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$^{16}O(d, n)$ Polarizations and Cross Sections from 3 to 4 MeV*

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The cross sections and polarizations of the neutron groups from the $^{16}O(d, n)^{17}F$ reaction leading to the ground and first excited states of ^{17}F have been measured in the deuteron energy range from 3 to 4 MeV. Time-of-flight techniques were employed throughout. Calculations were performed to determine to what extent the distorted-wave Born-approximation theory could describe the experimental results. While the cross-section angular distributions could be reproduced well, the polarization calculations were generally quite different from the experimental results, although "suggestive" in a few cases. Compound-nucleus contributions to the data appear to be significant. Spectroscopic factors were extracted and are in satisfactory agreement with those obtained by previous workers.

I. INTRODUCTION

Direct-interaction theories (DI) have been observed to reproduce angular distribution of stripping reactions on a large number of nuclei and over a rather wide range of energies. In many cases, spectroscopic factors, which compare well with other determinations, have been extracted. Since all popular DI theories are approximations, their applicability is best determined by seeing how well they are able to reproduce many kinds of data with one set of parameters. Polarization measurements represent one kind of data which provide a sensitive test of reaction theory. Ideally, fitting polarization data may resolve some parameter ambiguities and hence improve the extracted spectroscopic factors.

Recently, successes have been reported for reproducing cross-section and polarization data simultaneously with both the distorted-wave Born approximation (DWBA)[1] and the weakly bound projectile (WBP)[2] models. Of course, many more examples exist where polarization data have not been reproduced by any DI calculation to date. Many of these instances suffer from large compound-nucleus (CN) contributions which rarely can be taken into account in a polarization calculation. The question exists, however, as to whether or not some cases have not been well reproduced because of difficulties in determining the correct parameter values.

The $^{16}O(d,n)$ reaction has recently been studied by several authors[3-5] and observed to display angular distributions well reproduced by DI calculations and yielding spectroscopic factors close to unity. These studies extend down to deuteron energies of less than 3 MeV. Success in reproducing neutron polarizations from the $^{12}C(d,n)$ reaction as low as a deuteron energy of 2.3 MeV has been reported recently[6] (with the WBP model).

It was decided to measure the neutron polarizations from the $^{16}O(d,n)$ reaction in the deuteron energy range from 3 to 4 MeV available with the Case Western Reserve University (CWRU) Van de Graaff accelerator. These measurements might serve as further tests of various DI theories and might resolve some parameter ambiguities in a given model.

That CN contributions exist for the $^{16}O(d,n)$ reaction in this energy range is well established. The excitation functions of cross section show maxima and minima which cannot be reproduced by any DI calculation. All serious calculations performed to extract spectroscopic factors include some estimate of an average CN contribution. These estimates are usually based on a Hauser-Feshbach (HF) type calculation which assumes statistical conditions for the level densities in the CN. Both Davison *et al.*[3] and Dietzsch *et al.*[4] convinced themselves of the validity of this method for $^{16}O + d$. However, the maxima in the excitation functions of cross section, which shift in energy as one changes angle,[4] seem to belie this conclusion, at least to a degree. It also has been established that ^{16}O does not act as an inert, spherical core and that the low-lying levels of ^{17}F are not simple single-quasiparticle states.[7]

These difficulties appear to be amply demonstrated in the recently reported results of Thornton, Fogel, and Morris[8] for $^{16}O(d,n)$ neutron polarizations in the energy range from 4 to 6 MeV. It is concluded there that interference between the CN and DI mechanisms is considerable.

The neutron polarizations reported in this work supplement the work of Ref. 8. Both cross-section and polarization measurements were performed here with the same target so as to provide a rather complete set of experimental results which proved to be amenable to theoretical analyses. DWBA calculations were performed and compared with the data. Hauser-Feshbach calculations were included in comparison with the cross-section data. Spectroscopic factors were extracted and compared to the other recent results. While the polarization data showed the same difficulties as observed in the work of Ref. 8, it was noted that the general shape of the ground-state angular distribution remains the same from 3.5 to at least 5.5 MeV. Considerable effort was spent to see how well the DWBA could reproduce this shape simultaneously with all other available data.

The results of calculations made elsewhere,[9] in the spirit of the WBP, to compare with these data are briefly discussed as well.

II. EXPERIMENTAL PROCEDURE

The CWRU 4-MV pulsed-terminal Van de Graaff accelerator with postacceleration bunching[10] provided 1.2-nsec (typical) pulses of 2.8- to 3.9-MeV deuterons at a 1-MHz repetition rate with average currents of 1–2 μA.

