Study of the Two-Body Force through the (He^3,t) Charge-Exchange Reaction on O^{17} and O^{18}†

LUISA F. HANSEN, MARION L. STELTS, JOSE G. VIDAL, AND J. J. WESOLOWSKI
Lawrence Radiation Laboratory, University of California, Livermore, California

AND

V. A. MADSEN
Oregon State University, Corvallis, Oregon

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A study of the (He^3,t) reaction on O^{17} and O^{18} has been made at 17.3 MeV, using gas targets of enriched isotopes. The elastic He^3 differential cross sections have also been measured and an optical-model analysis performed. The triton angular distributions show the predominance of a direct reaction mechanism. They have been analyzed using a distorted-wave Born-approximation formalism assuming a two-body interaction V_{0i} between the incident and target nucleons; i.e., $V_{0i}=\boldsymbol{\tau}_0\cdot\boldsymbol{\tau}_i(V_{\sigma\tau}\boldsymbol{\sigma}_0\cdot\boldsymbol{\sigma}_i+V_\tau)f(\mu_{0i})$. The strengths of the spin-isospin interaction $V_{\sigma\tau}$ and the pure isospin interaction V_τ have been found to be 34.7±6 and 52.0±10 MeV, respectively. The form factors $f(\mu_{0i})$ for both interactions were taken to have a Yukawa shape with a range of 1 F. For the (He^3,t) transitions to the analog state, a further analysis has been made using an exact coupled-channel-equation calculation.

INTRODUCTION

THE particle model of nuclear inelastic scattering has been successful in the treatment of proton and neutron inelastic scattering[1] and charge-exchange (p,n) reactions.[2,3] Satchler[1] has obtained from the experimental data an effective nucleon-nucleon interaction represented in terms of a simple local potential. A general formalism has been developed[4] for the direct inelastic scattering based on the particle model, which is applicable to the treatment of the direct (p,n)[4] and (He^3,t) reactions. It is a distorted-wave Born-approximation (DWBA) calculation that assumes a two-body force of the form $V_{0i}=\boldsymbol{\tau}_0\cdot\boldsymbol{\tau}_i(V_{\sigma\tau}\boldsymbol{\sigma}_0\cdot\boldsymbol{\sigma}_i+V_\tau)f(r_{0i})$, where $V_{\sigma\tau}$ is the strength of the spin-isospin interaction and V_τ the strength of the pure isospin or charge-exchange interaction.

The analysis of the (He^3,t) reaction in O^{18} is particularly interesting because it allows one to extract independently the values of $V_{\sigma\tau}$ and V_τ. The $O^{18}(He^3,t)F^{18}$ reaction to the ground state and 1.70-MeV levels in F^{18} are transitions from a $[J=0^+,T=1]$ initial state to a $[J=1^+,T=0]$ final state, and they are dependent only on the spin-isospin potential $V_{\sigma\tau}(r)$. On the other hand, the (He^3,t) reaction to the 1.045-MeV analog level in F^{18} is a $\Delta J=0$ and $\Delta T=0$ transition and is dependent only upon the charge-exchange potential $V_\tau(r)$. From the analysis of the triton differential cross sections to these levels, one can obtain in principle the strength and shape of $V_{\sigma\tau}(r)$ and $V_\tau(r)$. However, because of experimental difficulty in resolving the 1.045-MeV level from neighboring states separated by less than 40 keV, only an upper limit could be obtained for V_τ.

The $O^{17}(He^3,t)F^{17}$ reaction to the ground state is a $\Delta J=0$ and $\Delta T=0$ transition and is dependent upon both potentials. Therefore, the simultaneous analysis of the (He^3,t) reaction in O^{17} and O^{18} allows one to check the consistency of the values for $V_{\sigma\tau}$ and V_τ obtained from the O^{18} analysis.

The dependence of the magnitude of these potentials on the optical parameters used in the calculations, as well as on the wave functions used to represent the initial and final states, has been studied. Calculations were made assuming the ground-state wave functions of O^{18} and F^{18} to be pure $[d_{5/2}]^2$ configurations and the results compared with those obtained using Kuo-Brown[5] and De Llano *et al.*[6] wave functions for these levels.

To limit the number of parameters used in the calculations, the elastic He^3 scattering in O^{17} and O^{18} was measured at the same energy as the (He^3,t) measurements. In this way, the optical parameters for the incoming channel in the DWBA calculations were well determined.

A coupled-channel calculation was also carried out for the (He^3,t) reactions to the analog state. The results agree remarkably well with the ones obtained with the microscopic DWBA calculations.

EXPERIMENTAL PROCEDURE

The measurements were made with the He^3 beam from the Livermore 90-in. variable-energy cyclotron. The energy of the beam at the center of the gas cell was 17.3 MeV.

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[1] G. R. Satchler, in *Proceedings of the Symposium on Recent Progress in Nuclear Physics with Tandems*, edited by W. Hering (Max Planck Institute for Nuclear Physics, Heidelberg, 1966).

[2] C. Wong, J. D. Anderson, J. W. McClure, B. Pohl, V. A. Madsen, and F. Schmittroth, Phys. Rev. **160**, 769 (1967).

[3] C. Wong, J. D. Anderson, S. D. Bloom, V. A. Madsen, and F. Schmittroth, International Conference on Nuclear Structure, Tokyo, 1967 (unpublished).

[4] V. A. Madsen, Nucl. Phys. **80**, 177 (1966).

[5] T. T. S. Kuo and G. E. Brown, Nucl. Phys. **85**, 40 (1966).

[6] M. De Llano, P. A. Mello, E. Chacon, and J. Flores, Nucl. Phys. **72**, 379 (1965).

Gas targets of enriched oxygen isotopes were used. The O^{16} gas was 100% pure. The O^{17} was about 48% enriched and the O^{18} gas 93% and 99.8% enriched (from two different samples used). The mass spectrograph analyses of the O^{17} gas gave the following composition: O^{17}–48.6%; O^{16}–44.5%; O^{18}–6.96%; for the first O^{18} sample: O^{18}–93.0%; O^{16}–6.58%; O^{17}–0.42%.

The gas cell has a 2.54-cm diameter with a 290° continuous window made of 0.10-mil ($=2.54\,\mu$) Havar (cobalt-based alloy) foil. The cell was mounted at the center of a 40-in. scattering chamber and filled to a pressure of 280 mm Hg. The pressure and temperature in the gas cell were monitored continuously during the runs by reading remotely the dials of a precision manometer and a thermocouple meter on a television screen.

The outgoing charged particles were detected with three silicon solid-state ΔE-E counter telescopes and particle identification circuits as described in a previous paper.[7] Their spectra were stored in the PDP5 analyzer. Because of the range differences for He^3 and tritons which required different thickness detectors for good identification, their measurements were made in separate runs. For the He^3 measurements the He^3 and α particles were counted simultaneously, while for the triton measurements the protons and deuteron and triton outgoing particles were stored in the PDP5.

The differential He^3 cross sections were measured from 18.5° to 92° at 2.5-deg intervals, while the triton differential cross sections were measured between 20° and 150° at 5-deg intervals.

EXPERIMENTAL RESULTS

The He^3 elastic differential cross sections for O^{16}, O^{17}, and O^{18} are shown in Fig. 1. Measurements on O^{16} were required to correct the results obtained from O^{17} and O^{18} since O^{16} was the main impurity in these gas targets.

The $O^{17}(He^3,t)F^{17}$ reaction proceeded mainly to the ground state of F^{17}. This was expected since this level is the analog of the target nucleus (O^{17} and F^{17} are mirror nuclei). The integrated cross section from 0° to 180° for this level was 3.10±0.31 mb. The (He^3,t) cross section to the 0.50-MeV level was 0.70±0.10 mb, which is lower by a factor of 5. The 3.10-MeV ($\frac{1}{2}^-$), 3.86-MeV ($\frac{5}{2}^-$), and 4.69-MeV ($\frac{3}{2}^-$) levels were barely excited above the background for the very forward angles (below 25°). The 5.10-MeV ($\frac{1}{2}^+$) level and a level at 5.75 MeV, which was not resolved from nearby states, were about equally excited with cross sections about two-thirds that of the 0.50-MeV ($\frac{1}{2}^+$) level. A small continuous triton background starting at the first excited state seems to be the result of a sequential three-body breakup process:

$$O^{17}+He^3 \to F^{19}+p \qquad \searrow t+O^{16}.$$

The measured triton angular distributions for the $O^{17}(He^3,t)F^{17}$ reaction to the ground state and 0.50-MeV level are shown in Fig. 2. They are both forward-peaked with small oscillations, more pronounced for the ground state.

