# How important are two-step processes in $^{16}O(^{3}He, d)^{17}F$?*

H. T. Fortune, L. R. Medsker, J. D. Garrett,‡ and H. G. Bingham†
*Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19174*
(Received 12 June 1975)

Angular distributions were measured for the $^{16}O(^{3}He, d)^{17}F$ reaction leading to the first four states of $^{17}F$. Comparison with distorted-wave Born-approximation (DWBA) calculations yields spectroscopic factors of 0.94 and 0.83 for the ground and first-excited states, respectively. Comparison with unbound DWBA predictions calculated from the known proton widths of the next two states indicates the presence of a large two-step component for population of the $\frac{1}{2}^-$ state and possibly of the $\frac{5}{2}^-$ state.

[NUCLEAR REACTIONS $^{16}O(^{3}He, d)$, $E=18.0$ MeV, measured $\sigma(E_d, \theta)$. DWBA analysis.]

## I. INTRODUCTION

One signature of a two-step process is the observation of a cross section that is larger than the cross section for a one-step process should be. The difficulty lies in the determination of what the one-step yield "should be." Fortunately, there are cases in which this is known. One example is stripping to an unbound state whose width is known from elastic scattering. The reaction $^{16}O(^{3}He, d)$-$^{17}F$ is a particularly good case to study. The $\frac{1}{2}^-$ and $\frac{5}{2}^-$ states at excitation energies[1] of 3.11 and 3.86 MeV, respectively, are unbound to proton emission and their widths are known from proton scattering.[1-6] Since they are unbound only to proton decay to the ground state (g.s.) of $^{16}O$, the total width is essentially equal to the proton width. These two states are extremely weakly populated in $(^{3}He, d)$, whereas the $\frac{5}{2}^+$ ground state and the $\frac{1}{2}^+$ state at 0.495 MeV (which are largely single-particle states) are very strongly populated. In fact, the ratio of cross sections is about 100. So, any two-step process that involves single-particle $2s_{1/2}$ or $1d_{5/2}$ transfer in one of the two steps could make a significant contribution to the negative-parity states.

We have measured the $^{16}O(^{3}He, d)^{17}F$ cross section for these four states and compared the results for the 3.11- and 3.86-MeV states with the expected cross section calculated from the known proton widths.

## II. EXPERIMENTAL PROCEDURE

A beam of 18-MeV $^{3}He$ ions from the Penn tandem bombarded a target of natural oxygen contained in a gas cell with no entrance window. Outgoing deuterons, excited through a Mylar window 13 $\mu$m in thickness, were momentum analyzed in a multiangle spectrograph and were detected in nuclear-emulsion plates. Mylar absorber foils placed in front of the emulsion prevented tritons and particles of charge $Z \geq 2$ from striking the emulsion. A spectrum is displayed in Fig. 1.

Absolute cross sections were calculated from a knowledge of the integrated charge and the gas-cell pressure (20 Torr) and are believed accurate to ±20%.

Our measured excitation energies for the two negative-parity states are 3104± 3 keV and 3857 ± 4 keV. Angular distributions for the ground and 0.495-MeV state are displayed in Fig. 2, and those for the 3.11- and 3.86-MeV states are displayed in Fig. 3.

## III. ANALYSIS

Distorted-wave Born-approximation (DWBA) calculations were performed with the use of the code DWUCK[7] for the two bound states and the code DOXY[8] for the two unbound states. Optical-model parameters were standard (see, e.g., Ref. 9) and are listed in Table I. The DWBA calculations give

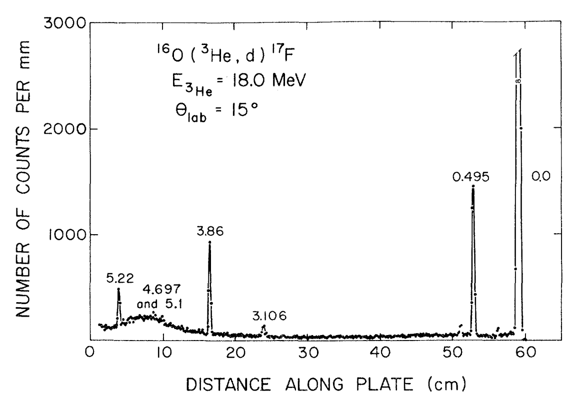


FIG. 1. Spectrum of the $^{16}O(^{3}He, d)^{17}F$ reaction. States above 0.6 MeV are unbound to proton decay.

