$^{18}O(p,d)^{17}O$ and $^{18}O(p,t)^{16}O$ Reactions by a Polarized Proton Beam

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The (p,d) and (p,t) reactions on ^{18}O have been studied using the 24.4-MeV polarized proton beam of the Saclay cyclotron. Differential cross sections and analyzing powers (asymmetries) have been measured for eight deuteron and seven triton groups. These data are also compared with distorted-wave Born-approximation (DWBA) calculations as a test of their validity for a light nucleus. Some of the deuteron angular distributions are not accounted for by the calculations, and in fact for some transitions the results suggest that two-step processes might be involved. The reliability of the spectroscopic information deduced from the (p,d) reaction is thoroughly discussed. In the triton optical potential a spin-orbit term with a well depth of about 4 MeV is necessary in order to fit the (p,t) analyzing power data for the transitions with $L=0$ and $L=1$. For higher angular momentum transfers acceptable fits are obtained only if a radial cutoff is used. The analysis of the transition to the 8.88-MeV $(J^{\pi}=2^{-})$ state in ^{16}O indicates that the d state component in the triton wave function may be important for (p,t) reactions leading to unnatural-parity states.

I. INTRODUCTION

The distorted-wave Born approximation (DWBA) is currently used to study the structure of the nuclear states involved in a reaction. It is, however, acknowledged that this method is more difficult to apply in light nuclei ($A<20$) than in heavier ones, even for supposedly simple processes like (p,d) and (p,t) reactions at medium incident energies.[1-6] On the other hand a satisfactory knowledge of the states involved can be profitably used to test the method employed in the analysis of a reaction experiment. From this point of view the oxygen isotopes seem suitable nuclei, because a large number of theoretical studies have recently been devoted to their nuclear structure.[7-14]

In the present paper we report a study of the $^{18}O(p,d)^{17}O$ and of the $^{18}O(p,t)^{16}O$ reactions with a polarized proton beam of 24.4 MeV. Some of the transitions considered here were previously measured by Lutz *et al.*[15] with an unpolarized beam at 18.2 MeV. It was felt that the additional informations given by the analyzing powers (asymmetries) could be profitably used.

The experimental data have been compared with DWBA calculations, yielding some interesting results. Some transitions show an anomalous behavior in the sense that they cannot be accounted for by a standard calculation. Also the presence of relatively strong transitions, which would be forbidden within the nuclear model used,[8-14] suggests that they cannot be due to a simple pickup mechanism. In this connection the possibility of obtaining reliable spectroscopic informations from a standard DWBA analysis is discussed.

II. EXPERIMENTAL METHOD

Differential cross section and analyzing-power angular distributions were measured with the polarized proton beam of the Saclay AVF cyclotron at an incident energy of 24.4 MeV. The average beam current on target was about 7 nA, with an energy spread of approximately 50 keV. The beam polarization, continuously monitored with a carbon polarimeter, was 85%.

The 98% pure ^{18}O isotope was contained in a cylindrical gas cell of 3-cm diam. with entry and exit windows of 2-mg/cm^2-thick Havar foils, at a pressure of 0.5 atm. The gas pressure was monitored by means of a precision-dial manometer. The scattered particles were detected with an array of 16 ΔE-E telescopes. The ΔE detectors were Si surface-barrier junctions 150 μm thick; the E detectors, about 4 mm thick, were lithium-drifted Si junctions. The over-all energy resolution was 90–120 keV.

The counting geometry was defined for each telescope by pairs of tantalum collimators located at 85 and 144 mm from the center of the gas cell. The rear collimator was 1 mm wide and 8 mm high; the front one was a 1-mm-wide slit. Events were recorded on-line with a CAE-90-10 computer. For each telescope the computer calculated the quantity $(E+\Delta E)^{1.73}-E^{1.73}$ which is different for each type of particle[16] and allows computation of a mass spectrum. Thus, separated deuteron and triton spectra were obtained. Proton elastic scattering was measured without mass identification of the particles.

The error bars shown on all graphs refer to the statistics only. When all other sources are taken into account it is reasonable to assign a ±6% error to the cross-section evaluation as a conservative estimate of the reproducibility of the data points. This arises primarily from errors in solid angles and detector efficiencies and does not affect the analyzing-power measurements.

The analyzing power is defined as follows: $A(\theta)=(1/P_B)\ [(N_+ - N_-)/(N_+ + N_-)]$. The quantity P_B is the measured beam polarization; N_+ and N_- are the counts in a given peak for incoming protons with spin up and down, respectively. The spin direction in the polarized proton beam was parallel or antiparallel to a quantization axis normal to the reaction plane and was periodically reversed during the measurement. The Basel sign convention is followed. Other details of the experimental apparatus have been described in Ref. 17.

III. ELASTIC SCATTERING DATA AND OPTICAL-MODEL PARAMETERS

We have carried out DWBA calculations using the DWUCK and Nelson-Macefield codes,[18] which include two-particle form factors. The optical-model potentials used to generate the distorted waves in the reaction channels have the form:

$$V_{\mathrm{opt}}(r)=V_C(r)-V_0 f(X_0)+4iW_D\frac{df(X_W)}{dX_W}-iW_V f(X_W)+\left(\frac{\hbar}{mc}\right)^2 V_{\mathrm{so}}\frac{1}{r}\frac{df(X_{\mathrm{so}})}{d}\vec{L}\cdot\vec{S},$$

where

$$f(X_i)=(1+\exp X_i)^{-1}\,;\quad X_i=(r-R_iA^{1/3})/a_i\,,$$

and V_C is the Coulomb potential due to an uniformly charged sphere of radius $R_C A^{1/3}$.

The differential cross sections and the analyzing powers for proton elastic scattering on ^{18}O at 22.5, 24.4, and 29.8 MeV have been analyzed with the code MAGALI.[19] The experimental energy dependence is satisfactorily described by the optical-model analysis. The experimental data and their optical-model fits shall be reported in a forthcoming paper.[20] The parameters relevant to the energy of 24.4 MeV are listed in Table I as set P1.

As for the deuteron potential, the set D1 is that given in Ref. 21 by Denes, Daehnick, and Drisko, which had been obtained from an elastic scattering experiment on ^{17}O at 15 MeV. Data on triton elastic scattering on ^{16}O at 12 MeV were obtained by Glover and Jones.[22] One of the optical potentials given by these authors is listed here as T1, while the set T2 has been obtained by reanalyzing their data and including a spin-orbit term, which had been omitted in T1.

