$^{18}O(d,t)^{17}O$ and the ground-state wave function of ^{18}O†

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A new measurement of the reaction $^{18}O(d,t)^{17}O$, and a distorted-wave Born-approximation analysis, yield spectroscopic factors of 1.48 and 0.29 for the $\frac{5}{2}^+$ ground state and $\frac{1}{2}^+$ first-excited state, respectively. The ratio 0.195 ± 0.015 is still in serious disagreement with a recent theoretical value of 0.27. Inclusion of inelastic two-step processes, through the 2^+ of ^{18}O, changes the ratio to 0.24, closer to the theoretical value.

[NUCLEAR REACTIONS $^{18}O(d,t)$, $E=17$ MeV; measured $\sigma(E_t;\theta)$. ^{17}O levels deduced S, ^{18}O(g.s.) deduced wave function; DWBA and CCBA analysis.]

We have used the $^{18}O(d,t)^{17}O$ reaction to measure the relative strengths of the $(2s_{1/2})^2$ and $(1d_{5/2})^2$ components in the ^{18}O (g.s.) wave function. This ratio is of interest since the previously measured value[1,2] was the only datum from transfer reactions that could not be reproduced by a recent theoretical model of ^{18}O.[3] This model, (hereafter referred to as LSF) yielded a wave function for the ^{18}O ground state of the form:

$$a(1d_{5/2})^2 + b(2s_{1/2})^2 + c(\text{collective}),$$

with $a \approx 0.85$, $b \approx 0.44$, and $c \approx -0.30$. If the ground and first-excited states (0.87 MeV) of ^{17}O are simply a $1d_{5/2}$ and a $2s_{1/2}$ neutron, respectively, outside of an ^{16}O core, then the predicted distorted-wave Born-approximation (DWBA) spectroscopic factors for pickup from ^{18}O are $S(\frac{5}{2}^+) = 2a^2$ and $S(\frac{1}{2}^+) = 2b^2$. For the "constrained II" wave functions of LSF, the ratio of spectroscopic factors is

$$R = \frac{S(\frac{1}{2}^+)}{S(\frac{5}{2}^+)} = \frac{b^2}{a^2} = 0.267.$$

A DWBA analysis[2] of some earlier $^{18}O(d,t)^{17}O$ data[1] yielded a value of $R = 0.17 \pm 0.04$, in rather serious disagreement with the above value. (The uncertainty in this ratio includes a 10% uncertainty in the DWBA prediction, beyond the statistical errors.) Other neutron-pickup experiments[4-9] on ^{18}O yield even smaller numbers for the ratio. These are listed in Table I, along with the recent theoretical results of Ref. 3. The experimental values of the ratio range from a low of 0.05 from a recent (p,d) experiment[7] to a high of 0.19 in Ref. 1. A recent (d,t) experiment[8] at $E_d = 52$ MeV gives $R = 0.14$, very near the middle of the range and only roughly $\frac{1}{2}$ the theoretical value.

This large discrepancy could result from several causes:
(1) The first two states in ^{17}O are *not* predominantly $1d_{5/2}$ and $2s_{1/2}$, respectively, but contain significant admixtures of other configurations;
(2) the LSF wave function for the ^{18}O(g.s.) is incorrect;
(3) the earlier pickup data and/or analysis are incorrect;
(4) the $^{18}O(d,t)$ and $^{18}O(p,d)$ reactions are not purely single-step neutron pickup.

The first suggestion appears unlikely in view of the large spectroscopic strengths (~0.9) in $^{16}O(d,p)^{17}O$.[10] The accuracy of the LSF wave functions is indicated by their ability to reproduce virtually all of the experimental information on the low-lying levels of ^{18}O. As indicated above, the ratio R is the sole piece of particle transfer data poorly accounted for in the LSF model. We have remeasured the $^{18}O(d,t)^{17}O$ reaction to test suggestion (3) and have investigated the effects of multistep processes [suggestion (4)] by a coupled-channels Born-approximation (CCBA) analysis of the data.

TABLE I. Spectroscopic factors for $^{18}O \rightarrow {}^{17}O + n$ prior to the present work.