All measurements were performed with a Ta_2O_5 target produced by anodizing tantalum. Energy loss for protons in the target was determined by measuring an excitation function of the γ-ray yield over a resonance at 3.473 MeV in the reaction $^{18}O(p,p'\gamma)$.[11] The target contained ^{18}O in natural abundance. The energy loss was converted to mg/cm^2 of ^{16}O with a computer code[12] based on the empirical formula for stopping power due to Barkas and Berger.[13] A check was performed on this result by comparing the $^{16}O(d,n)$ neutron yields with yields obtained from a gas cell filled at a pressure adjusted to produce approximately the same energy loss in both targets. The over-all determination of the ^{16}O density was taken to be 0.23 mg/cm^2 with an estimated accuracy of better than ±10%. The spread in deuteron energy was approximately 90 keV.

The 0° reaction angle was determined by optical alignment and checked by nuclear reaction to an accuracy of ±0.3°.

A. Cross-Section Measurements

Three angular distributions and two excitation functions of cross section were obtained. Two shielded neutron detectors of NE-102 plastic scintillator observed the neutron fluxes at 3-m flight paths. Each detector was a 5-cm-diam by 5-cm-long cylindrical cell viewed by an RCA 7850 photomultiplier tube. For the angular distribution measurements one detector was fixed at 40° reaction angle and served as a monitor.

The neutron time of flight was measured using conventional techniques. The over-all time resolution was approximately 2 nsec. A charge integrator measured the charge collected on the target. An absolute calibration of the Faraday cup and integrator was performed with known currents to an accuracy of ±2%.

B. Polarization Measurements

Angular distributions of neutron polarizations were determined at the same three deuteron bombarding energies for which cross-section angular distributions were obtained. Excitation functions of polarizations were measured at a reaction angle of 30° in approximately 100-keV energy steps.

The neutron polarizations were obtained with a helium-xenon gas polarimeter. The polarimeter consists of a He-Xe gas cell and two "side detectors" of NE-102 plastic scintillator. The gas cell is a scintillator, viewed on each end through 18-mm glass windows by an RCA 8575 photomultiplier tube. It has an active volume 2 in. in diameter by 2 in. high and has 90-mil stainless-steel walls. The beam was collimated so as to illuminate only the active region of the cell. The side detectors are right circular cylinders with their axes parallel to the axis of the gas cell. They are 2 in. in diameter by 2 in. high and each was viewed by an RCA 7850 photomultiplier tube and located with their axes 15 cm from the axis of the gas cell, at equal "right" and "left" scattering angles.

Neutrons incident on the He-Xe cell were scattered by this admixture (~90% helium) so that they were incident on the side detectors perpendicular to the axis of the detector. The whole assembly was mounted behind a movable lead-lined LiOH collimator which shielded the side detectors from the direct beam. The mounting was such that the assembly could be rotated about an axis through the collimator and the center of the gas cell, so as to interchange the positions of the two side detectors.

The gas cell has been described in detail elsewhere.[14] For this experiment it was filled to a pressure of 1700 psi. Its internal walls had been coated with evaporated aluminum (1 μm) and MgO smoke (~0.1 mm). The walls and end windows were coated with approximately 50 and 25 μg/cm^2 of evaporated p-p diphenylstilbene, respectively.

The neutron polarization data were taken in two-dimensional arrays (see Fig. 1). The first dimension was the time of flight (TOF) between the target and the gas cell. The second dimension was proportional to α-recoil energy in the cell as a neutron scattered into one of the two side detectors. This latter quantity was obtained by accurately summing the linear signals from each end of the gas cell. Two such arrays were stored in a

4096-channel analyzer for each run, corresponding to a neutron scattered into one or the other side detector. In addition, a valid event required each of the following: (i) coincidence between both ends of the gas cell, (ii) a linear signal from either side detector larger than a fixed lower level, and (iii) an event in either side detector following an event in the gas cell by more than 4 but less than 32 nsec. The first condition suppressed photomultiplier noise, improved timing and determined the α-recoil detection efficiency. The second condition determined the detector efficiencies of the side detectors. The last condition served to reduce background due to target γ rays which were Compton scattered to the side detectors as well as accidental asynchronous room background.

Because the analyzing power varies rapidly with neutron energy for the energies observed in this experiment (<2 MeV), the side detectors were set at one of three different scattering angles: 80, 90, or 100° (lab), selected to maximize the analyzing power for the ground-state transition.

III. REDUCTION OF DATA

All data reduction was performed with the CWRU PDP-9/L computer. This computer is equipped with a storage oscilloscope and lends itself to the interactive applications which were employed extensively in the data analysis. This facility greatly aided both the quality and ease of data reduction.

A. Reduction of Cross-Section Data

Data consisted of two 512-channel TOF spectra for each run, one for each of the two detectors. The number of counts under the peaks was extracted using a summing program with fitted background. There were some difficulties in this process due to $^{18}O(d,n)^{19}F$ contaminant peaks and to a small overlap of the two peaks from the two neutron groups of interest. These difficulties were always resolved or an additional error was estimated for the net sum and folded in with the other uncertainties. Yields were corrected for out scattering in the target backing, target cup, and air.