Poor quality fits were, however, obtained for many transitions with these potentials. Therefore, and also in order to test the reliability of the spectroscopic factors, a number of calculations were performed with other optical potentials. Part of the fits obtained are shown in the Figs. 1–8 and the optical parameters used are given in Table I.

IV. $^{18}O(p,d)^{17}O$ REACTION

A. Experimental Results and DWBA Analysis

Transitions to 8 states in ^{17}O have been investigated. The experimental angular distributions are given in the Figs. 1–6.

As customary in a DWBA analysis, the Woods-Saxon-well depth for the captured neutron was adjusted to reproduce the experimental energy separation, while standard values were chosen for

TABLE I. Optical-model parameters.

Set	Particle and experiment	R_c (fm)	V_0 (MeV)	R_0 (fm)	a_0 (fm)	W_D (MeV)	W_v (MeV)	R_w (fm)	a_w (fm)	V_{so} (MeV)	R_{so} (fm)	a_{so} (fm)
P1	$p+{}^{18}O$; 24.4 MeV	1.10	50.1	1.10	0.740	5.60	···	1.30	0.660	4.25	0.90	0.520
P2	$p+{}^{17}O$; 24.4 MeV	1.10	55.1	1.07	0.690	5.55	···	1.39	0.630	5.46	1.03	0.550
P3	p; Ref. 23 [a]	1.20	50.1	1.17	0.750	7.00	···	1.32	0.588	6.20	1.01	0.750
D1	$d+{}^{17}O$, 15 MeV; Ref. 21	1.25	85.3	1.10	0.902	9.00	···	1.60	0.509	9.40	1.10	0.902
D2	$d+{}^{16}O$, 12–19 MeV; Ref. 24	1.30	106.0	0.97	0.800	7.00	···	1.50	0.700	7.57	0.97	0.800
D3	d; Ref. 25 [b]	1.30	98.3	1.05	0.850	12.00	···	1.60	0.572	6.50	0.90	0.600
D4	d; from D1	1.25	85.3	1.10	0.902	18.00	···	1.60	0.509	4.70	1.10	0.902
D5	d, from P2 [b]	1.10	114.5	1.07	0.717	10.40	···	1.39	0.670	5.00	1.03	0.590
T1	$t+{}^{16}O$; 12 MeV	1.40	146.8	1.40	0.551	···	18.4	1.40	0.551	···	···	···
T2	$t+{}^{16}O$; 12 MeV	1.40	142.7	1.43	0.495	···	17.3	1.46	0.370	4.15	1.43	0.469

[a] Parameters evaluated for 24.4-MeV proton energy.

[b] The parameters listed refer to 18-MeV deuteron energy (g.s. transition at 24.4-MeV incident proton energy). The energy dependence given in Refs. 23, 25, and 26, respectively, has been used.

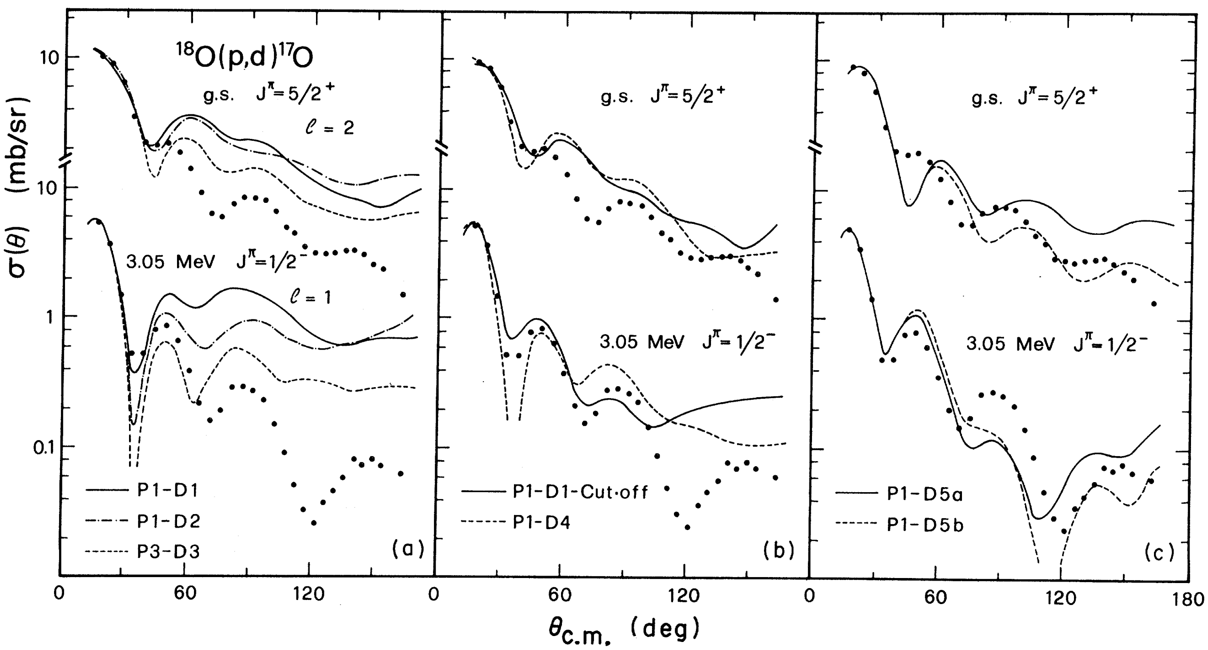

FIG. 1. Differential cross sections for two transitions in the $^{18}O(p,d)^{17}O$ reaction and DWBA predictions using various sets of optical parameters (a) and different procedures to reduce the contributions coming from the nuclear interior [(b) and (c)], where D5 a and D5 b indicate deuteron potentials calculated with the prescriptions of Refs. 30 and 26, respectively.