Source	Ref.	$\frac{5}{2}^+$	$\frac{1}{2}^+$	Sum	Ratio
(p,d)	4	1.60	0.22	1.82	0.14
(p,d)	5	1.10	0.11	1.21	0.10
(p,d)	6	1.64	0.24	1.88	0.15
(p,d)	7	1.31	0.07	1.38	0.05
(d,t)	1	1.53	0.29	1.82	0.19
(d,t)	2	...	...	...	0.17 ± 0.04
(d,t)	8	1.53	0.21	1.74	0.14
HI	9	1.22	0.20	1.42	0.16
Theory	3				
Constrained I		1.42	0.39	1.81	0.273
Unconstrained		1.51	0.37	1.88	0.245
Constrained II		1.44	0.38	1.82	0.267

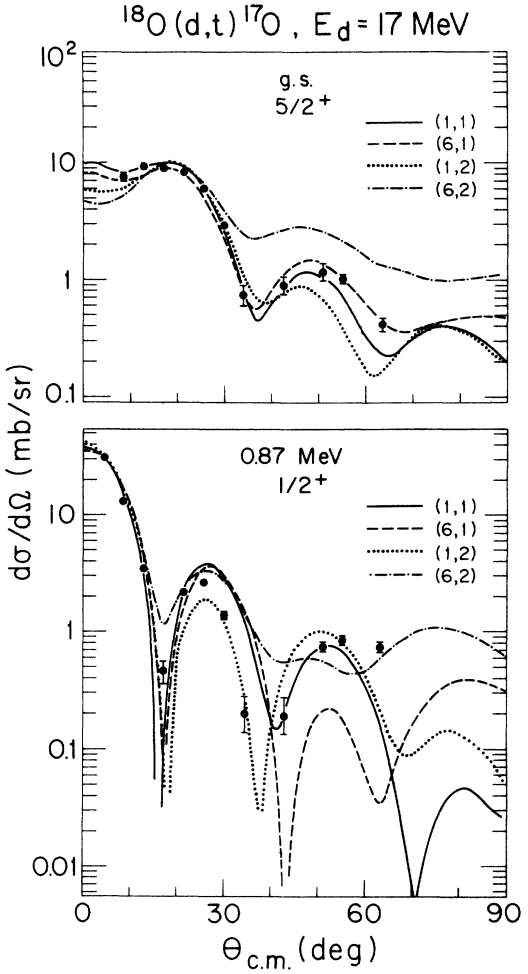

FIG. 1. Experimental and theoretical angular distributions for $^{18}O(d,t)^{17}O$ to the ground state and first-excited state of ^{17}O. For each state, the four curves all have the same normalization. The labels in parentheses refer to potential combinations from Table II.

The experiment was performed with a 17-MeV deuteron beam from the University of Pennsylvania FN tandem Van de Graaff accelerator. Outgoing tritons were detected in nuclear emulsion plates after being momentum analyzed in a multiangle magnetic spectrograph.

Since the experimental quantity of interest is a ratio, obtaining absolute cross sections was not crucial here. Nevertheless, we have attempted to extract reliable absolute cross sections. The experiment was performed twice—once with a solid (WO_3) target and once with a gaseous (O_2) target. In both experiments elastic and inelastic deuterons were detected on the plates and in a monitor detector placed at 45° to the beam. For the gas target run, the gas-cell pressure gave a good measure of the target thickness, which, however, had to be corrected for contaminants of ^{16}O and ^{14}N. For this correction the elastic scattering (40°–90°) was used. We thus have three independent measurements of absolute cross section: (1) normalizing the measured elastic scattering to the predictions of an optical model, (2) normalizing the inelastic $^{18}O(d,d')^{18}O(1.98)$ scattering to that measured in Ref. 1 (after correcting for the slight energy dependence), and (3) from the gas-cell pressure and elastic scattering combined. The various methods agree to better than 15%, which is the uncertainty we quote. Of course, the uncertainty in the ratio of cross sections to the two states is much less.