The triton spectrum from the $O^{18}(He^3,t)F^{18}$ reaction

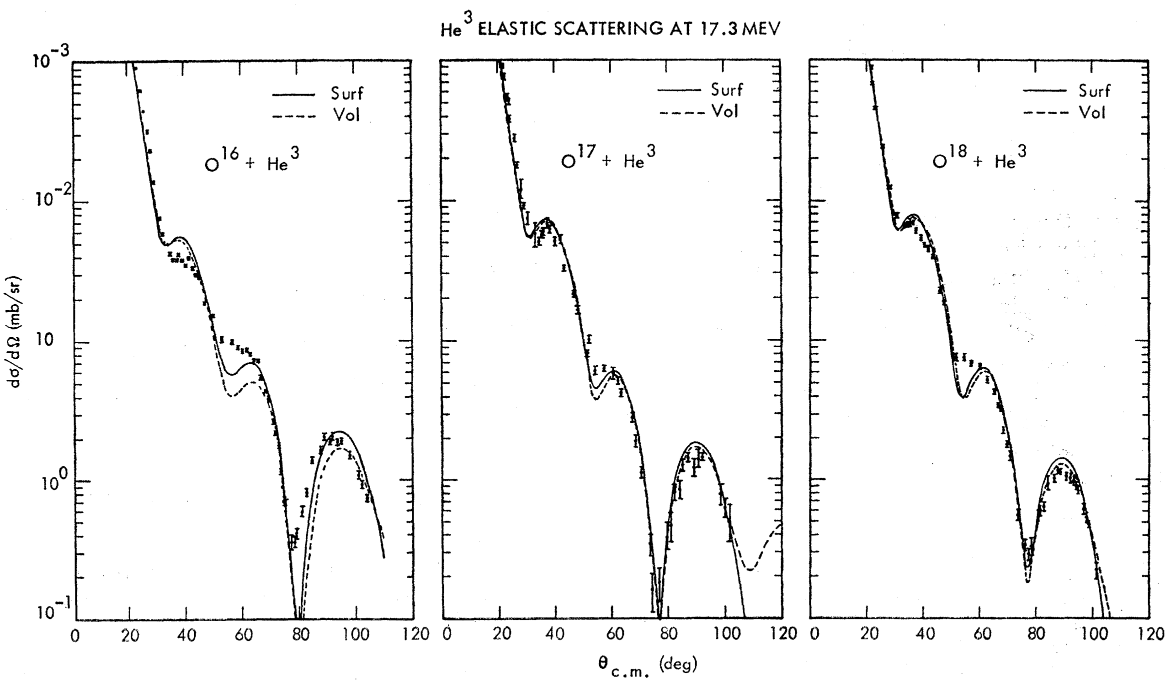

FIG. 1. He^3 elastic differential cross sections for O^{16}, O^{17}, and O^{18} at 17.3 MeV and the optical-model fits to the data calculated with LOKI.

[7] L. F. Hansen, H. F. Lutz, M. L. Stelts, J. G. Vidal, and J. J. Wesolowski, Phys. Rev. **158**, 917 (1967).

is shown in Fig. 3. The analog state at 1.045 MeV could not be resolved from the three nearby states. Also, the resolution was not sufficient to separate the 3.058–3.130-MeV levels or the 3.725–3.790–3.939-MeV levels. The assignments of angular momentum and parity for these levels were taken from the recent works of Olness *et al.*[8] and Poletti.[9]

The triton angular distributions for the $O^{18}(He^3,t)F^{18}$ reaction are shown in Fig. 4. They show oscillatory patterns which are especially pronounced for the ground state (1^+) and the 1.70-MeV level (1^+). The angular distribution for the analog state (plus the unresolved 3^+, 5^+, and 0^- states) is very close in magnitude and shape to the F^{17} ground-state angular distribution. This suggests that the same angular momentum transfer is predominant in both cases. For the $O^{17}(He^3,t)F^{17}$ ground-state transition, $L=0$, 2, and 4 are allowed, although $L=0$ is expected to be favored (theoretically the ratios of the cross sections obtained from the calculations are 1:0.18:0.03). Furthermore, the triton angular distribution to the first excited state of F^{17}, a pure $L=2$ transition, has maxima and minima which (although not very pronounced) are not in phase with those of the ground state. Since the magnitude of the cross section for $L=2$ for the $1d_{5/2}\rightarrow 1d_{5/2}$ transition (ground state) and the $1d_{5/2}\rightarrow 2s_{1/2}$ transition (0.5-MeV level) are about equal, the $O^{17}(He^3,t)F^{17}$ ground-state reaction probably is mainly an $L=0$ transition. Hence, the $O^{18}(He^3,t)F^{18}$ angular distribution which includes the analog state and which resembles the F^{17} ground-state distribution in both magnitude and shape is also mostly an $L=0$ transition. Therefore, one would conclude that the contribution from the 3^+ and 5^+ levels is small and that most of the measured strength of the 1-MeV group belongs to the analog transition. An estimate of the contribution from the 3^+ of about 20% of the measured cross section, obtained from the (p,n) reaction on O^{18},[10] seems to corroborate the above arguments.

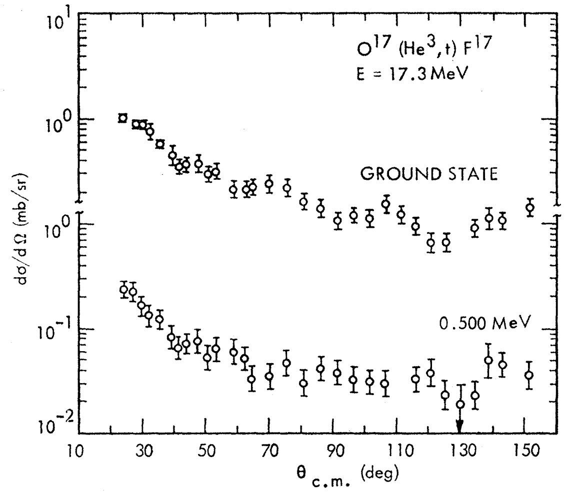

FIG. 2. Measured triton differential cross sections from the $O^{17}(He^3,t)F^{17}$ reaction at 17.3 MeV.

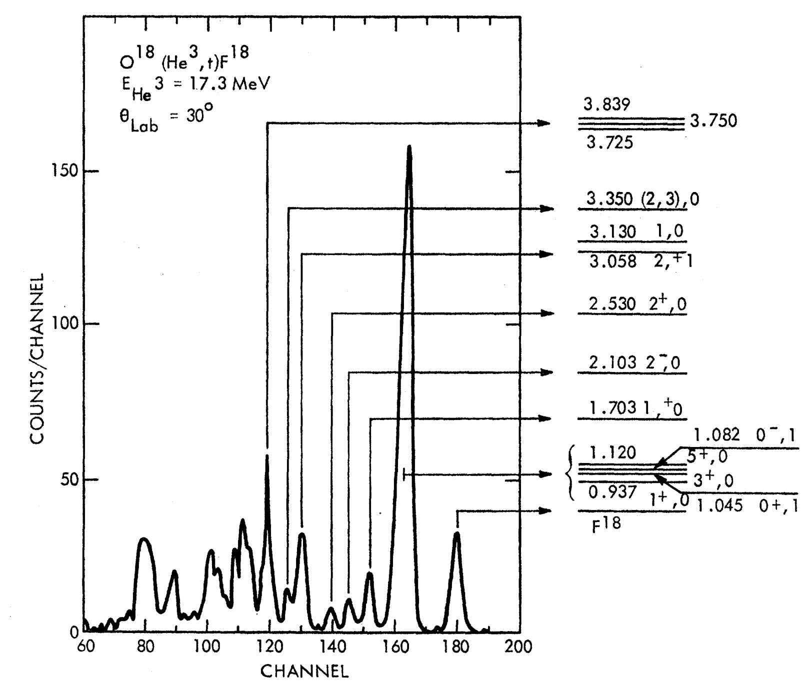

FIG. 3. Triton energy spectra for the $O^{18}(He^3,t)F^{18}$ reaction at 30°.