TABLE I. Optical-model parameters used in analysis of the reaction $^{16}O(^{3}He, d)^{17}F$ (see, e.g., Ref. 9).

| Channel | $V$ (MeV) | $r_0 = r_{0so}$ (fm) | $a = a_{so}$ (fm) | $W$ (MeV) | $W' = 4W_D$ (MeV) | $r'_0$ (fm) | $a'$ (fm) | $V_{so}$ (MeV) |
|---|---|---|---|---|---|---|---|---|
| $^{3}He + ^{16}O$ | 177 | 1.14 | 0.72 | 13 | 0 | 1.60 | 0.77 | 8 |
| $d + ^{17}F$ | 105 | 1.02 | 0.86 | 0 | 64 | 1.42 | 0.65 | 6 |
| $p + ^{16}O$ | ··· | 1.26 | 0.60 | ··· | ··· | ··· | ··· | 6 |

reasonable fits for the bound states (Fig. 2) and yield spectroscopic factors of 0.93 and 0.84 for the g.s. and first-excited state, respectively. These are slightly less than the single-particle value of 1.0, but are consistent with other measurements.[1]

For the unbound states there is no arbitrary normalization[8]—the absolute magnitude of the predicted cross sections is fixed by the measured values of the proton widths. The $\frac{1}{2}^-$ state has a width of $19 \pm 1$ keV.[2] Two measurements of the proton width of the $\frac{5}{2}^-$ state give $\Gamma_p(\text{lab}) = 1.63 \pm 0.23$ keV[2] and $\Gamma \lesssim 1.5$ keV.[6] In what follows, we use $\Gamma_p(\text{c.m.}) = 1.5$ keV. Clearly, a better value for this width is needed.

The single-particle widths for $1p_{1/2}$ and $1f_{5/2}$ at the appropriate energies are 1.05 MeV and 44.2 keV, respectively. Thus, the spectroscopic factors for these two states are quite small—about 0.02 and 0.03, respectively.

The curves for the unbound states are compared with the data in Fig. 3. The DWBA curve for the $\frac{5}{2}^-$ state gives a reasonably good account of the shape of the angular distribution, but is too low by about 30%. This is barely outside the usual uncertainty of ~20% normally associated with DWBA calculations, but is in the opposite direction to discrepancies previously encountered in stripping to unbound states—in which the calculation overestimates the cross section. Of course, pending a more accurate measurement of the proton width of the $\frac{5}{2}^-$ state, the magnitude is still somewhat uncertain. For the $\frac{1}{2}^-$ state, the data disagree with DWBA in both shape and magnitude. The maximum near 40° in the data is almost completely missing in the calculated curve, and the predicted magnitude is about a factor of 6 too low. Thus, the majority of the yield for the $\frac{1}{2}^-$ state arises from some process other than direct one-step proton transfer. The cross section at 160°

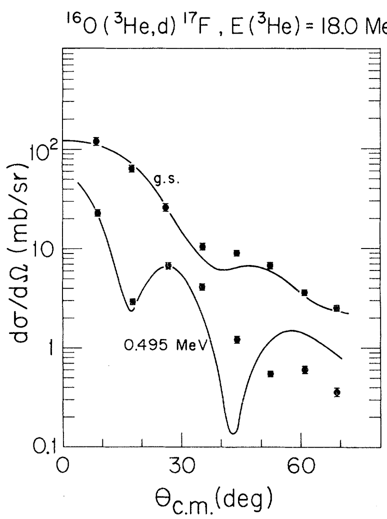


FIG. 2. Angular distributions for the $^{16}O(^{3}He, d)^{17}F$ reaction leading to the $\frac{5}{2}^+$ g.s. and $\frac{1}{2}^+$ 0.495-MeV state. The curves are the results of DWBA calculations and have been arbitrarily normalized to the data. Resulting spectroscopic factors are 0.93 for the g.s. and 0.84 for the 0.495-MeV state.

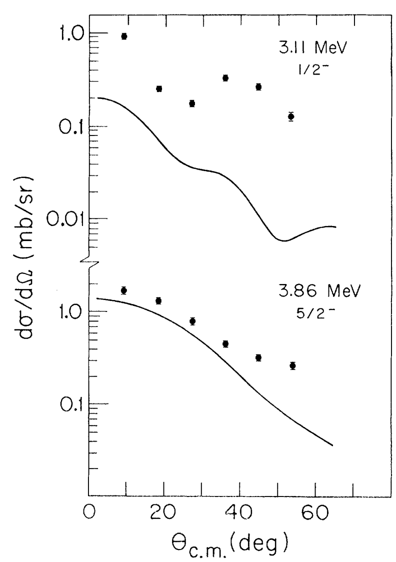


FIG. 3. Angular distributions for the $^{16}O(^{3}He, d)^{17}F$ reaction leading to $\frac{1}{2}^-$ and $\frac{5}{2}^-$ states at excitation energies of 3104 and 3857 keV, respectively. The curves are the results of DWBA calculations and have been normalized by using the measured proton widths.