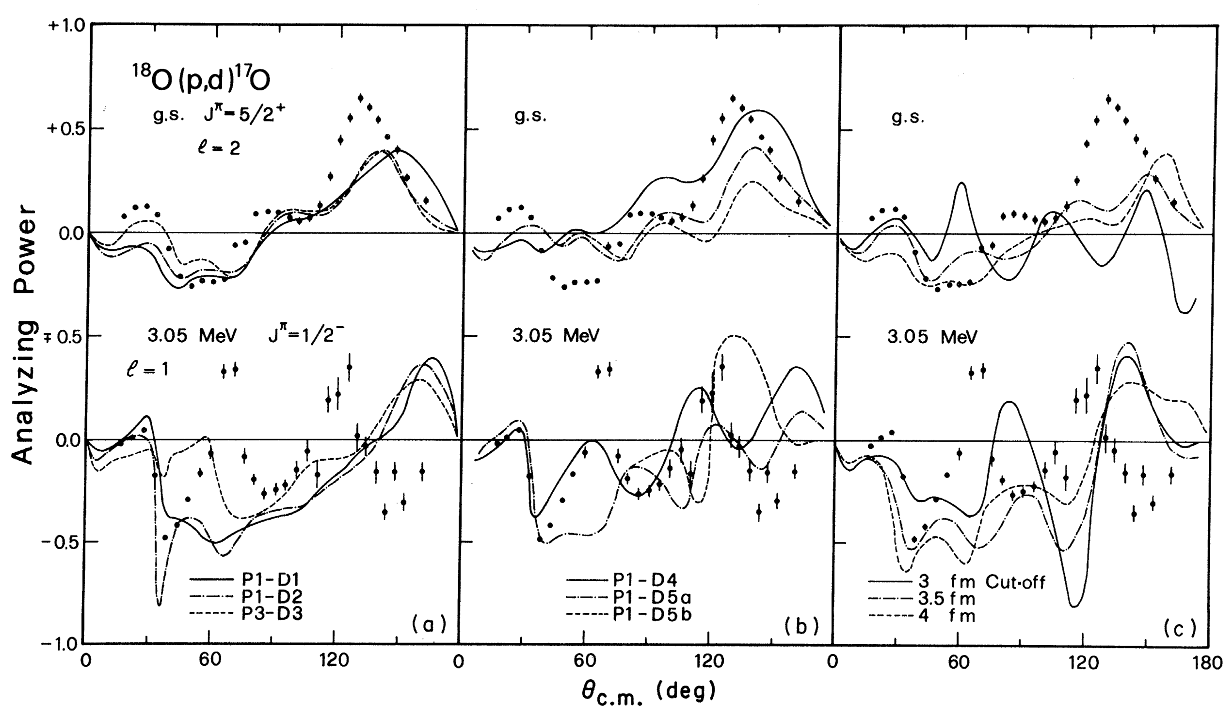

FIG. 2. Analyzing power angular distributions for two transitions in the $^{18}O(p,d)^{17}O$ reaction and DWBA predictions using various sets of optical model parameters [(a) and (b)]. In part (c) is shown the effect of a radial cutoff.

the radius and diffuseness: $R = 1.25$ fm and $a = 0.65$ fm. A Thomas term for the spin-orbit interaction, 6 MeV in depth, was also included. It is worthwhile mentioning that a complex form factor, generated according to the same procedure outlined by Shepard, Edwards, and Kraushaar,[27] did not provide, in the present case, any better fits.

The two codes used allow corrections for the nonlocality of the optical potentials and for the finite range of the interaction in the local energy approximation. The calculations were carried out with values of 0.85 fm and 0.54 fm, respectively, for the proton and deuteron nonlocality ranges[28] and 0.65 fm for the finite range.[29]

Standard DWBA calculations miss the positions of the second maximum in the differential cross sections for the ground state (g.s.) and the 0.87-MeV state transitions [Figs. 1(a) and 3], and do not fit the analyzing power data for the 3.05-MeV state [Fig. 2(a)]. One can note that while the two transitions leading to the g.s. and to the 3.05-MeV state require, respectively, an $l = 2$ and an $l = 1$ momentum transfer, they exhibit differential cross sections with a rather similar diffraction pattern. Therefore, it is *a priori* evident that the DWBA, with any choice of the parameters, cannot fit at the same time the differential cross sections of these two transitions. It should be also remarked that the calculated differential cross sections do not fall off rapidly enough for angles beyond the

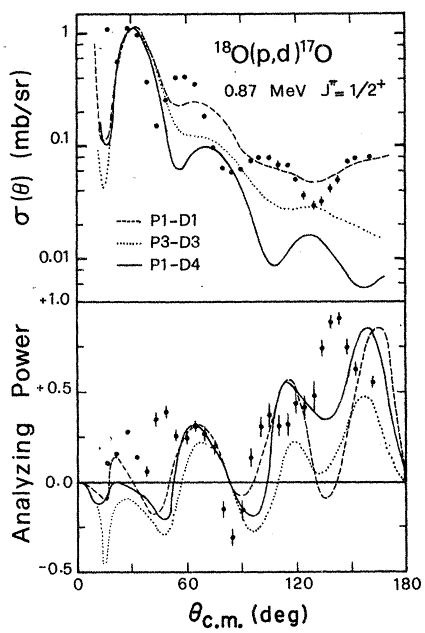

FIG. 3. Deuteron angular distributions for an $l = 0$ transition and DWBA curves, using various sets of optical-model parameters.

main peak. This behavior is fairly common in light nuclei.[1]

Improved fits to the experimental data are sometimes obtained if the contributions to the reaction from the nuclear interior are reduced,[1, 30] which has been achieved in the past by using different procedures. A simple one is to use a sharp radial cutoff. However, since the choice of the cutoff radius is largely arbitrary, one can also attempt to get the same effect in other ways. A second procedure is to calibrate the optical-model parameters against DWBA calculations,[2] and a third one is to use a deuteron optical potential generated from known nucleon potentials.[30] We refer to the papers of Johnson and Soper[30] and to Refs. 1 and 2 for comments on the physics content of these procedures.

The second one generates deuteron potentials with a strong imaginary term, like our set D4, obtained by adjusting the parameters of the set D1. To reproduce the analyzing power data a drastic change was also required in the spin-orbit term.

In order to apply the third procedure both the approximate formulas given in Refs. 1 and 30 and the seemingly more accurate presciption of Bauer and Bloch[26] were used. The deuteron potential D5 was thus obtained by starting from the proton optical potential P2, obtained from an elastic scattering experiment on ^{17}O at 24.4 MeV, and assuming the energy dependence of nucleon potentials given in Ref. 23.

DWBA calculations were carried out with all three procedures described above. The main conclusions are: (i) As expected, the differential cross sections show a steeper slope, in better agreement with the experimental data [Figs. 1(b), 1(c)], except in the case of the $l = 0$ transition (Fig. 3); (ii) the use of radial cutoffs gives very unsatisfactory fits to the analyzing powers [Fig. 2(c)]; (iii) deuteron potentials deduced from those of nucleons give fits of quality comparable to those obtained through the other procedures; (iv) no real improvements are apparent in those cases, like $l = 0$ and $l = 2$ transitions, where the calculated curves miss the position of the second maximum [Figs. 1(b), 1(c) and 3]; (v) the best quality fits, especially for the analyzing-power angular distributions, are given by the adjusted deuteron potential D4.