[8] J. W. Olness and E. K. Warburton, Phys. Rev. **151**, 792 (1966).
[9] A. R. Poletti, Phys. Rev. **153**, 1108 (1967).
[10] J. D. Anderson, Lawrence Radiation Laboratory Report No. UCRL-14760-T, 1966 (unpublished).

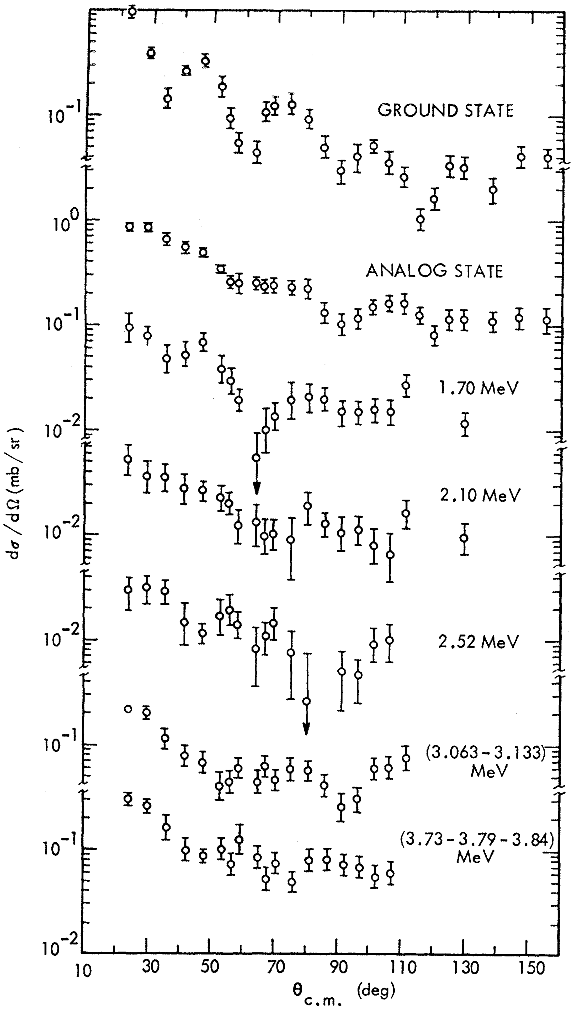

FIG. 4. Measured triton differential cross sections from the $O^{18}(He^3,t)F^{18}$ reaction at 17.3 MeV.

ANALYSIS OF THE He^3 ELASTIC SCATTERING DATA

The He^3 elastic angular distributions from O^{16}, O^{17}, and O^{18} were analyzed with the usual optical-model potential

$$U(r)=V_c-V(e^x+1)^{-1} -i\{[\alpha W-4(1-\alpha)W_D d/dx'](e^{x'}+1)^{-1}\} +(\hbar/m_\pi c)^2(V_s+iW_s)(\boldsymbol{\sigma}\cdot\mathbf{l})r^{-1}(d/dv)(e^x+1)^{-1}, \quad (1)$$

where

$$x=(r-r_0A^{1/3})/a,$$
$$x'=(r-r_0'A^{1/3})/a',$$
$$0\leq\alpha\leq1.$$

The quantity V_c is the Coulomb potential from a uniformly charged sphere of radius 1.25 $A^{1/3}$F. Following Satchler's[11] nomenclature, a "constrained" spin-orbit coupling was used (the same geometrical parameters for the real and spin-orbit potentials). No imaginary spin-orbit potential was used.

The calculations were made with the optical-model code LOKI[12] modified by the inclusion of a least-squares search routine. Pure volume absorption ($\alpha=1$) and pure surface absorption ($\alpha=0$) were tried. The best fits to the data obtained are shown in Fig. 1 and the optical parameters are given in Table I. The differential cross sections were reproduced equally well with either potential, and a mixture of volume and surface absorption ($0<\alpha<1$) did not appreciably improve the fits. Calculations without the spin-orbit potential did not change the results significantly.

The parameters given in Table I were obtained by minimizing χ^2, which is defined as

$$\chi^2=\sum_{i=1}^{n}\{[\sigma_{\text{th}}(\theta_i)-\sigma_{\text{expt}}(\theta_i)]/\Delta\sigma_{\text{ex}}(\theta_i)\}^2, \quad (2)$$

where the nomenclature used is self-explanatory.

CHARGE-EXCHANGE FORMALISM

The analysis of the triton differential cross sections has been carried out with a distorted-wave formalism. The main physical assumption is that there exists an effective nucleon-nucleon interaction, which is taken to be the sum over the projectile nucleon-target nucleon pairs. The interaction potential is restricted to being central with a mixture of spin-isospin exchange. The cross section is given by the following equation[4]:

$$\frac{d\sigma}{d\Omega}=\left(\frac{2m}{4\pi\hbar^2}\right)^2\frac{k_f}{k_i}\frac{1}{(2J_i+1)(2J'+1)}\sum_{II'LM}(2I+1)(2I'+1) \times\left|\sum_{j_1j_2}D_{j_1j_2}(II'L)F_{LM}{}^{j_1j_2}(2L+1)^{-1/2}\right|^2. \quad (3)$$

It is formed by an incoherent sum of contributions from the angular momentum transfers

$$I':\ (0\leq I'\leq1),$$
$$I:\ (|j_2-j_1|\leq I\leq|j_1+j_2|),$$

and

$$L:\ (|l_2-l_1|\leq L\leq|l_1+l_2|).$$

Each of these contributions consists of a coherent sum of angle-dependent, single-particle amplitudes $F_{LM}{}^{j_1j_2}$ weighted by the coefficients $D_{j_1j_2}$ which are defined by Madsen.[4]

These coefficients contain information about the single-particle coupling, the effective nucleon-nucleon interaction, and the details of the nuclear wave functions in the spectroscopic amplitudes.

[11] G. R. Satchler, Nucl. Phys. **A100**, 497 (1967).

[12] E. H. Schwarcz (private communication).

TABLE I. Optical-model parameters obtained for the elastic scattering of He^3 from O^{16}, O^{17}, and O^{18} at 17.3 MeV.

Nuclei	V (MeV)	r_0 (F)	a (F)	W (MeV)	W_D (MeV)	r_0' (F)	a' (F)	V_s^* (MeV)	χ^2
O^{16}	159.73	1.302	0.615	19.76	0	1.383	0.929	4.10	5.27×10^3
	145.13	1.383	0.631	0	18.73	1.404	0.631	4.53	4.59×10^3
O^{17}	158.27	1.307	0.635	21.72	0	1.351	0.928	5.37	5.86×10^2
	146.08	1.378	0.638	0	22.08	1.361	0.636	0	6.18×10^2
O^{18}	156.31	1.298	0.618	25.54	0	1.308	0.910	7.39	1.29×10^2
	144.67	1.362	0.639	0	28.08	1.363	0.596	0	1.57×10^3

