7% as well as to the Doleschall calculation without the ${}^1S_0$ n-p interaction. Figures 3 and 4 present the measured analyzing power ${}^{T}T_{20}$ along with the predictions of the same calculations referred to in connection with Figs. 1 and 2. In these and subsequent figures, the labeling of the calculated curves is the same as in Figs. 1 and 2. Cross sections for incident deuterons in the $m=0$ and $m\pm1$ substates are presented

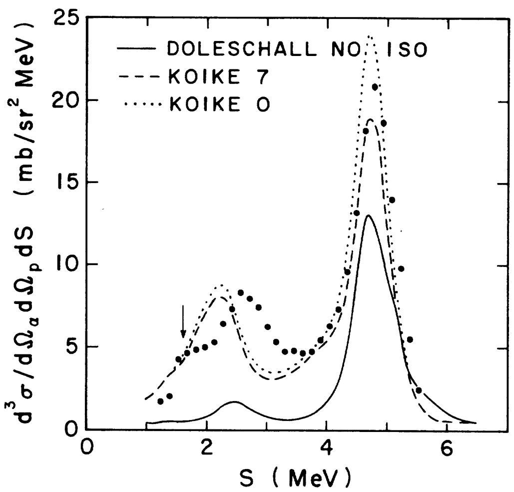

FIG. 2. Laboratory cross section for the ^{4}He$(d,p\alpha)n$ reaction for $\theta_p=62°$, $\theta_\alpha=32°$ as a function of S, the laboratory energy along the kinematic locus. Solid circles: measurements; solid line: Doleschall calculation ($M2$ model) without the ${}^1S_0$ interaction; dashed line: Koike calculation without the ${}^1S_0$ interaction, 7% deuteron D state; dotted line: Koike calculation, 0% deuteron D state.

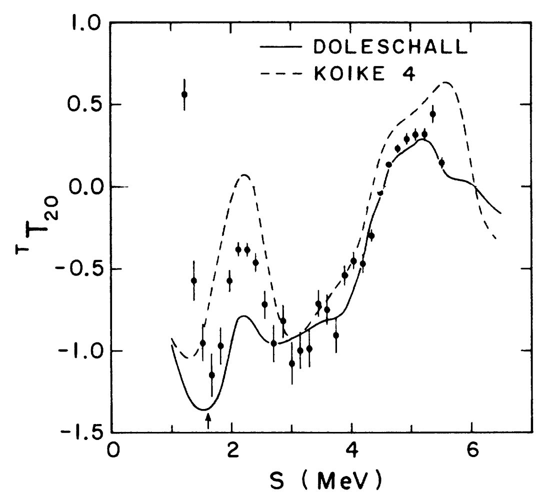

FIG. 3. The transverse analyzing power ${}^{T}T_{20}$ for the ^{4}He$(d,p\alpha)n$ reaction for $\theta_p=62°$, $\theta_\alpha=32°$ as a function of S, the laboratory energy along the kinematic locus. The curves are labeled as in Fig. 1.

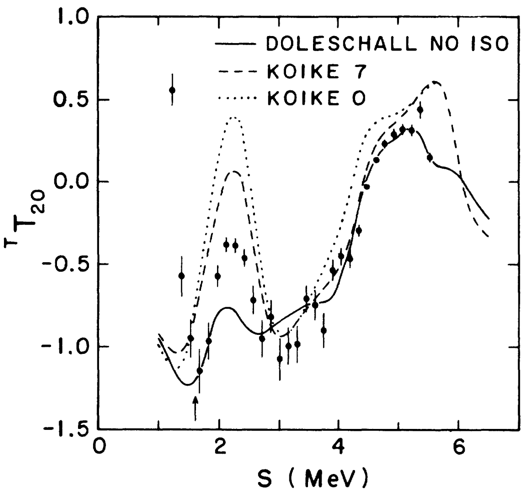

FIG. 4. The transverse analyzing power $^TT_{20}$ for the ^{4}He$(d,p\alpha)n$ reaction for $\theta_p=62°$, $\theta_\alpha=32°$ as a function of S, the laboratory energy along the kinematic locus. The curves are labeled as in Fig. 2.