B. Spectroscopic Factors

Many theoretical works have been published on the structure of the low-lying states of $^{17}O^{7-10}$ and $^{18}O^{10-14}$.

The ^{18}O g.s. can be described as a two-particle state in the $1d_{5/2}$ and $2s_{1/2}$ orbits plus smaller

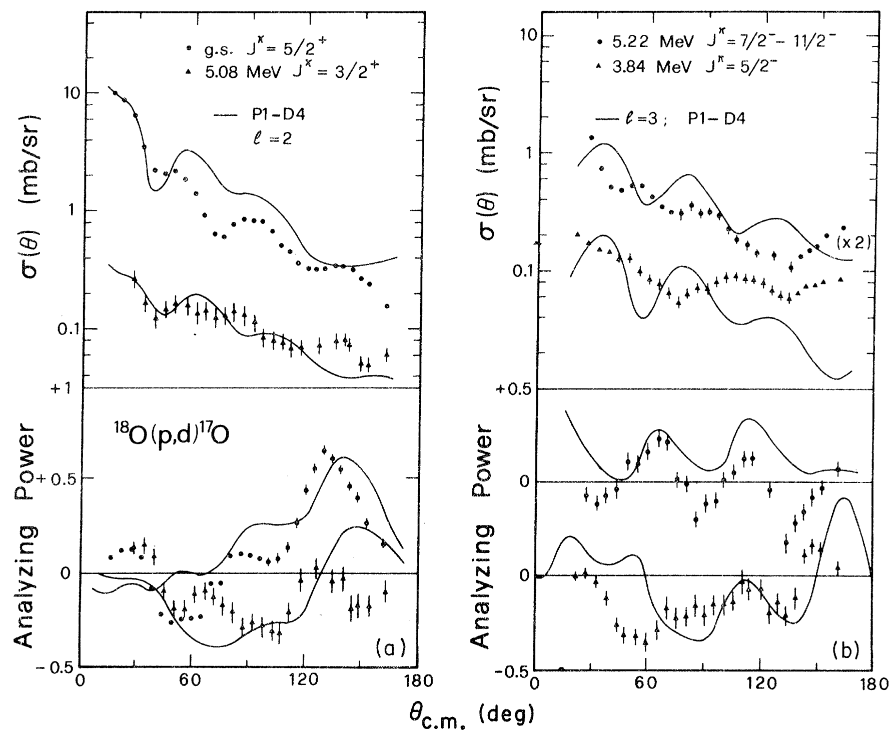

FIG. 4. Deuteron angular distributions for two $l=2$ transitions (a). In part (b) are shown the data for two transitions leading to negative-parity states compared with DWBA curves calculated for an $l=3$ transfer.

components from other configurations. A reasonable assumption for the ^{18}O g.s. wave function is:

$$\psi(^{18}\mathrm{O}) = \alpha(1d_{5/2})^2 + \beta(2s_{1/2})^2 + \gamma(1d_{3/2})^2 + \delta ,$$

where δ gives the amplitude of collective or 4 particles-2 holes (4p-2h) configurations. Table II lists the amplitudes given in Refs. 10–14, together with the values determined from the present experiment. The transitions leading to the g.s. and to the first excited state in ^{17}O, should exhaust most of the $1d_{5/2}$ and of $2s_{1/2}$ strengths, respectively, and therefore these relations should hold: $S_{gs} = 2\alpha^2$ and $S_{0.87} = 2\beta^2$.

In Fig. 4(a) are plotted the data for the transitions to the $\frac{3}{2}^+$ state at 5.08 MeV and to the g.s., which show a marked correspondence between the positions of the maxima of the differential cross sections. The angular distribution of the analyzing power for the $\frac{3}{2}^+$ state is somewhat similar to the one of the $\frac{5}{2}^+$ g.s., but has on the average more negative values. The latter effect is reproduced by DWBA calculations. One could then speculate that the transition leading to the $\frac{3}{2}^+$ state is indeed due to a direct neutron pickup from the $1d_{3/2}$ orbit, even if the agreement with the DWBA curves is poor.

The data for three $l=1$ transitions to the states with $J=\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{3}{2}^-$, respectively, are shown in Fig. 5. The analyzing powers for the transitions to the $\frac{1}{2}^-$ and to the first $\frac{3}{2}^-$ state are correctly predicted by DWBA calculations and show a strong j-dependence. A $\frac{3}{2}^-$ state may be populated by a neutron pickup from the $1p_{3/2}$ shell or by a multistep process. From the above analysis we have drawn the conclusion that the reaction mechanism should be a simple pickup for the transition to the 4.55-MeV state. Therefore, this state should contain a sizeable $(1p_{3/2})^{-1}$ component, which often is not taken into account[8,10] in the wave function calculations for ^{17}O. Given the unsatisfactory fits for the second $\frac{3}{2}^-$ level, similar arguments cannot

TABLE II. Amplitudes for ^{18}O ground-state-configuration admixture.

	α	β	γ	δ	$1p_{1/2}$ strength
Federman and Talmi (Ref. 12)	0.84	0.38	⋯	0.39	1.70
Engeland (Ref. 13)	0.85	0.39	0.19	0.28	1.84
Kanestrom and Koren (Ref. 14)	0.92	0.30	0.25	⋯	2.00
Ellis and Engeland (Ref. 11)	0.96[a]	⋯	⋯	0.20	1.80
Zuker (Ref. 10)	0.68	0.24	⋯	0.69	1.52
This experiment	0.81	0.19	0.25	0.50	0.88[b]

[a] Takes into account all $(2s, 1d)^2$ configurations, i.e., the reported value corresponds to $(\alpha^2 + \beta^2 + \gamma^2)^{1/2}$.

[b] Strength due to the 3.05-MeV transition only.