Experimental angular distributions for the two relevant states are displayed in Fig. 1 along with a variety of curves, which will be discussed below. We have first analyzed the data in the usual way—assuming the reaction to proceed via single-step neutron pickup. Calculations were done in distorted-wave Born approximation (DWBA) using the code DWUCK.[11]

To ascertain the dependence of the spectroscopic factor ratio on the optical potentials, calculations were performed using two different deuteron potentials and two triton potentials, all of which have been used successfully in this mass region.[12–14] These potentials are listed in Table II, and the curves calculated with the four possible potential combinations are shown in Fig. 1; the normalization of all the curves for each state is the same. It will be noted that, despite some differ-

TABLE II. Optical-model parameters used in analysis of $^{18}O(d,t)^{17}O$.

Pot.	Channel	V (MeV)	$r_0 = r_{so}$ (fm)	$a = a_{so}$ (fm)	$W' = 4W_D$ (MeV)	W (MeV)	r'_0 (fm)	a' (fm)	V_{so} (MeV)	r_{oc} (fm)	Ref.
1	$d + ^{18}O$	105	1.02	0.86	70.6	0	1.42	0.65	6.0	1.02	12
6	$d + ^{18}O$	100	1.40	0.60	0	12.65	1.74	0.80	0	1.40	13
1	$t + ^{17}O$	177	1.138	0.724	0	12	1.602	0.769	5.0	1.40	12
5	$t + ^{17}O$	130	1.31	0.724	0	12	1.602	0.769	5.0	1.40	14
	$n + ^{17}O$	Varied	1.26	0.60	•••	•••	•••	•••	$\lambda = 25$		

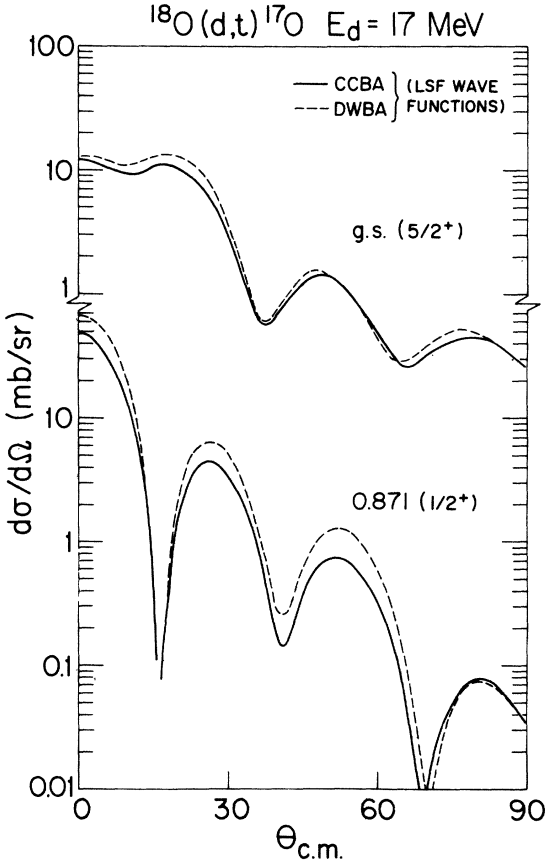

FIG. 2. Comparison of DWBA and CCBA using wave functions from LSF (Ref. 3).

ences at large angles, all the curves agree to better than 10% in the stripping peaks.

As a further test, 35 calculations, with 7 deuteron and 5 triton potentials from the literature, were performed. Despite the fact that these potentials are taken from different mass regions and energy domains, the values of R obtained were remarkably consistent ($\bar{R} = 0.195 \pm 0.005$). These results indicate that, if the reaction is describable by ordinary zero-range DWBA, then the uncertainty in R is less than 10%, even after including the statistical errors. This result is consistent with the work of Clement and Perez,[15] who find that a careful analysis of single-nucleon transfer data can produce errors of less than 10%. Nevertheless, R still differs considerably from that resulting from the LSF wave functions, the difference being far outside any reasonable uncertainty estimate.