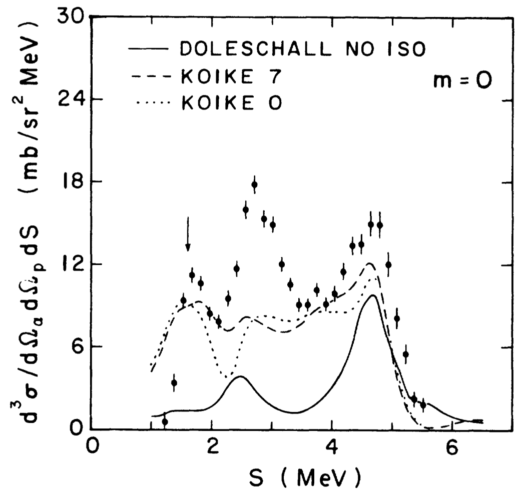

FIG. 6. Cross section for deuterons in the $M=0$ substate. Curves are labeled as in Fig. 2.

in Figs. 5 and 6 and in Figs. 7 and 8, respectively.

Strong peaks corresponding to the ^{5}He ground-state FSI are evident in the cross sections in Figs. 1 and 2 at values of $S=2.5$ and 4.8 MeV. ^{5}Li g.s. FSI peaks are expected to occur at $S=2.5$ MeV and $S=4.2$ MeV, but they appear to be less prominent than the ^{5}He peaks. All of the Koike calculations reproduce the magnitudes of these peaks very well, with the best agreement being for the calculation in which the D-state probability is 4%. Positions of both of the ^{5}He peaks are correctly given by the Doleschall calculations but the magnitudes are seriously underpredicted. The point on the kinematic locus at which $E_{np}=0$ occurs at $S=1.60$ MeV, and a shoulder in the measured cross section is evident in this region. As mentioned above, the Koike calculation does not include the $^1S_0$ interaction in the n-p channel, and no such enhancement in the cross section is predicted by these calculations. On the other hand, the Doleschall calculations support the identification of this increase in the cross section with the production of the d^*, since the calculation which includes the $^1S_0 n$-p interaction clearly shows a peak where $E_{np}=0$, while the calculation which omits this interaction does not. As is the case for the ^{5}He g.s. peaks, the magnitude of the d^* peak in the calculation is somewhat smaller than the measured value, but the position of the peak is in good agreement with the data.

Figures 3 and 4 present the measured and calculated analyzing power. The measured $^TT_{20}$ varies over a large range, from a minimum of -1.1 to a maximum of almost 0.6. A pronounced minimum occurs close to the region where $E_{np}=0$. All of the calculations reproduce the magnitude of this minimum relatively well, but the positions of the calculated minima are at lower energies than

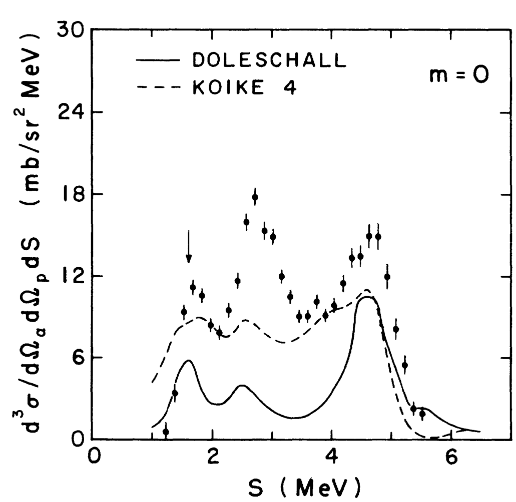

FIG. 5. Cross section for deuterons in the $m=0$ substate. Curves are labeled as in Fig. 1.