ANALYSIS OF THE O^{17}(He^3,t)F^{17} REACTION

For the O^{17}(He^3,t)F^{17} reaction, the projectile is treated as a hole in the closed $1s$ shell and the target is taken as a single neutron outside a closed shell. In this case, the general formalism is very much simplified and the cross section is given by Eq. (74) in Ref. 4:

$$\frac{d\sigma}{d\Omega}=\frac{2J_f+1}{\pi}\sum_L C(l_il_jL;000)^2[2V_{\sigma\tau}^2+(V_\tau^2-V_{\sigma\tau}^2)\times(2l_i+1)(2l_f+1)W(J_il_iJ_fl_f;\tfrac{1}{2}L)^2]\chi_L^{J_1J_2}(\theta)\,,\quad(4)$$

where L is the angular momentum transfer and $C(l_il_fL;000)$ and $W(J_il_iJ_fl_f;\frac{1}{2}L)$ are the Clebsch-Gordan and Racah W coefficients, respectively. The quantity $V_{\sigma\tau}$ is the strength of the effective projectile nucleon–target nucleon spin flip and isospin interaction, and V_τ is the strength of the pure charge-exchange interaction. After integration over the internal coordinates of the projectile, these potentials reduce to effective interactions between the center of mass of the projectile and the target nucleons, i.e.,

$$V=\sum_i V(r_{0i})\boldsymbol{\tau}_0\cdot\boldsymbol{\tau}_i[V_{\sigma\tau}\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}_i+V_\tau]\,,\quad(5)$$

where $r_{0i}=|\mathbf{R}_0-\mathbf{r}_i|$ is the vector between the center-of-mass coordinate (R_0) of the projectile and the coordinate (r_i) of the ith bound nucleon in the target nucleus, and τ_0 and σ_0 are the isospin and spin of the projectile. $\chi_L^{J_1J_2}(\theta)$ includes the rest of the factors appearing in Eq. (3):

$$\chi_L^{J_1J_2}(\theta)=\left(\frac{2m}{4\pi\hbar^2}\right)^2\frac{k_f}{k_i}\sum_M|F_{LM}^{j_1j_2}(2L+1)^{-1/2}|\quad(6)$$

and is calculated numerically by using the code DRC.[13]

The (He^3,t) ground-state reaction in O^{17} is a $\frac{5}{2}+\to\frac{5}{2}+$ isobaric analog transition. The allowed momentum transfers are $L=0$, 2, and 4, and Eq. (4) becomes

$$d\sigma/d\Omega_{\text{g.s.}}=(1/\pi)[((7/5)V_{\sigma\tau}^2+V_\tau^2)\chi_0^{\frac{5}{2}\frac{5}{2}}(\theta)+(8/7)(2V_{\sigma\tau}^2+V_\tau^2)\chi_2^{\frac{5}{2}\frac{5}{2}}(\theta)+(6/35)(31V_{\sigma\tau}^2+5V_\tau^2)\chi_4^{\frac{5}{2}\frac{5}{2}}(\theta)]\,.\quad(7)$$

On the other hand, the (He^3,t) reaction to the 0.500-MeV level in F^{17} is a $\frac{5}{2}+\to\frac{1}{2}+$ transition and $L=2$ is the only allowed value. In this case Eq. (4) becomes

$$d\sigma/d\Omega_{0.50\text{ MeV}}=(1/\pi)(3V_{\sigma\tau}^2+V_\tau^2)\chi_2^{\frac{5}{2}\frac{1}{2}}(\theta)\,.\quad(8)$$

The distorted wave functions $\psi^{(+)}$ and $\psi^{(-)}$ required to calculate the transition amplitude $F_{LM}^{j_1j_2}$ were obtained as follows: The $\psi^{(+)}$ distorted wave function for the He^3 scattering was generated by using the optical parameters obtained from the measured He^3 elastic scattering on O^{17}. The $\psi^{(-)}$ distorted wave function for the triton scattering was calculated by using the optical parameters from the elastic scattering of tritons from O^{16} at 12 MeV measured by Glover and Jones.[14] (In the charge-exchange reaction the triton energy was about 2.5 MeV higher.) Optical parameters obtained from the measured elastic scattering of He^3 on O^{16} at 17.3 MeV were also used to generate $\psi^{(-)}$ (after appropriate modification for the Coulomb interaction). Since O^{16} is a self-conjugate nucleus ($N=Z$), charge symmetry can be used to justify this procedure.[15] The shape of the calculated differential cross sections was very similar for both sets of parameters.

The bound-state wave functions for the neutron and proton were generated with a Woods-Saxon real potential with a radius parameter $r_0=1.25$ F, $a_0=0.65$ F and a potential well depth of 55 MeV. This gave 4.14 MeV for the binding energy of the neutron in O^{17}. The initial- and final-state wave functions in O^{17} and F^{17} were assumed to be pure ($1d_{5/2}$) configuration.

The space part of the effective projectile-nucleon interaction $V(R_0,r_i)$ in Eq. (5) was chosen to be a Yukawa interaction $e^{-\alpha r}/\alpha r$. The best agreement with the shape of the measured angular distributions was obtained for a range of about 1 F ($\alpha=1$ F^{-1}) in agreement with the results of nucleon inelastic scattering analysis.[1] The strengths of the spin-isospin potential $V_{\sigma\tau}$, and isospin potential V_τ, were found to depend on the optical parameters used to generate the distorted wave $\psi^{(+)}$ and $\psi^{(-)}$. Variations of around 10% were found for fits of comparable quality. Four sets of optical parameters were used. In sets 1 and 2, the incoming waves were generated from parameters obtained from the analysis of He^3-O^{17} data by using a Woods-Saxon imaginary potential. The triton parameters in set 1 were those of Glover *et al*[14] at 12 MeV, while in set 2

[13] W. R. Gibbs, V. A. Madsen, J. A. Miller, W. Tobocman, E. C. Cox, and L. Mowry, NASA Technical Note No. TN D-2170, 1964 (unpublished).

[14] R. N. Glover and A. D. W. Jones, Nucl. Phys. **81**, 268 (1966).

[15] J. D. Anderson and H. F. Lutz, Lawrence Radiation Laboratory Report No. UCRL-14568, 1966 (unpublished).

TABLE II. Optical-model parameters used in the calculations of the $O^{17}(He^3,t)F^{17}$ reaction to the ground state and 0.500-MeV level.

Particle	Reaction	Energy (MeV)	V (MeV)	r_0 (F)	a (F)	W (MeV)	W_D (MeV)	r_0' (F)	a' (F)	χ^2	Comments
He^3	He^3+O^{17}	17.3	146.9	1.404	0.636	24.10	⋯	1.404	0.636	7.20×10^2	Sets 1 and 2[a]
t	$t+O^{16}$	12.0	146.8	1.40	0.550	18.4	⋯	1.40	0.550	1.50×10^3	Sets 1[b]
t	He^3+O^{16}	17.3	149.2	1.374	0.644	24.26	⋯	1.374	0.644	6.57×10^3	Set 2[a]
He^3	He^3+O^{17}	17.3	146.08	1.378	0.638	⋯	22.83	1.361	0.636	6.18×10^2	Sets 3 and 4[a]
t	He^3+O^{16}	17.3	145.0	1.375	0.650	⋯	22.59	1.382	0.592	6.31×10^3	Set 3[a]
t	He^3+O^{16}	16.6	122.8	1.546	0.568	⋯	18.90	1.546	0.550		Set 4[c]

[a] Present work. [b] Glover *et al.* (Ref. 14). [c] Lutz *et al.* (Ref. 16).

they were obtained from the present He^3-O^{16} data at 17.3 MeV by using a Woods-Saxon imaginary potential.

In sets 3 and 4, the incoming waves were generated from parameters obtained from the analysis of the He^3-O^{17} data by using a surface imaginary potential (derivative Woods-Saxon). In set 3, the outgoing channel optical parameters were obtained from the analysis of the He^3-O^{16} data. In set 4, the parameters were from an analysis by Lutz *et al.*[16] of the 16.6-MeV He^3-O^{16} data of Artemov *et al.*[17] In both sets, a surface imaginary potential was used.

Table II gives the parameters used for the four sets. They differ slightly from those given in Table I for the best fits because of limitations in the DRC code[13]; i.e., (1) it does not include a spin-orbit potential in the calculation of the distorted waves, and (2) the same geometrical parameters for the real and imaginary potential are required for a Woods-Saxon volume potential. Although there were no significant differences in the differential cross sections given by these four sets, better over-all agreement was found with the surface potentials (sets 3 and 4).

Different assumptions for the ratio of the potential depths $V_{\sigma\tau}$ and V_τ in solving Eqs. (7) and (8) resulted in different values for these potentials as shown in Table III. Clearly the analysis of the $O^{17}(He^3,t)F^{17}$ reaction alone did not allow a determination of a unique set of values for $V_{\sigma\tau}$ and V_τ. Later on in the paper, these values will be discussed in conjunction with the results obtained from the $O^{18}(He^3,t)F^{18}$ reaction.