We then considered the fourth possible explanation of the discrepancy, viz. the reaction mechanism. We performed a coupled-channels Born-approximation (CCBA) calculation using the code CHUCK,[11] using the potential combination (1, 1). [With this set and DWBA, $R(1,1) = 0.22$.] The additional routes considered proceed via the excitation of the 1.98 MeV (2^+) level in ^{18}O; the strength of the inelastic excitation was taken to reproduce the measured[16] $B(E2)$ for this state (this corresponds to $\beta = 0.3$). The transfer amplitudes were taken from the $^{18}O(1.98)$ wave function of LSF. The CCBA and DWBA curves are compared in Fig. 2. It can be seen that the multistep routes are *not* negligible; the effect amounts to ~10% in the case of the $\frac{1}{2}^+$ level. These curves still do not fit the measured cross sections. If the strengths of the single-step direct routes are adjusted [leaving the $^{18}O(2^+)$ wave function unchanged] to reproduce the experimental cross sections, the curves in Fig. 3 result. These also give a somewhat better account of the angular-distribution shapes than do any of the DWBA curves. The amplitudes required for this fit are $a = 0.81, b = 0.40$, giving a value of R of 0.242. We estimate the uncertainty in this number

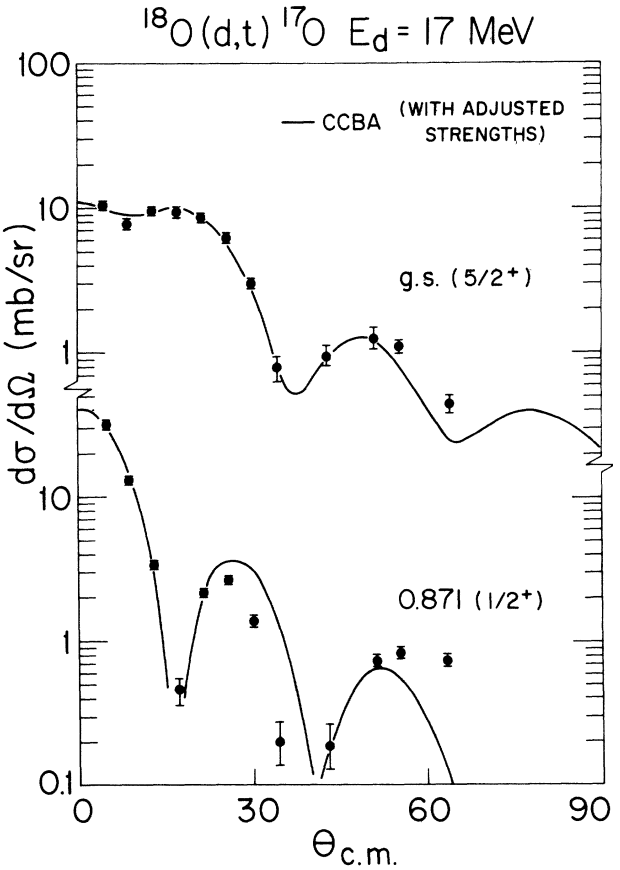

FIG. 3. Comparison of the data with CCBA curves after adjusting the ^{18}O(g.s.) wave function slightly to fit the observed cross section magnitudes. (See text and Table III.)

TABLE III. Summary of the present analysis.

Method	$S(\frac{5}{2}^+)$	$S(\frac{1}{2}^+)$	Sum	Ratio
DWBA	1.48 ± 0.27	0.29 ± 0.05	1.77 ± 0.32	0.195 ± 0.015
CCBA	1.30	0.31	1.61	0.242 ± 0.024
LSF II	1.44	0.38	1.82	0.267

(within the model assumed) to be ~10%, though, of course, such an estimate is more difficult in the case of the more complicated reaction process. The DWBA and CCBA results are summarized in Table III.

Thus, for the present data at least, the inclusion of inelastic two-step processes changes the ratio of spectroscopic factors by about 20% and brings the ratio into closer agreement with the value obtained by LSF. The new value of 0.242 is still somewhat low, but by only about one probable error. It would be interesting to see if a similar analysis of the other data caused as large a change in R. It is certainly surprising to find two-step processes having such a large effect in a transfer reaction of roughly single-particle magnitude.

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