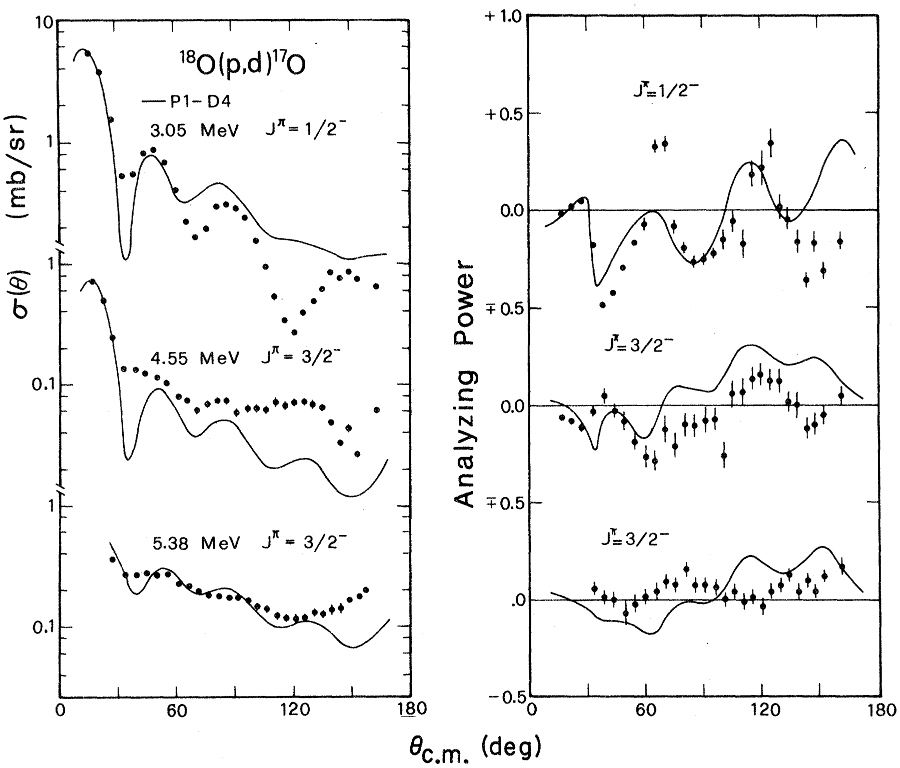

FIG. 5. Experimental and calculated deuteron-angular distributions for three $l=1$ transitions. The j dependence of the analyzing powers for the transitions leading to the 3.05- and 4.55-MeV states is clearly shown.

be applied to this transition, which is then discussed in the following section.

The transition to the $\frac{1}{2}^-$ state at 3.05 MeV should contain most of the $1p_{1/2}$ hole strength. If this state contains 2p-1h and 4p-3h configurations, with the holes in the $1p_{1/2}$ shell, it should be populated by a neutron pickup from the $(2s_{1/2},\ 1d_{5/2})^2(1p_{1/2})^4$ and $(2s_{1/2},\ 1d_{5/2})^4(1p_{1/2})^{-2}$ configurations in ^{18}O. From the amplitude of these components the total $1p_{1/2}$ strength, and therefore the maximum value for $S_{3.05}$, can be evaluated. The value obtained in the present experiment, which is definitely larger than the one quoted in Ref. 15, accounts for nearly half of the above strength.

The spectroscopic factors listed in Table III have been derived from different DWBA calculations. In view of the wide range of the parameters used, the relative deviations in the quoted values are quite satisfactory. The experimental amplitudes reported in Table II have been deduced from the average spectroscopic factors of Table III. Owing to the very poor fit to the differential cross section for the transition to the 0.87-MeV state, the β value may have a large error. The value given for γ may be slightly underestimated if the transition to the $\frac{3}{2}^+$ state at 5.08 MeV does not exhaust the $1d_{3/2}$ strength.

It must be finally remarked that, in spite of the

TABLE III. Spectroscopic factors for $^{18}O(p,d)^{17}O$ transitions.

DWBA calculation	0.00 MeV $\frac{5}{2}^+, l=2$	0.87 MeV $\frac{1}{2}^+, l=0$	3.05 MeV $\frac{1}{2}^-, l=1$	4.55 MeV $\frac{3}{2}^-, l=1$	5.08 MeV $\frac{3}{2}^+, l=2$
P1-D1	1.14	0.06	0.82	0.11	0.11
P1-D2	1.14	0.06	0.82	0.13	0.10
P3-D3	1.42	0.06	1.01	0.16	0.15
P1-D4	1.30	0.07	1.04	0.16	0.16
P1-D5	1.47	0.10	0.82	0.16	0.16
P1-D1; 3.3 fm cutoff	1.36	0.07	0.78	0.12	0.10
Mean values	1.31	0.07	0.88	0.14	0.13

difficulties encountered in the fitting procedure, the spectroscopic amplitudes thus obtained are in satisfactory over-all agreement with the various theoretical predictions.

C. Reaction Mechanism

The transition to the second $\frac{3}{2}^-$ state at 5.38 MeV exhibits a different angular distribution of the analyzing power and a larger differential cross section in comparison to those for the 4.55-MeV state. If the reaction mechanism is the same, these differences cannot be explained on the basis of the known wave functions of the two states which, at least in the weak coupling model,[8,10] are very similar.

The data for the transition to the ^{17}O states at 3.84 MeV ($J^\pi = \frac{5}{2}^-$) and to the 5.22-MeV state are given in the Fig. 4(b). The spin of the latter state[31] has to be one of the values $\frac{7}{2}^-$, $\frac{9}{2}^-$, and $\frac{11}{2}^-$. These two transitions would be forbidden in a direct neutron pickup if the g.s. of ^{18}O does not contain components such as $1f_{5/2}$ and $1f_{7/2}$. The DWBA curves, calculated for an $l=3$ transfer, do not fit the differential cross sections at all. Because of this, and in spite of the agreement found for the 5.22-MeV analyzing power, the presence of sizeable f-shell components, which had been suggested earlier,[32] is not supported by the present experiment. It is therefore to some extent surprising

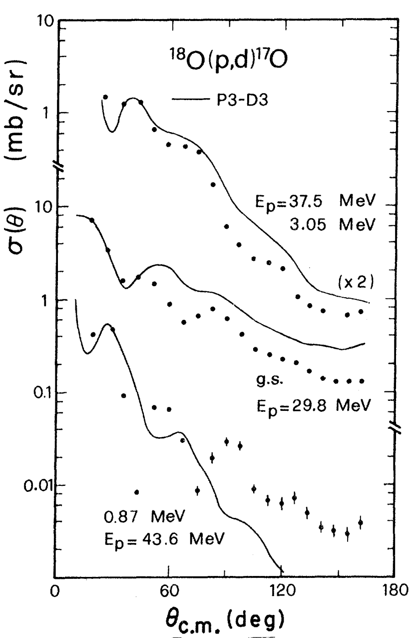

FIG. 6. Deuteron differential cross sections for the transitions and the incident energies indicated on the graph. The DWBA curves give fits of a quality similar to that obtained at 24.4 MeV.

that these levels are about as excited as the neighboring $\frac{3}{2}^-$ levels. This fact can be understood if the low-lying odd-parity states in ^{17}O are mainly due to $(2s_{1/2}, 1d_{5/2})^4(1p_{1/2})^{-3}$ configurations[8,10] and if one supposes that the reaction proceeds through a multistep mechanism. However, the number of steps cannot be as large as in a compound nucleus reaction, since the angular coherence in this latter process, arising from statistical fluctuations,[33] is smaller than that shown by the analyzing power measured in the present experiment.