The detection efficiency was determined both from measurements and the results of Monte Carlo calculations using a modified version of the code DETEC.[15] The modifications were designed to include the effects of $C(n,n)$ scattering and scintillator-photomultiplier resolution. The data were taken with known fluxes of neutrons provided by the $T(p,n)$ reaction. The resultant efficiency curve

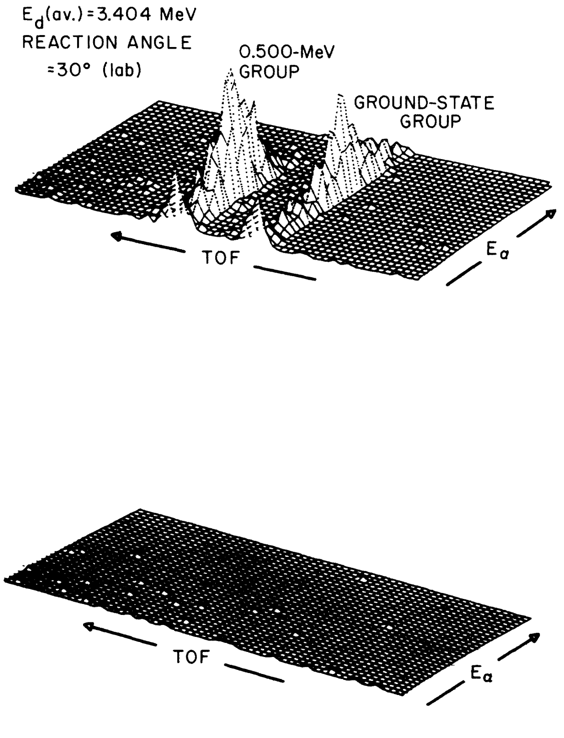

FIG. 1. Upper display represents sample data array from a neutron-polarization run. Lower display represents the corresponding background data array.

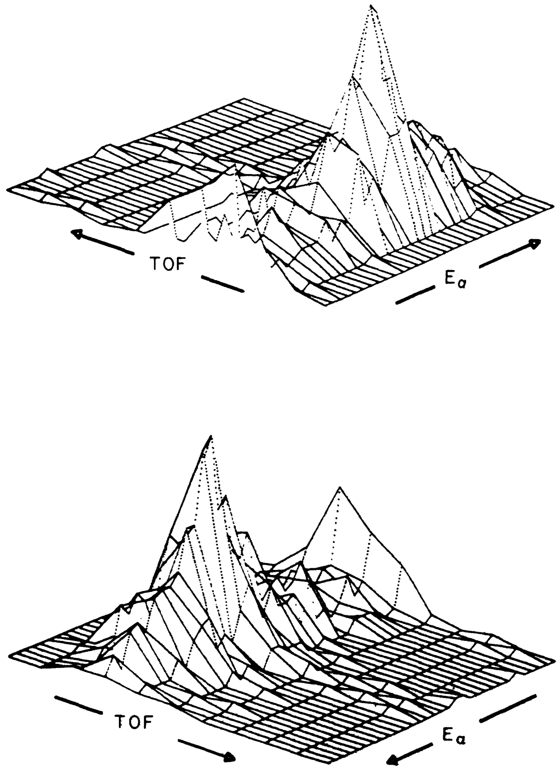

FIG. 2. Blowup of ground-state neutron group in Fig. 1 as viewed from different angles. See text.

is estimated to have an over-all relative uncertainty better than ±2% and an absolute uncertainty better than ±4%.

The effective efficiency was obtained by performing an average over the energy spread of the incident neutrons. The estimated errors for absolute cross sections are less than ±12%, while those for relative cross sections are less than ±5%. The incident energy was determined by calibrating the accelerator energy with standard reactions to an accuracy of ±10 keV.

B. Reduction of Polarization Data

An example of one of the two data arrays stored for each run is shown in Fig. 1. One can discern the two peaks corresponding to the two neutron groups observed in this experiment. A background run taken with enough paraffin in the collimator to attenuate the direct neutron beam by a factor of 10^6 is shown in the lower display of Fig. 1. The small peaks seen are individual counts. The background was always this small.