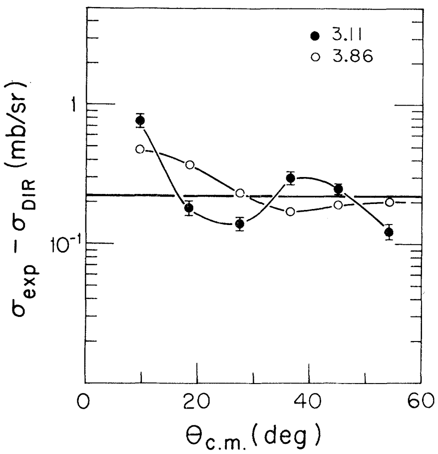


FIG. 4. The difference between measured angular distributions and the predictions for direct single-proton transfer. The solid horizontal line represents the average.

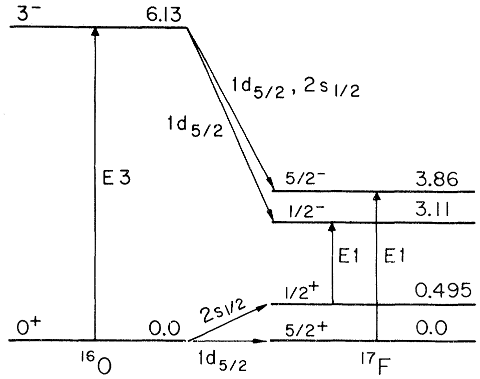


FIG. 5. Possible two-step routes that involve inelastic scattering followed or preceded by $2s_{1/2}$ or $1d_{5/2}$ proton transfer.

is less than 1% of that at forward angles, so it is unlikely that a compound-nucleus mechanism can account for the observed yield.

The direct transfer accounts for a much larger fraction of the cross section for the $\frac{5}{2}^-$ state than for the $\frac{1}{2}^-$ state—70% compared to ~15%. However, the measured cross section is larger for the $\frac{5}{2}^-$ state, so that (in absolute units) the excess of the measured yield over that predicted is about the same for both states. This is demonstrated in Fig. 4, where we have plotted as a function of angle the difference between the measured cross section and the predicted direct one-step cross section for both states. The $\sin\theta$-weighted average "nondirect" cross section is about 0.23 mb/sr for both states. There is, however, a noticeable difference in the shape.

The most likely explanation is that these two states are being populated by a second-order process. Because of the extremely large cross sections for the g.s. and first-excited state, it would seem that a two-step process that involves inelastic scattering followed or preceded by $2s_{1/2}$ or $1d_{5/2}$ single-proton transfer would be large.

The possible two-step routes that involve inelastic scattering in one of the steps are depicted in Fig. 5. The inelastic steps all have[1] large matrix elements, and the proton transfers are likely to have roughly single-particle strengths. There is no reason to expect one of the two states to be preferentially populated over the other in either of these two-step processes. This is consistent with the observation that that part of the cross section that does not rise from direct one-step transfer is roughly the same for the two states.

It would be of interest to see if a two-step DWBA calculation could account for these relatively large "non-one-step" cross sections and if it could describe the difference in angular-distribution shapes. Unfortunately, it is not yet possible to perform a two-step DWBA calculation for unbound final states. So such a test must await further theoretical developments.

*Work supported by the National Science Foundation.

‡Present address: Niels Bohr Institutet, Copenhagen, Denmark.

†Deceased.

[1]F. Ajzenberg-Selove, Nucl. Phys. A166, 1 (1971).
[2]S. R. Salisbury, G. Hardie, L. Oppliger, and R. Dangle, Phys. Rev. 126, 2143 (1962).
[3]R. A. Blue and W. Haeberli, Phys. Rev. 137, B284 (1965).
[4]V. Gomes, R. A. Douglas, T. Polga, and O. Sala, Nucl. Phys. 68, 417 (1965).
[5]E. A. Silverstein, L. Oppliger, and R. A. Blue, Bull. Am. Phys. Soc. 9, 68 (1964).
[6]R. E. Segel, P. P. Singh, R. G. Allas, and S. S. Hanna, Phys. Rev. Lett. 10, 345 (1963).
[7]P. D. Kunz (private communication).
[8]C. M. Vincent and H. T. Fortune, Phys. Rev. C 2, 782 (1970).
[9]R. R. Betts, H. T. Fortune, and R. Middleton, Phys. Rev. C 11, 19 (1975).