A likely hypothesis, which might be tested with a coupled-channel calculation, is a two-step process via a collective excitation[34] of ^{18}O and a subsequent $1p_{1/2}$ neutron pickup. In fact some of the difficulties found here in the DW analysis may be due to the deformed structure of the ^{18}O g.s.[35]

As it is well known, the knowledge of the energy dependence may be useful to clarify the nature of the reaction mechanism. The above findings prompted us to include the two reactions studied here in an extensive research on the energy dependence of transfer reactions on light nuclei.[20] We present here some preliminary results, which are relevant to the problems so far discussed.

The anomalies found at 24.4 MeV in the angular distributions for the $l=0$ and $l=2$ transitions are also present at different incident energies (Fig. 6). Therefore these anomalies can hardly be attributed to resonating processes.

The energy dependence both for the forward-peak cross section and for the cross section integrated over the experimental angular range is generally well reproduced by a DWBA calculation. The spectroscopic factors, therefore, do not show any appreciable energy dependence. The agreement is less satisfactory for some transitions to negative-parity states and becomes very poor for that leading to the $\frac{5}{2}^-$ state. The latter shows a steeper energy dependence than either the calculated one or that experimentally found for other nonforbidden transitions, giving a further indication of the presence of reaction mechanisms other than a direct neutron pickup.

V. ^{18}O$(p,t)^{16}$O REACTION

A. General Comments

Some recurring difficulties are encountered in the DWBA analysis of (p,t) reactions. Since the absolute values of the differential cross sections are sensitive to a number of factors entering the calculations,[6,36,37] only the relative values of the DWBA cross sections are usually compared with the experimental data. Only recently has some systematic check of the reliability of the relative spectroscopic amplitudes been performed.[6,20,36] These studies show that the experimental energy dependence is poorly reproduced by the calculations and therefore both the absolute and the relative spectroscopic amplitudes deduced through a DWBA analysis are energy dependent.[6,20]

The method is, however, able to reproduce the diffraction pattern of the differential cross sections. Only few analyses of polarized-beam experiments on two-neutron transfer reactions have been reported so far.[4,5,38] Nelson, Chant, and Fisher[4] pointed out the improvements which can be obtained using a finite-range correction and Hardy *et al.*[5] observed some transitions with analyzing-power angular distributions which do not appear to be characteristic of the transferred quantum numbers. The analysis reported here is mainly concerned with the informations that can be derived in fitting the analyzing-power angular distributions.

The theory for two-nucleon transfer reactions has been formulated by several authors in an essentially equivalent way.[39,40] If l_1, l_2 are the individual orbital angular momenta of the transferred nucleons in the target nucleus and $L, S,$ and J are the quantum numbers of the transferred pair, the expressions of the differential cross section and the analyzing power consist of coherent sums over $L, S,$ and the single-particle configurations. However, if the triton wave function is assumed to contain a pure singlet s state, the following selection rules[39] hold, for a (p, t) reaction on an even target nucleus:

$$S=0; \quad L=J=J_f;$$

$$\Delta\pi = (-1)^{l_1+l_2} = (-1)^L = (-1)^{J_f},$$

where J_f is the spin of the residual nucleus. In this case the sum over L and S reduces to only one term, and the allowed $L=J_f$ value dominates the shape of the angular distributions.

In our form-factor calculations a standard Woods-Saxon well was assumed ($R=1.25$ fm, $a=0.65$ fm, and $V_{so}=6$ MeV). The depth was ad-