Sums for each peak were performed with a background subtraction. TOF and pulse-height channels for the sum were chosen for each peak with the aid of a three-dimensional viewing code on the storage oscilloscope of the PDP-9/L computer. The arrays in Figs. 1 and 2 are reproductions of polaroid photographs of the display provided by this code. The code allows one to pick out and examine any region easily and quickly. It is, for example, easy to see that there are a number of background events in the very low pulse-height channels associated with each peak. This "tail" was found to be statistically consistent with zero polarization and

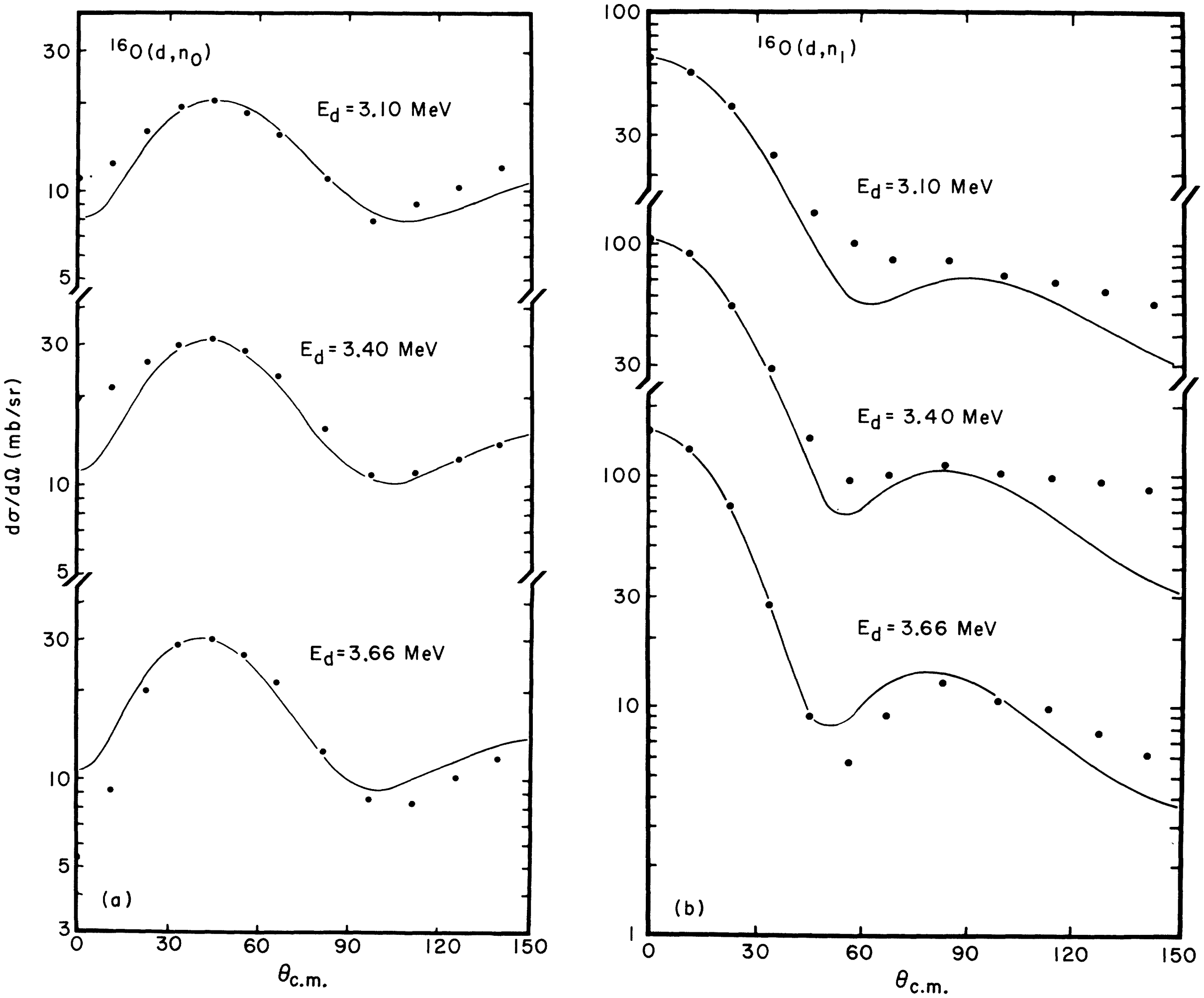

Fig. 3. (a) Cross-section angular distributions for the ground-state neutrons. Solid lines represent DWBA calculations as discussed in the text. Cross sections are in the center-of-mass system. (b) Cross-section angular distributions for the first excited state. Solid lines are DWBA calculations.

was excluded from the sum. This procedure was adopted and discussed by Meier, Schaller, and Walter.[16]