TABLE III. Values for the strength of the potentials $V_{\sigma\tau}$ obtained from the $O^{17}(He^3,t)F^{17}$ reactions to the ground state and 0.5-MeV level for three different assumptions of the ratio $V_{\sigma\tau}/V_\tau$. The values are tabulated as a function of the optical parameter used to generate the distorted waves. The numbers in the brackets are the values of χ^2.

Optical param.	State	$V_{\sigma\tau}=V_\tau$	$V_{\sigma\tau}=V_\tau/1.5$	$V_{\sigma\tau}=\frac{1}{2}V_\tau$
Set 1	g.s.	35 [1.562]	28 [1.550]	25 [1.963]
Set 2		40 [2.226]	35 [2.214]	30 [2.338]
Set 3		40 [0.890]	35 [0.989]	28 [0.956]
Set 4		40 [0.808]	30 [0.610]	25 [0.632]
Set 1	0.500 MeV	25 [1.147]	20 [0.878]	20 [1.405]
Set 2		28 [1.488]	25 [1.539]	20 [1.411]
Set 3		30 [1.447]	25 [1.015]	25 [1.745]
Set 4		28 [0.987]	25 [1.065]	20 [0.961]

[16] H. F. Lutz, J. J. Wesolowski, S. F. Eccles, and L. F. Hansen, Nucl. Phys. **A101**, 241 (1967).

[17] K. P. Artemov, V. Z. Gol'dberg, B. I. Islamov, V. P. Rudakov, and I. N. Serikov, Soviet J. Nucl. Phys. **1**, 450 (1965).

Figure 5 shows a comparison of experiment and theory made by using the optical parameters of set 4, for the assumption, $V_\tau=1.5\ V_{\sigma\tau}$.

ANALYSIS OF THE $O^{18}(He^3,t)F^{18}$ REACTION

In the $O^{18}(He^3,t)F^{18}$ reaction, the target has two nucleons outside the closed shell. This case is analogous to the $C^{14}(He^3,t)N^{14}$ reaction, and the pertinent formalism and selection rules have been treated in detail by Wong *et al.*[2]

The triton differential cross sections were calculated by using Eq. (3), and the sensitivity of the theoretical calculations to the nuclear wave functions was studied. Calculations were made by assuming a pure $[d_{5/2}]^2$ configuration for the O^{18} and F^{18} wave functions and these were compared with the results obtained with Kuo-Brown[5] and De Llano *et al.*[6] wave functions for these nuclei. These wave functions are shown in Table IV.

Theoretical triton differential cross sections were calculated for the ground state, analog state (1.045-MeV level), and the 1.70-MeV level in F^{18}. Although De Llano *et al.* also give wave functions for the 2.10- and 2.52-MeV levels, they had the wrong parity assignment for the 2.10-MeV level[9] and wrong J value for the 2.52-MeV level.[8] For these reasons calculations were not carried out for these levels, although the differential cross sections were measured. The wave function for the 1.045 MeV in F^{18} (analog state) was taken to be the same as that for the ground state in O^{18}.

Figure 6 shows the calculated triton differential cross sections with these wave functions for the ground state and the analog state in F^{18}. For the ground state, the differences between them are mainly in phase at the forward angles. The magnitude of the calculated cross sections for V_τ set to unity are 1.31, 2.99, and 3.19 μb for pure $[d_{5/2}]^2$, Kuo-Brown[5] and De Llano[6] wave functions, respectively. For the analog state, the three calculations are very much in phase and only the strength of the oscillations at the forward angles shows differences. For this level the magnitude of the calcu-

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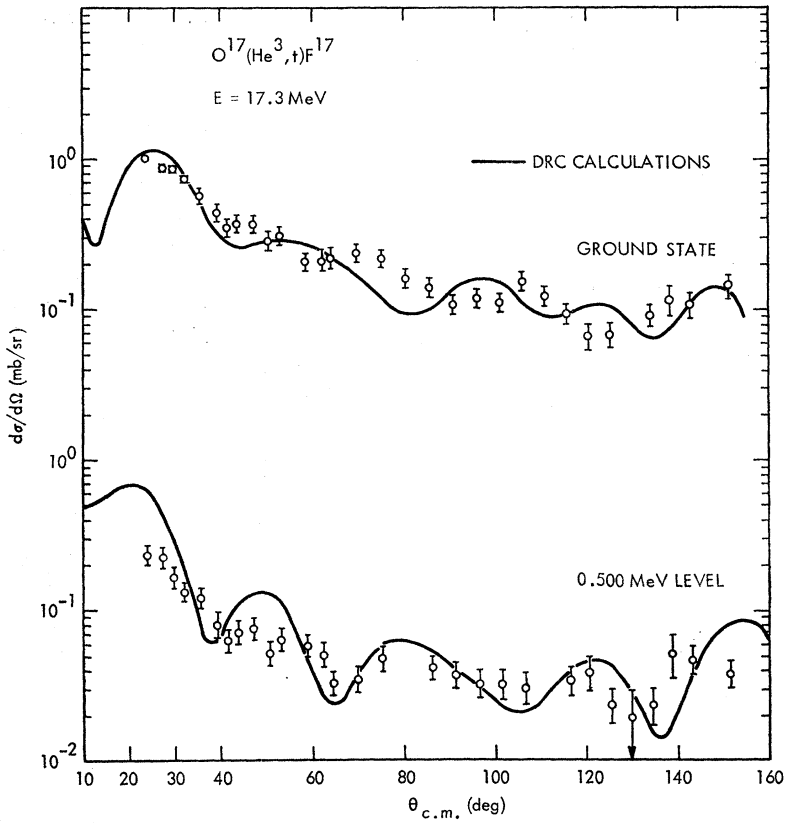

FIG. 5. Fits to the triton differential cross sections from the $O^{17}(He^3,t)F^{17}$ reaction calculated with DRC, using the optical parameters given by set 4 in Table II.

lated cross sections are 0.844 μb ($[d_{5/2}]^2$ configuration), 0.988 μb (Kuo-Brown), and 1.161 μb (De Llano *et al.*). The experimental integrated cross sections were 1.84±0.20 mb and 3.20±0.32 mb for the ground state and analog group, respectively. The normalization of theory to experiment determines the strength V_τ of the interaction causing the transition.

The $O^{18}(He^3,t)F^{18}$ ground-state reaction is a $(0^+,1)\rightarrow(1^+,0)$ transition, so that the allowed angular momenta transfers are $I-I'=1$ and $L=0$, 2. Since $I'=1$, only the spin-flip–isospin-flip part of the effective two-body interaction in Eq. (5) is different from zero. Thus, from normalizing the calculated triton differential cross section to the measured one, a value of $V_{\sigma\tau}$ is obtained. On the other hand, the $O^{18}(He^3,t)F^{18}$ reaction to the 1.045-MeV level is a $(0^+,1)\rightarrow(0^+,1)$ transition, and in this case $I=I'=0$ and $L=0$ are the only allowed angular momenta transfers. As a result of these selection rules, only the term proportional to V_τ in Eq. (5) is different from zero. Finally, the $O^{18}(He^3,t)F^{18}$ reaction to the 1.70-MeV level is a $(0^+,1)\rightarrow(1^+,0)$ transition, thus allowing one to obtain a value of $V_{\sigma\tau}$. For this level, the only wave function available is that given by De Llano *et al.* This wave function is not completely correct since it does not predict the correct energy.

TABLE IV. Wave functions for the ground states of O^{18}, F^{18}, and the 1.70-MeV level in F^{18} used in the DWBA calculations.