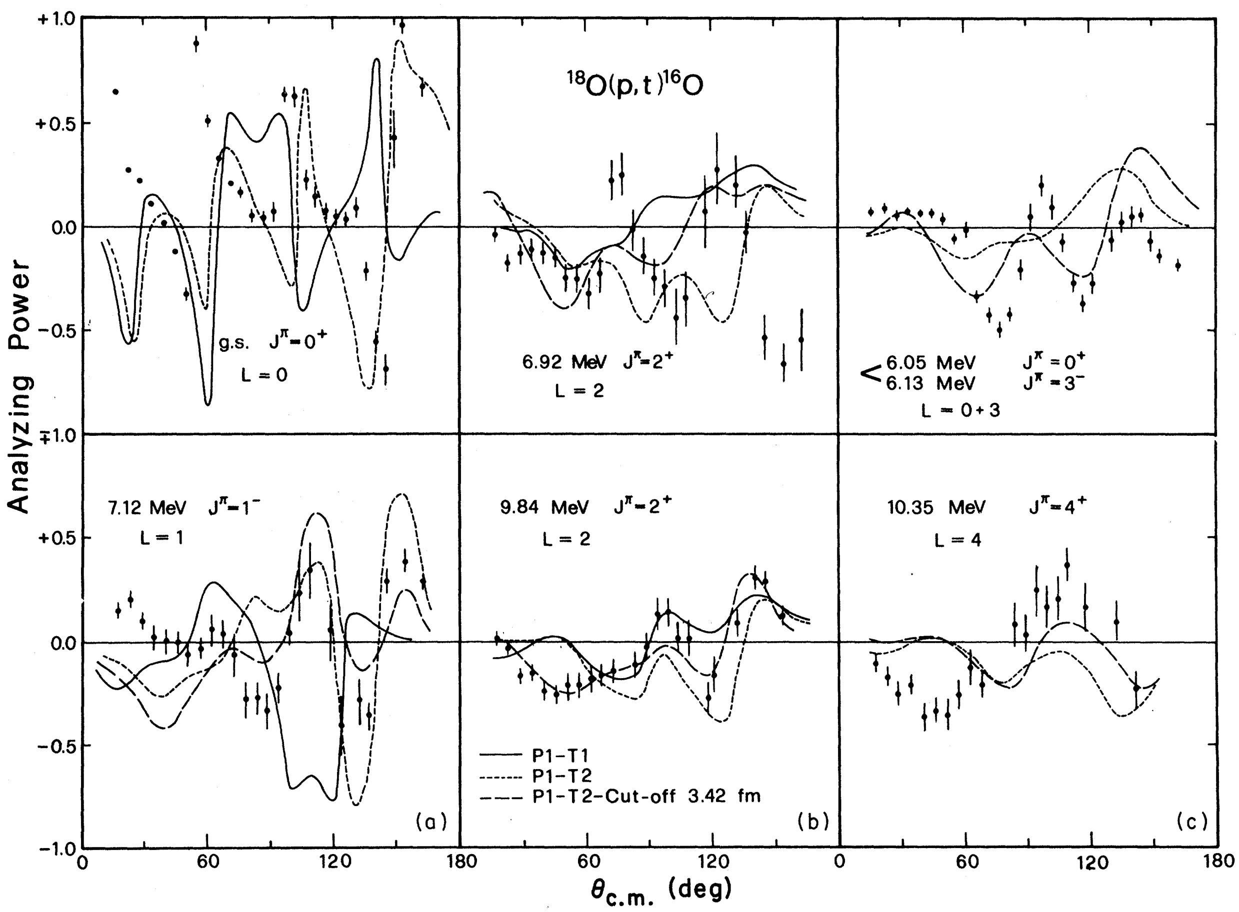

FIG. 7. Analyzing-power angular distributions for several $^{18}O(p,t)^{16}O$ transitions, compared with DWBA calculations, showing the effect of a triton optical potential with (T2) and without (T1), a spin-orbit term, and of a radial cutoff.

justed so as to reproduce for each neutron a separation energy equal to one half the sum of the experimental two-neutron separation energy between the two ground states and of the excitation energy of the final state. This procedure gives the proper asymptotic behavior and has been found adequate in the cross section evaluation of (p, t) reactions on light nuclei.[36] Moreover the shape of the angular distributions was found to be rather insensitive to any reasonable variation in the parameters describing the radial wave functions of the two transferred neutrons. The spectroscopic amplitudes from Zuker[10] wave functions were used.

The triton optical potentials reported in the literature and appropriate to the present experiment, like those of Glover and Jones[22] or of Hiebert, Newman, and Bassel,[41] give very similar results. As a starting point in the calculations reported here, we choose the triton potential T1.

B. Discussion of the DWBA Analysis

Improved fits to the analyzing-power angular distributions at backward angles are obtained introducing a spin-orbit term in the triton optical potential. These improvements are very noticeable for the $L=0$ and $L=1$ transitions [Fig. 7(a)]. This effect has been found also using optical potentials different from T1 and T2. Some authors,[4, 38] who have analyzed polarization data from (p, t) or (t, p) reactions, have drawn the conclusion that a spin-orbit term is not required in the triton optical potential. It must be, however, observed that the measurements by Nelson, Chant, and Fisher[4] and by Keaton *et al.*[38] are limited to forward angles ($\theta < 90°$).

With the above mentioned potentials the calculated curve for the g.s. transition results slightly out of phase with respect to the experimental one. A better agreement is obtained with the potential P3 for protons (Fig. 8) or different triton potentials as those of Ref. 41. These last potentials, when applied to other transitions, do not give sizeable differences. This occasional disagreement for a particular transition and a particular choice of optical potentials proves that the DWBA method is very critical when no suitable matching conditions for the angular momenta[42] can be found, as is the case for the g.s. transition at this incident energy. In fact, at 24.4-MeV proton incident energy, matching conditions exist only for intermediate Q and L values; they are indeed good for the transition to the $J^\pi=2^+$ level at 6.92 MeV ($L=2$; $Q=-10.36$ MeV), but cannot be achieved for the transition to the 10.35-MeV state ($L=4$; $Q=-14.07$ MeV) or for the g.s. transition ($L=0$; $Q=-3.72$ MeV). A similar trend of the matching conditions, although for different L and Q values, exists at different incident energies.

The transition to the 2^+ state at 9.84 MeV ex-

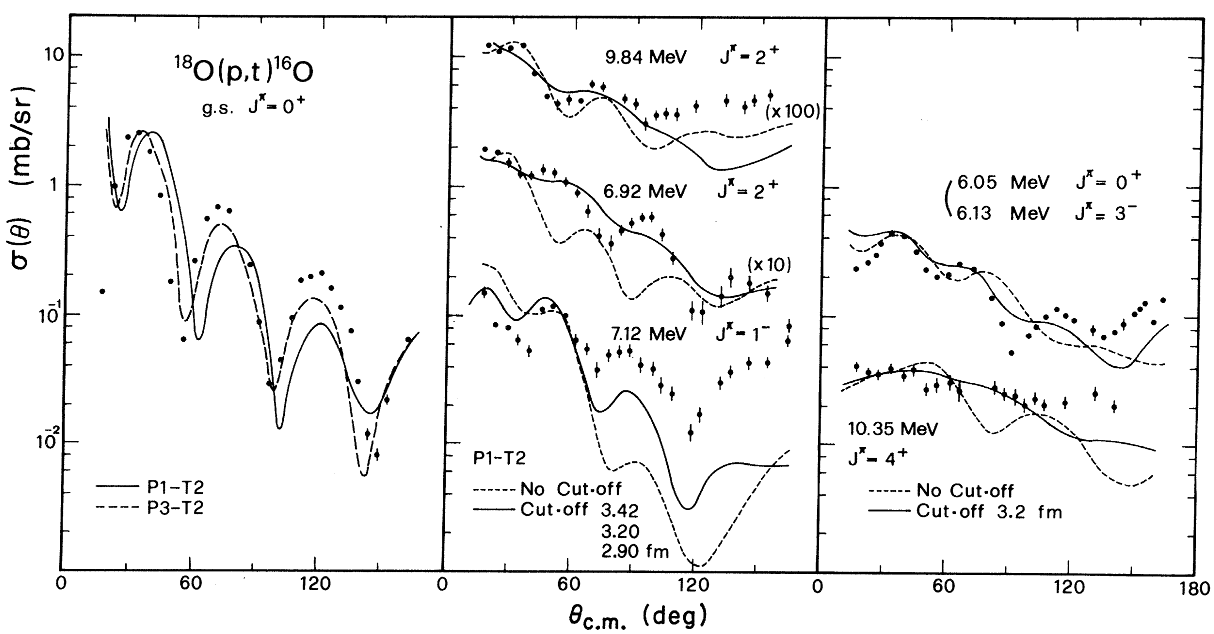

FIG. 8. Differential cross sections for different transitions in the $^{18}O(p,t)^{16}O$ reaction, compared with DWBA predictions. The effect of a radial cutoff is shown.