A left/right (L/R) ratio was extracted for each neutron group with the peak sums from the two arrays stored for each run. A second run was performed, with the positions of the side detectors interchanged. The L/R ratios from the two runs were combined in the standard way to yield the final value of L/R; i.e.,

$$(L/R) = [(L/R)_1 \times (L/R)_2]^{1/2}\,.$$

The analyzing power for each run was calculated with an existing program[17] modified for our geometry. The code was not a Monte Carlo code but instead performed scatters off many centers in the He-Xe cell to many centers in a side detector, and performed an averaging process. Three modifications were made to this code: (i) The He(n,n) phase shifts of Hoop and Barschall[18] were replaced with the two-level resonance fit of Morgan and Walter[19] which was considered preferable over the neutron energies observed in this experiment, (ii) the selection of discrete scattering centers within the He-Xe cell were changed slightly in order to distribute the centers more evenly, and (iii) the algorithm for calculating detection efficiency in a side detector was replaced with efficiency "profiles" which were functions of neutron energy and entry point in the detector. This last modification was made because the side detectors in our experiment were cylindrical detectors illuminated perpendicular to their axes. This geometry requires proper representation of multiple-scattering contributions. The efficiency profiles were determined with the subroutine DETEC (see above) and are described in detail elsewhere.[20]

The final analyzing power calculations included corrections for double scattering in the He-Xe cell and for false asymmetries produced by the variation of reaction cross section across the cell. Finally, the analyzing power was averaged over the spread of neutron energies observed for each data point. The net analyzing power calculations

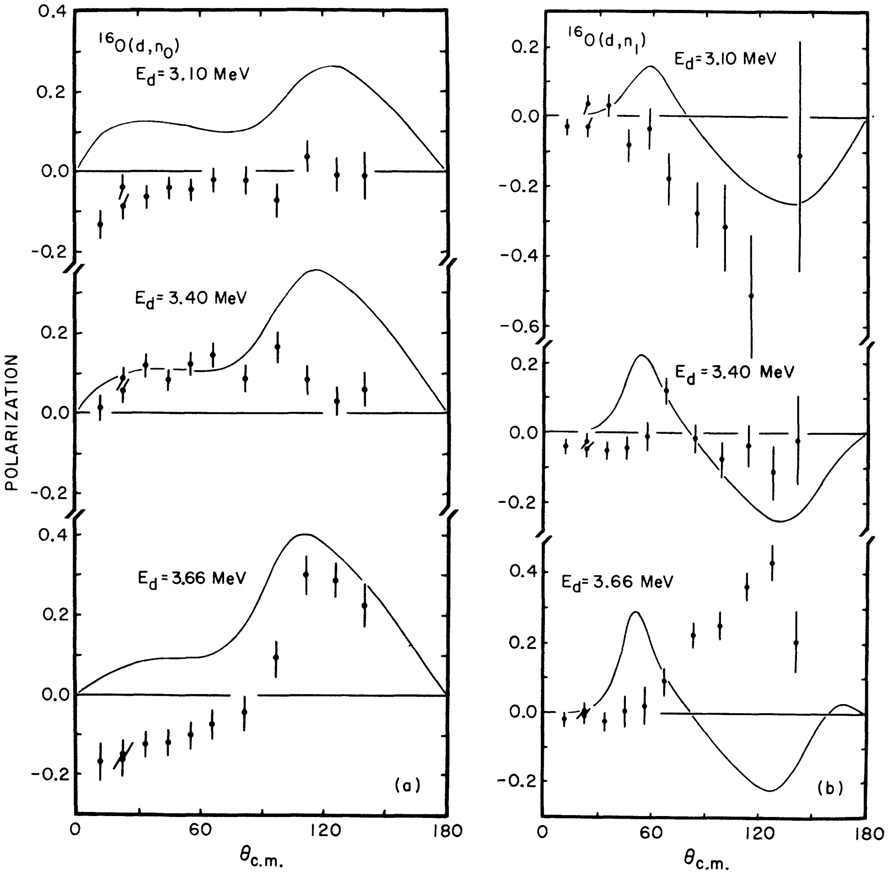

Fig. 4. (a) Neutron polarization angular distributions for the ground-state neutrons. The solid lines are DWBA calculations as discussed in the text. (b) Neutron polarization angular distributions for neutrons to the first excited state.

were considered to be accurate to ±2%.

Over-all checks were performed on the apparatus and data-reduction techniques by measuring the neutron polarizations from the $T(p,n)$ and $^{12}C(d,n)$ reactions at a few energies and angles so as to compare with the previously reported results of Walter *et al.*[21] and Meier, Schaller, and Walter,[16] respectively. The results of these checks were always found to be satisfactory. Uncertainties in the polarizations ranged from ±0.02 to ±0.33 with most uncertainties dominated by statistics and around ±0.04. Final results for both cross section and polarization measurements are shown in Figs. 3 and 4.

IV. THEORETICAL CALCULATIONS

Calculations have been performed to compare with the experimental results reported above. First, optical-model wave-function parameters were obtained for both the entrance and exit channels in the reaction calculations. Then Hauser-Feshbach calculations were made to estimate the average compound-nucleus contributions. Finally, DWBA calculations were performed. Each of these steps will be discussed in turn.