Nucleus	State	J,T	$[d_{5/2}]^2$	$[d_{5/2}d_{3/2}]$	$[s_{1/2}]^2$	$[s_{1/2}d_{3/2}]$	$[d_{3/2}]^2$
O^{18}	g.s.	$[0^+,1]$	0.901		0.324		0.280[a]
			0.788		0.520		0.321[b]
F^{18}	g.s.	$[1^+,0]$	0.571	−0.629	0.507	−0.143	−0.040[a]
			0.780	−0.431	0.454	−0.022	−0.087[b]
	1.70 MeV	$[1^+,0]$	0.621	0.496	−0.586	−0.148	0.092[b]

[a] Kuo-Brown wave functions (see Ref. 5).
[b] De Llano *et al.* wave functions (see Ref. 6).

Figure 7 shows the comparison between the calculated and measured angular distributions. For all the states shown, the calculated angular distributions are out of phase with the measured ones, mainly at the forward angles. It was observed that for the ground state and 1.70-MeV level, the phase agreement could have been improved noticeably if the calculations would have predicted similar contributions to the cross sections from the angular momentum transfer $L=0$ and $L=2$. In the present calculation the contribution from $L=2$ is, at the most, 2% of the total cross section. The slope of the differential cross sections from 0° to 180° for the ground state, calculated with Kuo-Brown or De Llano wave functions, agree better with the measurements than the calculations with a pure $[d_{5/2}]^2$ configuration, Fig. 7(a).

For the analog state, the differential cross sections calculated for the three wave functions are very similar in magnitude and phase, which corroborates previous results[2] that the $0^+\rightarrow 0^+$ analog transitions are nearly

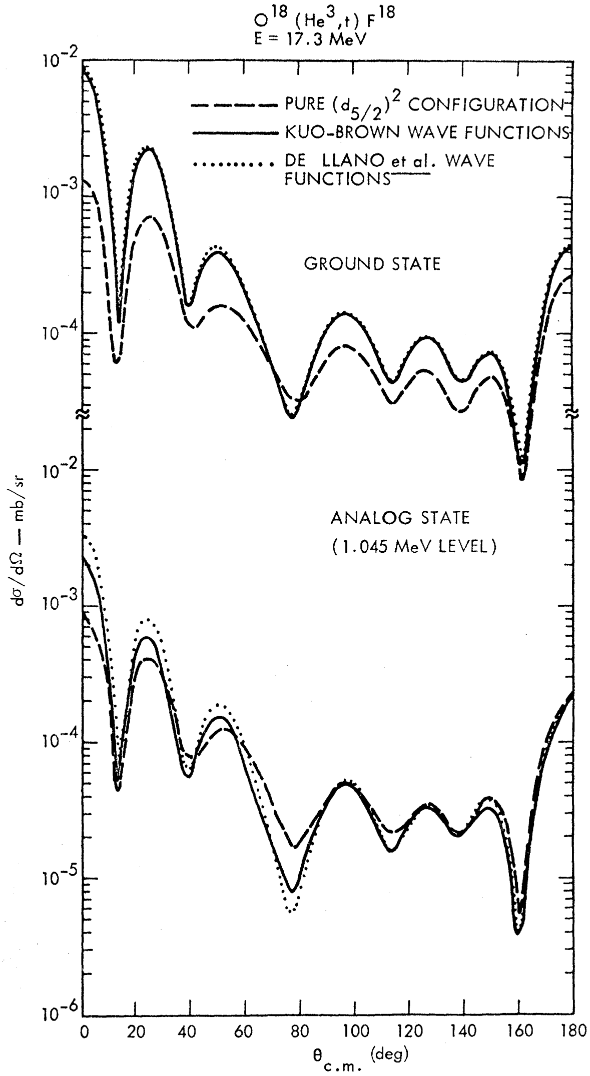

FIG. 6. Theoretical triton differential cross sections calculated with DRC for the $O^{18}(He^3,t)F^{18}$ reaction at 17.3 MeV, assuming different wave functions for the initial and final nucleus.

independent of configuration mixing. The calculation with a pure $[d_{5/2}]^2$ configuration shows less pronounced oscillations at the forward angles, and for this reason is in better agreement with the measurements [Fig. 7(b)]. However, since other unresolved states $(3^+,5^+)$ besides the analog can be contributing to the measured cross sections, the lack of a pronounced observed structure can be the result of contributions from transitions having different L values. Figure 7(c) shows the measured angular distributions for the 1.7-MeV level and the calculations with De Llano's wave function.

All these calculations used imaginary surface potentials to generate the distorted waves for the He^3 and tritons. For the He^3 channel, the optical parameters obtained from the analysis of the elastic scattering of He^3 on O^{18} were used, and for the triton channel the optical parameters from the elastic scattering of He^3 on $O^{16,16}$ (as in set 4 of Table III) were used. Calculations with optical potentials equivalent to the other sets given in Table III did not change the quality of the (He^3,t) fits, and the variations found in the values of $V_{\sigma\tau}$ and V_τ were not greater than 10%.

In Table V are given the values for the interaction potentials $V_{\sigma\tau}$ and V_τ obtained from the normalization of theory to experiment by equating the integrated cross sections, for the different wave functions used in the calculations. The values for $V_{\sigma\tau}$ obtained from the ground state and the 1.70-MeV level calculations made

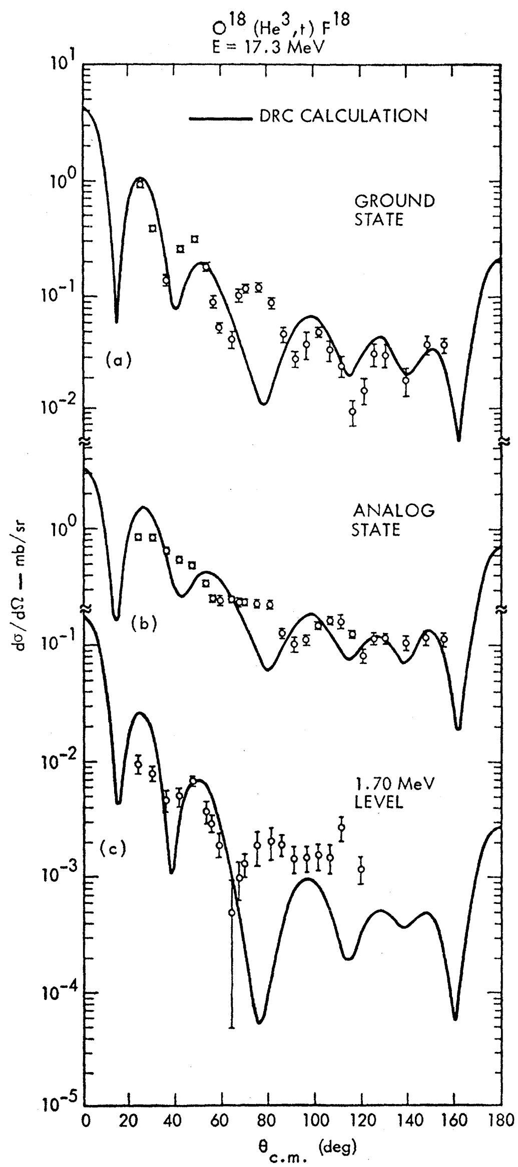

FIG. 7. Fits to the triton differential cross sections from the $O^{18}(He^3,t)F^{17}$ reaction calculated with DRC. The wave functions used in the calculations were Kuo-Brown's for the ground state, pure $[d_{5/2}]^2$ configuration for the analog state, and De Llano *et al.* for the 1.70-MeV level.

TABLE V. Values for the interaction potentials $V_{\sigma\tau}$ and V_τ obtained from the $O^{18}(He^3,t)F^{18}$ reaction by normalizing the calculated differential cross sections to the measurements.