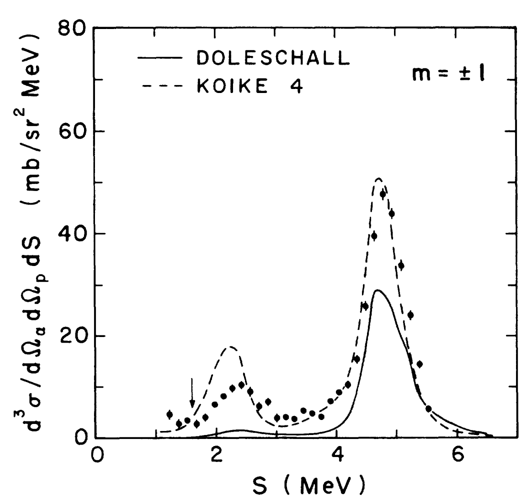

FIG. 7. Cross section for deuterons in the $m=\pm1$ substate. Curves are labeled as in Fig. 1.

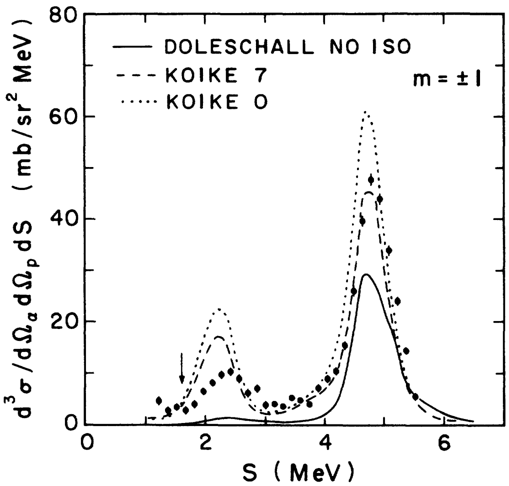

FIG. 8. Cross section for deuterons in the $m=\pm 1$ substate. Curves are labeled as in Fig. 2.

the measured value, with the Doleschall calculations showing the smallest discrepancy. It is important to note that the existence of a minimum in the analyzing power in this region of the spectrum does not *by itself* provide convincing evidence for d^* production in the breakup process: *all* of the calculations predict a pronounced minimum in ${}^{T}T_{20}$ in this region, and the differences between the calculations and the data are at least as great as the difference between the predictions with and without the singlet *np* interaction. The ${}^{T}T_{20}$ data in this region of the spectrum also do not permit a clear choice to be made regarding the amount of *D* state in the Koike calculations. These distinctions are more easily seen in the spectrum at larger *S* values, where the effect of the *n-p* singlet interaction should be negligible. In the region above 3 MeV, the Koike calculations with 4% and 7% *D*-state admixture show better agreement with the data than does the calculation which omits the tensor force. This confirms the conclusion of Ishikawa *et al.*[3] that inclusion of the tensor force is necessary for an adequate representation of the tensor-analyzing powers.

In our view the most convincing evidence for the identification of the enhancement in the cross section at $S=1.6$ MeV with the production of singlet deuterons is provided by Figs. 5–8, in which the $m=0$ and $m=\pm 1$ cross sections are shown separately. Figures 5 and 6 present measured and calculated cross sections for incident deuterons in the $m=0$ substate. What appears only as a shoulder at $S=1.6$ MeV in the unpolarized cross section emerges in these figures as a distinct peak. In contrast to this, the cross sections for deuterons in the $m=\pm 1$ substates shown in Figs. 7 and 8 show no maximum in the d^* kinematic region. The Koike calculations do show an enhancement in the d^* region for $m=0$, but its width is about twice that of the peak in the measured cross section. The Doleschall calculation which includes the ${}^1S_0$ interaction in the *n-p* channel reproduces the shape of this peak better than any of the Koike calculations. Specifically, the position and width of the predicted peak are in good agreement with the data. The measured cross section for $m=\pm 1$ shows no evidence of a maximum in the region where $E_{np}=0$. The Doleschall calculation for the $m=0$ case which contains no ${}^1S_0$ *n-p* interaction exhibits no enhancement in the d^* kinematic region. For both the $m=0$ and the $m=\pm 1$ cross sections, the ^{5}He g.s. FSI peaks are evident. Here again, the Koike calculations are in fairly good agreement with the $\sigma_\pm$ data and in qualitative agreement with the σ_0 data, for $S>3$ MeV.