A. Selection of Optical-Model Wave-Function Parameters

Since no deuteron elastic scattering measurements were performed as part of this work, elastic scattering analyses performed elsewhere were reviewed for the purposes of this work. The two principal sets of measurements considered were those of Dietzsch *et al.*[4] at deuteron energies of 2 to 3.6 MeV and those of Davison *et al.*[3] at deuteron energies of 4 to 6 MeV. One of these analyses, that of Davison *et al.*, was judged to be satisfactory for the purposes of this work and no reanalysis of any of these data has been performed here.

The two analyses were nearly identical except for one major difference. The analysis of Dietzsch *et al.*[4] did not include a spin-orbit term in the optical-model potential, whereas the analysis of Davison *et al.*[3] did. The differences in the results of the two analyses were judged to be significant and attributed to this difference. Since it was felt that the elastic scattering analysis should be performed with the inclusion of the spin-orbit term, the results of Davison *et al.*[3] have been adopted for this work. The form of the optical-model potential was

$$U(r) = V_C(r) - V_R f(x_R) - iW_I f(x_I) + 4ia_I W_S \frac{df(x_I)}{dr}$$

$$+\left(\frac{\hbar}{m_\pi c}\right)^2 V_{so} \frac{1}{r} \frac{d}{dr} f(x_{so}) \vec{1} \cdot \vec{\sigma},$$

where $f(x) = (1+e^x)^{-1}$ is the Woods-Saxon form factor. The arguments of the form factors are all of the form

$$x_m = \frac{r - r_m A^{1/3}}{a_m}.$$

The a_m are the diffuseness parameters. $V_C(r)$ is the Coulomb potential produced by a uniformly charged sphere of radius $1.2A^{1/3}$.

Davidson *et al.*[3] found that a $V_R r_0^n$ ambiguity existed with satisfactory fits obtained for real well depths from 80 to 110 MeV. Fluctuations in the experimental results attributed to compound-nucleus contributions led them to energy average their results.

Calculations were made here with the average set having a real well depth of 102 MeV. A few of the other parameters were varied as described below. These parameters are listed in Table I. This choice of parameters was further checked by calculating the deuteron elastic scattering at $E_d = 3.63$ MeV to compare with data of Dietzsch *et al.*[4] and the deuteron tensor polarization at $E_d = 8$ MeV to compare with data of Bjorkholm and Haeberli.[22] These comparisons were judged to be excellent. It is noteworthy that these results compare well with those found by Schwandt and Haeberli[23] recently for the elastic scattering of polarized deuterons by ^{40}Ca.

Neutron elastic scattering by ^{17}F data is not pos-

TABLE I. Optical-model parameters.

Particle	Name	V (MeV)	r_R (fm)	a_R (fm)	W_s (MeV)	r_I (fm)	a_I (fm)	V_{so} (MeV)	Finite range and low-energy approximation	Source
Deuteron	D1	102	1.04	0.87	5.50	2.05	0.41	8.1	Yes	Davison *et al.* (Ref. 3)
	D2	102	1.04	0.83	5.00	2.00	0.41	>10.0	No	Davison *et al.* (Ref. 3)
	D3	112	1.05	0.85	8.50	1.66	0.53	9.0	Yes	Schwandt & Haeberli (Ref. 23)
Neutron	N1	48.4	1.25	0.65	5.75	1.25	0.70	5.5	Yes	Rosen (Ref. 24)
	N2	48.4	1.32	0.65	8.10	1.25	0.48	9.0	No	Meier *et al.* (Ref. 25)

sible to obtain directly. However, neutron optical-model potentials have been determined previously by many workers, and sets of parameters averaged over a large energy range and many nuclei are available. These sets for neutrons are determined rather more unambiguously than those for deuterons. First, the nucleon-nucleus theoretical work is extensive and limits the range of most parameters. Second, determining optical potentials for scattering of a weakly bound composite particle like the deuteron is complicated by distortion effects.

Two neutron optical-model parameter sets have been adopted in this work. They are due to Rosen[24] and Meier *et al.*,[25] respectively, and are listed in Table I. Rosen's set has received wide application and was chosen for most of the calculations of this work. Meier's set was obtained in the DWBA analysis of the $^{14}N(d, n)$ reaction and differs mostly in having deeper imaginary and spin-orbit wells. Only slight differences were observed in the DWBA calculations with these two neutron sets.

B. Compound-Nucleus Calculations

Average compound-nucleus cross sections were calculated with the code HELENE.[26] This code performs a Hauser-Feshbach-type calculation including fluctuation corrections. All energetically possible binary reactions are considered in competition with each other.