State	Wave function	$V_{\sigma\tau}$ (MeV)	V_τ (MeV)
Ground state	$[d_{5/2}]^2$	37.50	
	Kuo-Brown[a]	24.8	
	De Llano *et al.*[b]	24.0	
Analog state (1.045-MeV level)	$[d_{5/2}]^2$		61.6
	Kuo-Brown[a]		56.9
	De Llano *et al.*[b]		52.5
1.70-MeV level	De Llano *et al.*[b]	25.8	

[a] See Ref. 5.
[b] See Ref. 6.

by using Kuo-Brown and De Llano wave functions, are very consistent among themselves and their average value is 24.9±0.9 MeV. For a pure $[d_{5/2}]^2$ configuration, the value is 37.50 MeV. From the quality of fits it is not possible to choose between these two values; however, the Kuo-Brown wave functions do not give a good fit value for the β decay of F^{18} into O^{18}.[1f] (The experimental value is $\log ft = 3.62 \pm 0.016$, while the values predicted by a pure $[d_{5/2}]^2$ configuration and Kuo-Brown wave functions are 3.67 and 3.40, respectively. This last value corresponds to a ft transition rate 60% higher than the experimental measurement.) Since the two-body interaction matrix elements involved in β decay are the same as those involved in the $L=0$ charge-exchange cross section, the value of $V_{\sigma\tau}$ obtained with a pure $[d_{5/2}]^2$ configuration is considered to be more meaningful.

For the analog state, the average value for V_τ obtained with Kuo-Brown and the De Llano wave functions is 54.7±2.2 MeV, while the pure $[d_{5/2}]^2$ configuration gives $V_\tau = 61.6$ MeV. These values represent only upper limits for this potential since possible contributions from the 3^+ and 5^+ levels were not experimentally resolved. The assumption $V_\tau = 2V_{\sigma\tau}$ assumed in Table III for the analysis of the $O^{17}(He^3,t)F^{17}$ reaction must be rejected, since it leads to a value of $V_\tau = 2\times 37.5$ MeV, larger than the upper limit of 61.6 MeV obtained from the analog transition in O^{18}. On the other hand, the values for $V_{\sigma\tau}$ obtained from the O^{17} ground-state transition will be 38.75 and 32.0 MeV for the assumptions $V_{\sigma\tau} = V_\tau$ and $V_{\sigma\tau} = \frac{2}{3} V_\tau$, respectively. A relation between the potentials closer to this last ratio seems to be favored from recent analysis of (p,n) charge-exchange reactions.[19] Averaging the value of 32.0 MeV with the 37.5 MeV obtained from the O^{18} ground-state transition, a value of $V_{\sigma\tau} = 34.7 \pm 6$ MeV is obtained. For the strength of the pure isospin interaction, the value will be $V_\tau = 52.0$ MeV if the relation $V_\tau = 1.5\, V_{\sigma\tau}$ is assumed. Comparing this value with the one obtained from the O^{18} analog transition of 61.6 MeV will imply that the contribution from the 3^+ and 5^+ levels can be as large as 43% of the measured cross sections. If the assumption $V_\tau = V_{\sigma\tau}$ were to hold, this would imply that the contribution of these levels was as high as 90% of the measured cross section, which is contrary to the experimental evidence on the strength of the analog transition. The values for the interaction potentials obtained from the transition to the 0.50-MeV level in F^{17} were not considered in obtaining the average values for $V_{\sigma\tau}$ because they were systematically low (Table III) which could reflect the presence of collective contributions to this state.

[19] C. Wong and J. D. Anderson (private communication).

COUPLED-CHANNEL EQUATION CALCULATION

It was of interest to determine whether an exact solution of the Schrödinger equation could improve the fits obtained with the microscopic DWBA calculation DRC for the (He^3,t) charge-exchange reaction. For this reason, a coupled-channel equations calculation was carried out for the (He^3,t) analog transitions in O^{17} and O^{18}.

In this approach, the potential proposed by Lane[20] to explain the quasi-elastic (p,n) reaction is used:

$$U(r) = U_0(r) + (\mathbf{t}\cdot\mathbf{T})V_1(r)/A\,,$$

where $U_0(r)$ is the optical potential given by Eq. (1), $\mathbf{t}$ and $\mathbf{T}$ are the isospins of the incident particle and target nucleus, respectively, and $V_1(r)$ is the isospin potential. The coupled-channel equations are the solutions to Schrödinger's equation with the potential $U(r)$. These equations, shown in the Appendix of Lane's paper[20] have been solved exactly by Schwarcz[21] and they have been applied extensively to the analysis of quasi-elastic (p,n) measurements.[21,22] Schwarcz's code LOKI 2A was modified for the (He^3,t) reaction. (In the coupled equations, the coefficients of the Coulomb potential must be modified to account for the double charge of the He^3 in the incoming channel and the charged triton in the outgoing channel.)

To compare the microscopic DWBA calculation (DRC) and the exact coupled-channel equation calculation (LOKI 2A) an isobaric potential $V_1(r) = V_1 f(r)$ was generated according to the identity

$$\tfrac{1}{2}(N-Z)^{1/2}(V_1/A)f(r) = [(N-Z)^{1/2}/2\pi]g_L{}^{J_iJ_f}(R_0)\,, \quad (9)$$

which holds for a pure charge-exchange transition. The quantity $g_L{}^{J_iJ_f}(R_0)$, calculated by DRC, is the radial integral between the initial and final states of the space part of the projectile-nucleon interaction.

For the $O^{18}(He^3,t)F^{18}$ reaction to the analog state Eq. (9) holds true, since in this reaction there is no momentum transfer. The kernel $g_{L=0}(R_0)$ generated by DRC for the calculated triton differential cross sections, assuming a pure $[d_{5/2}]^2$ configuration, is plotted in Fig. 8. The potential $V_1(r)$ found to match this kernel was a mixture of a Saxon and derivative Saxon potentials

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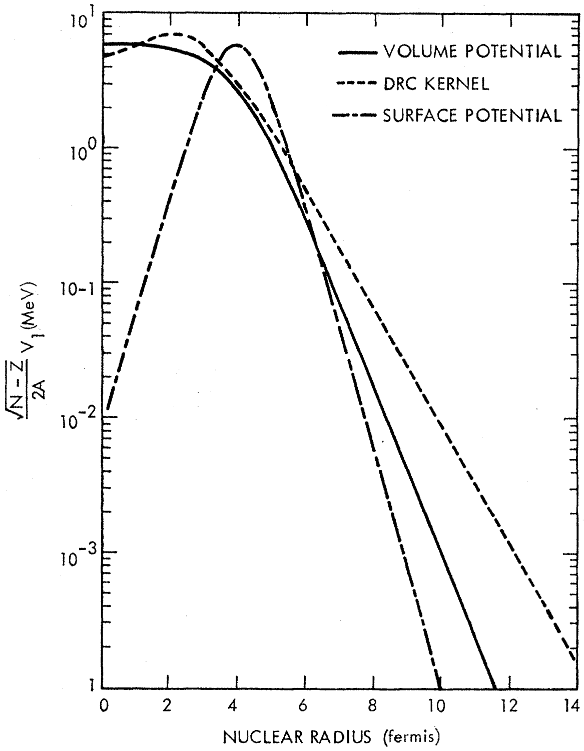

FIG. 8. Comparison between the shape of the isobaric potentials $V_1(r)$ from the coupled-channel equations calculation and the kernel $g_L(R_0)$ used in DRC from comparable fits to the triton differential cross section for the $O^{18}(He^3,t)F^{18}$ analog state at 17.3 MeV.

with the same geometrical parameters $r_0=0.90$ F and $a=a'=0.98$ F. The depth of the potentials were 90 and 120 MeV, respectively.

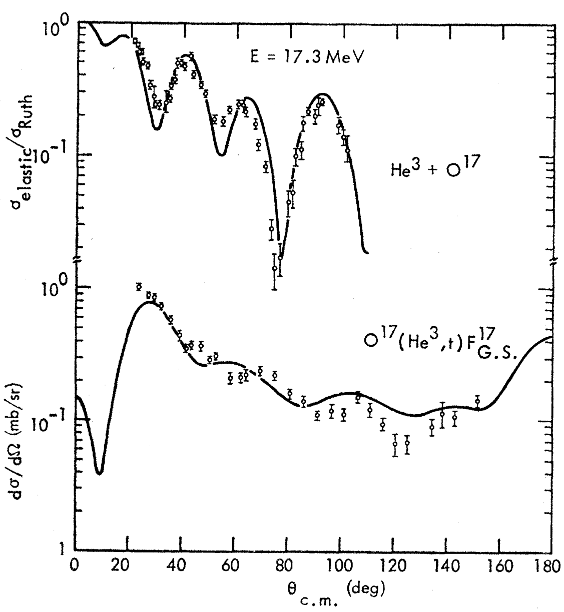

FIG. 9. Coupled-channel fits to the [He^3+O^{17}] elastic scattering and $O^{17}(He^3,t)F^{17}$ reaction to the ground state at 17.3 MeV.