For the deuteron bombarding energy and d^* emission angle corresponding to our data, the calculations of Werntz and Cannata[15] predict at $E_{np}=0$ a squared ratio of coefficients for singlet and triplet *np* production of $C_s^2/C_t^2 \approx 0.23$. In comparing their predictions of this ratio to the ^{2}H$(\alpha,\alpha p)n$ cross-section data of Bruno *et al.*[7] at a $\alpha+d$ c.m. energy of 4.3 MeV and a d^* c.m. angle of 77°, Werntz and Cannata find the measured value of C_s^2/C_t^2 to be smaller than the predicted value by about a factor of 5. The authors suggest that the discrepancy is caused by an overemphasis in their calculation on the negative-parity amplitudes, which enhances the $\sin\theta$ component of the angular distribution and thereby overpredicts the cross section in the vicinity of 90°. It is difficult to extract a reliable value of C_s^2/C_t^2 from our data, since it would require an accurate knowledge of the amplitudes for the ^{5}He and ^{5}Li g.s. FIS peaks near $S=2.5$ MeV, which appear to be making a contribution to the cross section in the $E_{np}=0$ region, particularly for the $m=\pm 1$ case. A lower limit on the ratio can be obtained if one assumes the contribution of the *N*-α FSI peaks to be negligible at $S=1.6$ MeV, and takes the $m=0$ component of the *n-p* triplet cross section at this energy to be one-half that of the $m=\pm 1$ cross section, with the remainder of the measured $m=0$ cross section assumed to be the singlet contribution. Setting the measured singlet-to-triplet cross-section ratio obtained in this way equal to the ratio calculated using the Watson-Migdal expressions,[5,6] one obtains a value of $C_s^2/C_t^2=0.10$ as a lower limit. We can extract an approximate upper limit on C_s^2/C_t^2 from our data by assuming that the tails of the *N*-α FSI peaks contribute approximately one-half of $\sigma_\pm$ at $E_{np}=0$, but make no contribution to σ_0. This yields a value of $C_s^2/C_t^2=0.22$. Combining the two limits gives $C_s^2/C_t^2 \approx 0.16 \pm 0.06$, which is consistent with the Werntz-Cannata prediction of an enhanced d^* production at low energy and c.m. angles near 100°. This result differs from the conclusion of Bruno *et al.*[9] that no significant d^* production occurs at $\theta_d^*=97°$, based on their cross-section measurements at $E_\alpha=11.3$ MeV discussed in Sec. I. This bombarding energy corresponds to $E_d=5.65$ MeV, so it would seem that the amount of d^* production for $\theta_d^* \sim 100°$ increases substantially as E_d goes from 5.65 to 7.0 MeV. That the d^* production cross section should be energy dependent in this region is not surprising, since it encompasses the region of the *N*-α $p_{3/2}$ resonances. It should be noted, however, that in the measurements of Bruno *et al.*, the kinematic region corresponding to d^* production at $\theta_d^*=97°$ is within 100 keV of a *n*-α FSI region, so that the possibility exists that destructive interference between the amplitudes corresponding to the two processes could contribute to the supression of a d^* peak in the cross section.

V. SUMMARY

The results of our measurements, particularly when presented as cross sections for deuterons in the $m=0$ and $m=\pm1$ substates, provide strong evidence of d^* production in the ^{4}He$(d,p\alpha)n$ reaction. A comparison of the data with the three-body calculations shows clearly the necessity of including both the tensor and the $^1S_0 n$-p interactions in the calculations in order to explain the behavior of the data. For the kinematic region where $S>3$ MeV, the three-body calculations which omit the $^1S_0$ n-p interaction are still able to reproduce the data fairly well. In the region where $S<3$ MeV, the agreement with the data is only qualitative. Werntz and Cannata attribute the enhancement in d^* formation in the breakup reaction at low bombarding energies to the Coulomb-caused difference in p-α and n-α spin-flip amplitudes which are dominated by the $p_{3/2}$ resonance at low N-α relative energies. It would thus seem imperative to develop a satisfactory method of incorporating the Coulomb interaction into the three-body calculations. It can be hoped that this improvement would permit the low-energy data to be reproduced as well as is already the case at higher energies, which should lead to a clearer understanding of the d^* production mechanism.

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