These calculations were performed in a relatively straightforward way except for one point. Since the optical-model parameters obtained in the analysis of elastic scattering data include the effects of both direct and compound-nucleus absorption, the theoretical cross sections must be reduced. The standard correction is taken to be

$$\sigma_{CN} = \left(\frac{\sigma_{tot} - \sigma_D}{\sigma_{tot}}\right)\sigma_{CN'} \equiv \alpha\sigma_{CN'},$$

where $\sigma_{CN'}$ is the cross section given by the comound-nucleus program, σ_{CN} is the corrected value, σ_{tot} is the total reaction cross section predicted by the optical-model calculations, and σ_D is the total direct-interaction cross section. The value of α was taken in this work to be 0.3.[3] This method is necessarily approximate, since the Hauser-Feshbach theory assumes that all reactions go via the compound nucleus.

C. DWBA Calculations

Calculations were performed using the DWBA code DWUCK[27] with the optical-model potentials of Table I. Calculations were begun using the average parameter sets of Davison *et al.* for the deuteron optical-model wave function and Rosen's parameters for the neutron set. These calculations were compared against all cross section and polarization data. It became apparent that while the cross sections could be reproduced reasonably well, the polarizations were varying too rapidly with energy. Indeed, no two of either the ground state or first excited state angular distributions have even the same general shape. These changes were all too rapid to offer any hope that they could be reproduced by DWBA calculations. The polarizations are apparently being strongly influenced by compound-nucleus contributions.

Figures 3 and 4 show the DWBA calculations with parameter sets D1 and N1 compared with the data. One may notice that the theoretical calculations of the ground-state neutron polarizations at $E_d = 3.66$ MeV are suggestive, in shape, of the data. In fact, the theoretical curve may be lowered, so as to better reproduce the data, by increasing the depth of the deuteron spin-orbit potential. If this is done, however, the neutron polarization data of Ref. 8, at slightly higher deuteron energy, is not fitted as well. These potentials, D1 and N1, do reproduce the highest deuteron energy data of that reference extremely well. Since the data change only slightly down through the 3.66-MeV data reported here, it is somewhat disappointing that no combination of deuteron parameters could be found which fit all these data simultaneously.

The first excited state neutron polarization calculations are suggestive of the data at $E_d = 3.10$ and 3.40 MeV. Note too (see Table II) that the spectroscopic factor determined at 3.66 MeV is abnormally large.

The point of noting these cases where the calculations "suggest" the data is not to argue that the theory is seen to reproduce the data in any systematic way. Rather, it is just to point out

TABLE II. Spectroscopic factors and integrated cross sections.

E_d (MeV)	σ_{exp} (±15%) (mb)	S (±30%)	σ_{DIR} (±30%) (mb)	σ_{CN} (±60%) (mb)
		$^{16}O(d, n_0)^{17}F$		
3.102	162	0.84	129	27
3.404	225	1.16	184	32
3.656	194	1.03	165	35
		$^{16}O(d, n_1)^{17}F$		
3.102	141	0.72	106	9
3.404	185	0.85	139	11
3.656	191	1.08	181	12

that there *may* be a direct mechanism trying to produce polarizations close to these calculations, but being mixed substantially with compound-nucleus contributions. These data certainly do not lend any support to the hope that the DWBA might, when performed carefully, be able to describe polarizations in reactions on light nuclei at low energies.

A few calculations were performed with a deuteron potential without finite-range or nonlocality corrections (D2). It was found that an unphysically large spin-orbit depth was required to produce results which looked qualitatively like those of Fig. 4. Finally, a few calculations were performed with Meier's set of neutron parameters (N2) and no significant change in the calculations was noted. The single most sensitive parameter for affecting the polarization calculations was found to be the deuteron spin-orbit depth.

The spectroscopic factors obtained by fitting the DWUCK calculations to the experimental data (with the Hauser-Feshbach calculations subtracted) at each of the three energies are listed in Table II. The 3.404-MeV ground-state result is somewhat high, since it is at a resonance seen in the excitation function shown in Fig. 5. The 3.66-MeV first excited state spectroscopic factor also appears to be abnormally high and again may be at a resonance seen in Fig. 5. Other groups have obtained spectroscopic factors of about 0.8 and 0.7 for the ground-state and first excited state transitions, respectively,[3,5] in general agreement with these results.