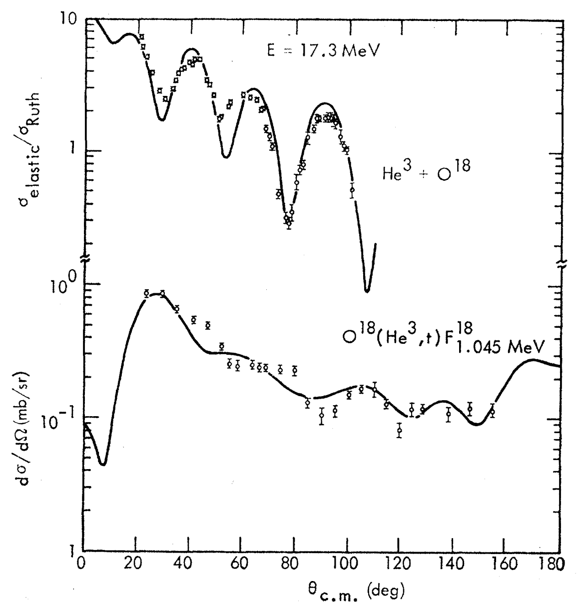

FIG. 10. Coupled-channel fits to the [He^3+O^{18}] elastic scattering and $O^{18}(He^3,t)F^{18}$ reaction to the 1.045-MeV level at 17.3 MeV.

With this isobaric potential $V_1(r)$, and for the same optical parameters for the incoming and outgoing channels used in DRC, LOKI 2A was run. The calculated differential cross sections obtained were very close to the ones given by DRC [Fig. 7(b)].

Since in the present work the (He^3,He^3) and the (He^3,t) cross sections were measured for O^{17} and O^{18}, an independent search for the potential $V_1(r)$ was tried, by fitting simultaneously both differential cross sections for each of the target nuclei using LOKI 2A.

TABLE VI. Optical parameters used in the coupled-channel equations calculation for the fittings shown in Figs. 9 and 10. The nomenclature corresponds to the one defined in Eq. (1) of the text. The subindex 1 refers to the isobaric potential.

	Nuclei	
	O^{17}	O^{18}
$V(He^3)$ (MeV)	147.1	143.5
$V(t)$ (MeV)	147.9	147.2
r_0(F)	1.365	1.366
a(F)	0.642	0.633
$W_D(He^3)$ (MeV)	22.1	26.1
$W_D(t)$ (MeV)	17.0	18.0
r_0'(F)	1.379	1.362
a'(F)	0.609	0.588
V_s(MeV)	10.3	12.7
V_1(MeV)	145.3	149.6
r_1(F)	1.554	1.455
a_1(F)	0.657	0.635
W_1(MeV)	58.5	50.1
r_1'(F)	1.600	1.600
a_1'(F)	0.600	0.600
χ^2	24.5	49.8

Starting from the parameters found for the elastic scattering given in Table I plus a tentative value for the isobaric potential $V_1 f(r)$, the final fittings were obtained by searching in all the parameters. The criteria in the search was to minimize the total χ^2 defined as $\chi_{tot}^2 = \chi_{(He^3,He^3)}^2 + \chi_{(He^3,t^2)}$.

The simultaneous search in the elastic scattering and the quasi-elastic scattering did not determine unequivocally the form of the interaction $f(r)$ for the isobaric $V_1(r)$. Comparable fittings were obtained with a real surface or volume potentials, without large differences in the optical parameters. These potentials are shown in Fig. 8. Although their shape is quite different from that of the kernel $g_{L=0}(R_0)$, the differential cross sections calculated from them are very similar to those obtained with DRC. Complex surface or volume forms for $V_1(r)$ gave slightly better agreement with the data. However, the difference from that obtained with pure real potentials was not conclusive enough to substantiate Satchler's[23] suggestion that the isobaric potential for (He^3,t) interaction required an imaginary potential. Figures 9 and 10 give the best fits obtained with LOKI 2A for the (He^3,He^3) and (He^3,t) differential cross sections in O^{17} and O^{18}, respectively. The corresponding parameters are in Table VI.

CONCLUSIONS

From the experimental results presented in this paper and their theoretical analysis, the following statements can be made.

The differential triton cross sections from the (He^3,t) on O^{17} and O^{18} show the features of a direct reaction mechanism, i.e., forward-peaked angular distribution with a more or less pronounced diffraction pattern.

The negative-parity states $\frac{1}{2}^-$, $\frac{5}{2}^-$, and $\frac{3}{2}^-$ at 3.10, 3.86, and 4.69 MeV, respectively in F^{17} and the 2.10 MeV (2^-) in O^{18} were weakly excited. This can be understood if these levels result from a coupling between the $\frac{5}{2}^+$ single-particle level and the $T=0$, 3^- collective level from the O^{16} core. In this case the (He^3,t) reaction to these negative-parity levels will be the result of transitions between two core levels ($T_c=0 \rightarrow T_c=0$). The matrix elements for the $\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_0$ operator for this transition will be zero in first order, which will be reflected in the low cross section observed.

The microscopic picture of the (He^3,t) charge-exchange reaction which assumes an effective two-body force interaction between the projectile nucleon–target nucleon pairs, gives fair agreement with the experimental results. A value of 34.7±6 MeV has been obtained for the spin-isospin interaction $V_{\sigma\tau}$, and a value of 52.0±10 MeV for the pure isospin interaction V_τ. This last value is in agreement with the one obtained from the Ti^{48}(He^3,t)V^{48} reaction[24] of 55 MeV. These values can be compared with the ones obtained from the (p,n) reactions for these nuclei at 13-MeV proton incident energy. Wong *et al.*[19] have obtained values for $V_{\sigma\tau}$ and V_τ of 16.5 and 27.4 MeV with a Yukawa form factor for a range of 1 F. From the strength of these interaction potentials for the effective two-body force in (p,n) reactions, the respective strengths for the (He^3,t) reactions can be predicted.[24] From the above values one obtains $V_{\sigma\tau}=28.6$ MeV and $V_\tau=47.5$ MeV for the effective two-body force in (He^3,t) reactions, which can be compared with $V_{\sigma\tau}=34.7\pm6$ MeV and 52.0±10 MeV obtained from these measurements.

Also, it has been shown in the present work that the values of $V_{\sigma\tau}$ and V_τ are sensitive to the optical parameters used to generate the distorted waves. If the strength of the effective two-body force is to be determined to better than 10% accuracy, correct optical parameters must be available for distorting the incoming and outgoing waves.

Furthermore, the accuracy with which the strength of the effective two-body force components $V_{\sigma\tau}$ and V_τ can be obtained is also dependent on the wave functions used for the initial and final states, which call for the necessity of good wave-function calculations. Recently, Arima *et al.*[25] have treated the even-parity states of F^{18} and O^{18} by allowing two-body matrix elements to be parameters in a fit to known even-parity levels. They predict a value for logft from the $F^{18} \rightarrow O^{18}$ β decay of 3.69, which is in very close agreement with the experimental value of 3.62. They did not tabulate wave functions, but it is expected that the value of $V_{\sigma\tau}$ and V_τ which one would obtain by using them would agree with the result of the pure $[d_{5/2}]^2$ calculation.

Finally, the simultaneous analysis of the (He^3,t) reaction and He^3 elastic scattering at a given incident energy, using the coupled-channel calculation, is not sufficient experimental information to obtain unambiguously the form factor for the isobaric potential. It was shown in this work that comparable fits to elastic and quasi-elastic He^3 cross sections could be obtained with quite different form factors, with or without an imaginary isobaric potential. Hence, other measurements such as the elastic scattering of tritons from the final nucleus in a given (He^3,t) reaction at the proper energy becomes necessary if one is going to obtain less ambiguous information on the shape and magnitude of the isobaric potential.

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