hibits a differential cross section similar in shape to the DW prediction and an analyzing power which is in satisfactory agreement at backward angles, but out of phase with respect to the calculated curve in the forward hemisphere [Fig. 7(b)]. A similar disagreement was found by Hardy *et al.*,[5] again in the case of $L=2$ transitions, in the (p, t) reaction on ^{15}N and ^{16}O. The other $L=2$ transition observed here, i.e., to the state at 6.92 MeV, shows a differential cross section and an analyzing power which disagree markedly with those for the 9.84-MeV state and with DWBA predictions. Even by varying the geometrical parameters entering the calculation it is not possible to get any significant improvement for all data. Better fits to the analyzing-power data may be obtained by introducing a radial cutoff. The cutoff value required for the best fit of the two $L=2$ transitions and also of the other transitions, except the one to the g.s., is always 3.42 fm. Unfortunately, the poor reliability of the cutoff procedure is confirmed also in this case by the fact that the differential cross sections require for many transitions lower values of the cutoff radius (Fig. 8). There is, however, a clear indication that better fits can be obtained by depressing the contributions coming from the nuclear interior.

One can attempt to obtain the latter effect, as done in Ref. 4, by using a finite-range correction.

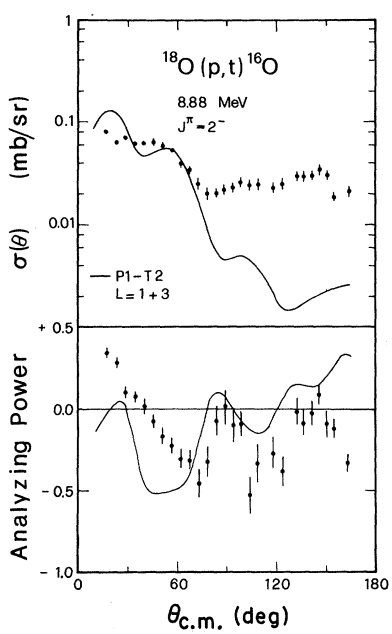

FIG. 9. Triton angular distributions for the transition to the unnatural-parity state ($J^{\pi}=2^{-}$) at 8.88 MeV in ^{16}O, compared with DWBA curves, calculated as a coherent sum of the $L=1$ and 3 contributions in the hypothesis of an $S=1$ transfer.

This correction, even in a more developed form such as that given by Chant and Mangelson,[43] does not give improvements in the case of the $^{18}O(p, t)$ reaction, and therefore all DW curves shown in the Figs. 7–9 come from zero-range calculations.

The excitation of the 2^- state at 8.88 MeV is of particular interest, since this transition is forbidden on the basis of the usual model for a (p, t) reaction. According to the parity-selection rule given above a transition to an unnatural-parity state is forbidden. It is found experimentally that the above transition, favored by a large spectroscopic amplitude,[9] has a strength similar to that of allowed transitions. Beside a multi-step process, another mechanism which could explain this transition is related to the actual triton wave function. In the triton, as in the deuteron, the nucleon-nucleon tensor force allows a d-state admixture, in which case a $S=1$ transition may occur. Recent evaluations[44] indicate a 6–8% amplitude for the d state. By calculating DW curves under this hypothesis, and by adding coherently the contributions coming from the two possible angular momenta transfers ($L=1, 3$), the fits of Fig. 9 are obtained.

VI. CONCLUSIONS

This study of the $^{18}O(p,d)^{17}O$ and of the $^{18}O(p, t)$-^{16}O reactions allows several conclusions.

In spite of the uncertainties in the reaction mechanism and of the difficulties encountered in the fitting procedure, the DWBA, when applied to the (p,d) transitions allowed by the model, gives reliable spectroscopic information.

For the ^{18}O g.s. the presence of large $(1d_{5/2})^2$ and 4p-2h (or deformed) configurations is confirmed by the present experiment, and we also obtain an indication that the $(1d_{3/2})^2$ component cannot be neglected. For the ^{17}O states the $\frac{1}{2}^-$ level at 3.05 MeV contains about one half of the $(1p_{1/2})^{-1}$ strength. The other low-lying negative-parity states are less excited and seem mainly, as predicted, $(2s_{1/2},\ 1d_{5/2})^4(1p_{1/2})^{-3}$ states. Configurations containing a $(1p_{3/2})^{-1}$ component do not seem, however, negligible in the case of the $\frac{3}{2}^-$ state at 4.55 MeV.

The agreement reached in fitting the analyzing-power angular distributions, although not always satisfactory, it at least of the same quality as that obtained for the differential cross sections, provided that an appropriate spin-orbit term is introduced in the deuteron and triton optical potentials. The strength of this term is about 5 MeV for deuterons and about 4 MeV for tritons. This last value is in agreement with the more recent values deduced from triton or ^{3}He elastic scattering.[45]

For both reactions there are transitions which are not fitted by a DWBA calculation. This difficulty cannot be ascribed, in our view, to a bad choice of the parameters used, but could instead be due to an inadequate treatment of the reaction mechanism, as in the case of the transitions to the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states in ^{17}O. Other facts, like the discrepancies between the calculated and the experimental angular distributions (cross sections or analyzing powers or both) in the case of the $L=0$ and $L=2$ transitions, may be due to an inadequate description of the pickup process. By depressing the contributions coming from the nuclear interior, better fits to the experimental data can generally be obtained. We have found it more appropriate to increase the deuteron imaginary-well depth in order to account for the slope of the (p,d) differential cross sections, and to use a radial cutoff to get reasonable results for the analyzing power of the (p,t) reaction. We believe that the result for the (p,t) reaction is particularly interesting, since in this case transitions previously classified as anomalous,[5] in the sense that the angular distributions seem not to be characterized by the transferred angular momentum, can be reasonably explained.

The analysis of the transition to the 8.88-MeV 2^- state in ^{16}O indicates that the d-state admixture in the triton wave function, which is normally neglected in a DWBA calculation, may be of some importance in the (p,t) reaction.

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