D. WBP Results

Another theory of deuteron stripping has been proposed recently by Coz and Pearson,[28] the WBP. There is a certain amount of evidence for this model[29] and some of the successes of the theory have been impressive. Proton polarizations from a number of (d, p) reactions have been reproduced,[2,30] as well as the neutron polarizations from the $^{12}C(d, n)$ reaction down to a deuteron energy of 2.3 MeV.[6]

Calculations were performed with a WBP com-

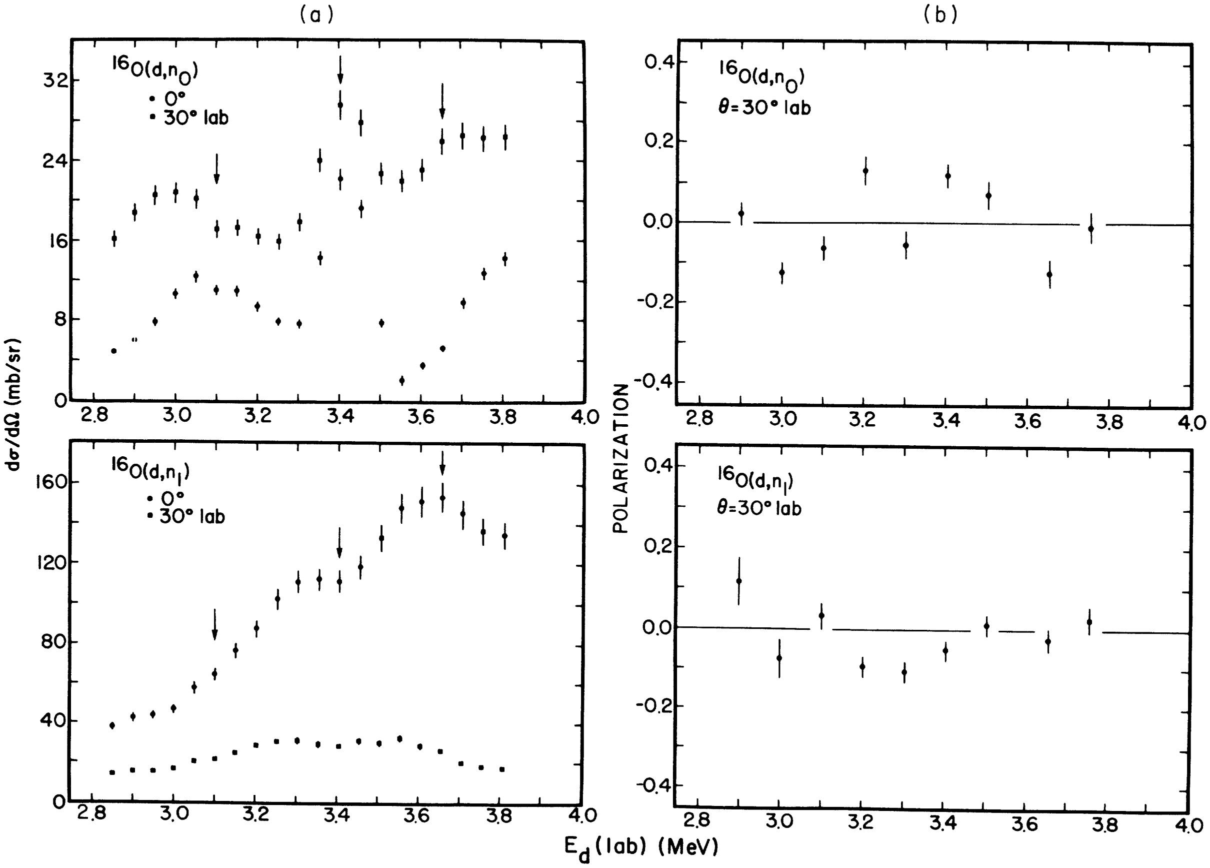

Fig. 5 (a) Cross-section excitation functions. The arrows indicate the three energies at which angular distributions were performed. The cross sections are in the center-of-mass system. (b) Neutron polarization excitation functions.

puter code by Zisserman and Pearson[9] to compare with the experimental results reported here. The single polarization angular distribution which could be reproduced was the first excited state transition at 3.66 MeV. This is probably not significant, since this shape is not maintained in the reported experimental results at 4.0 and 5.35 MeV.

V. CONCLUSIONS

Neutron polarization and cross-section measurements have been performed at deuteron energies from 3 to 4 MeV. The cross-section angular distributions show definite forward peaking indicative of direct processes. At the same time, the excitation functions of cross section show resonances indicative of compound-nucleus effects. The angular distributions of polarization show no common shape through all three bombarding energies for either transition.

Hauser-Feshbach and DWBA calculations were performed. The cross-section angular distributions were well reproduced and spectroscopic factors extracted which agree well with those obtained by other groups.[3,5] Although the theoretical calculations for neutron polarizations are somewhat suggestive of a few of the measured angular distributions, the over-all success of DWBA calculations to reproduce the polarization data reported here is judged to be poor. It is concluded that compound-nucleus contributions to the data are chiefly responsible for this failure.

WBP calculations performed by Zisserman and Pearson[9] did not reproduce the polarization data in any significant way.

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