# Nuclear Structure of $F^{18}$ †

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The nuclear structure of $F^{18}$ was studied with the reactions $O^{17}(He^3, d)F^{18}$, $O^{16}(He^3, p)F^{18}$, and $Ne^{20}(d, \alpha)F^{18}$ induced with 15-MeV $He^3$ and 11-MeV deuteron beams. Reaction products were magnetically analyzed and recorded on nuclear emulsions. Angular distributions for the first two reactions were analyzed with distorted-wave Born-approximation predictions, and spectroscopic formation was extracted from the data. The $J=2$ level at 3.06 MeV was assigned positive parity and $T=1$. The $J=2$ level at 3.84 MeV was assigned positive parity, and the 4.12-MeV level was assigned $J^\pi=3^+$. The three levels at 4.65, 4.74, and 4.96 MeV were identified as having $T=1$. The 4.65-MeV level was assigned $J^\pi=4^+$, and we have a strong preference for $J^\pi=0^+$ and $2^+$ assignments for the 4.74- and 4.96-MeV levels, respectively. Our results are in good agreement with the theoretical predictions of Kuo and Brown.

## I. INTRODUCTION

As a first approximation, the nucleus $F^{18}$ may be pictured as a simple system formed by the addition of a proton and a neutron to an inert $O^{16}$ core. In the $j$-$j$ coupling shell model the core nucleons fill the $1s_{1/2}$, $1p_{3/2}$, and $1p_{1/2}$ levels, and the lowest levels available for the added valence nucleons are then the $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ orbitals referred to as the $(sd)$ shell. One would expect that many of the features of the low-lying $F^{18}$ levels could be explained in terms of this simple model, and its attractiveness has stimulated considerable interest, both experimental[1–9] and theoretical,[1,10–12] in this nucleus.

The total number of possible states of two nucleons in the $(sd)$ shell is 28, and in $F^{18}$ there are 26 levels below 6-MeV excitation. However, the single-particle energies of the $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$ levels relative to the $O^{17}$ ground state are 0.0, 0.87, and 5.08 MeV, respectively, and the large $d_{3/2}$ single-particle energy implies that in $F^{18}$ many of the possible shell-model states might well be above 6 MeV. Moreover, the simple shell model cannot account for the low-lying, negative-parity states of $F^{18}$.

In 1955, Elliot and Flowers[13] calculated the properties of the low-lying $F^{18}$ levels with the intermediate-coupling shell model and the assumption of $(sd)^2$ configurations. The success of the calculation in explaining the existing experimental information strongly supported the intermediate-coupling shell-model picture of $F^{18}$. Recently, calculations have been performed[14] with the same model space, but with realistic nucleon-nucleon potentials rather than an assumed residual interaction; good agreement was obtained with the known experimental spins and energies of many of the low-lying positive-parity levels. These calculations, of course, cannot account for the negative-parity levels and, moreover, do not predict as many low-lying positive-parity levels as are observed experimentally.

The obvious step is to enlarge the model space by permitting excitations of the $O^{16}$ core. Two calculations[10,11] of the energies of core-excited states in $F^{18}$ have been published, and they show that the one-hole–three-particle (negative-parity) and two-hole–four-particle (positive-parity) states have approximately the correct energy to be the low-lying states that cannot be accounted for when only $(sd)^2$ final-state configurations are allowed.

The present study was undertaken to clarify the structure of $F^{18}$ by confirming or establishing the quantum numbers of some of the low-lying levels and obtaining quantitative information on their configurations and wave functions. Existing spectroscopic information[4,9,15–17] on these levels is given in Table I.

The three reactions $O^{17}(He^3, d)F^{18}$, $O^{16}(He^3, p)F^{18}$, and $Ne^{20}(d, \alpha)F^{18}$ were studied. Angular distributions of groups leading to many of the final states were

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[14] T. T. S. Kuo and G. E. Brown, Nucl. Phys. **85**, 40 (1966).
[15] T. Lauritsen and F. Ajzenberg-Selove, in *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Science—National Research Council, Washington, D.C., 1962).
[16] R. W. Ollerhead, J. S. Lopes, A. R. Poletti, M. F. Thomas, and E. K. Warburton, Nucl. Phys. **66**, 161 (1965).
[17] G. M. Matous, G. H. Herling, and E. A. Wolicki, Phys. Rev. **152**, 908 (1966).

TABLE I. Existing information on $F^{18}$ states below 7-MeV excitation.

| Level No. | $E_x$[a] (MeV) | $J^\pi$ [b] | Level No. | $E_x$[a] (MeV) | $J^\pi$ [b] |
|---|---|---|---|---|---|
| 0 | g.s. | $1^+$ | 19 | 4.741 | $(0^+; T=1)$ |
| 1 | 0.937 | $3^+$ | 20 | 4.844 | 1 |
| 2 | 1.043 | $0^+; T=1$ | 21 | 4.964 | $(2^+; T=1)$ |
| 3 | 1.081 | $0^-$ | 22 | 5.295 | $1^+, 2, 3$ |
| 4 | 1.131 | $5^+$ | 23 | 5.502 | |
| 5 | 1.701 | $1^+$ | 24 | 5.603 | $0^-, 1^-, 2^-(1^-; T=0/1)$ |
| 6 | 2.101 | $2^-$ | 25 | 5.668 | $0^-, 1^-, 2^-(1^-; T=0/1)$ |
| 7 | 2.524 | $2^+$ | 26 | 5.786 | |
| 8 | 3.060 | $2^{(+)}(2^+; T=1)$ | 27 | 6.092 | $2^-, 3^-, 4^-$ |
| 9 | 3.134 | $1^{(-)}$ | 28 | 6.139 | |
| 10 | 3.358 | $2^+, 3^+$ | 29 | 6.235 | $2^-, 3^-, 4^-$ |
| 11 | 3.724 | 1 | 30 | 6.264 | $1^+$ |
| 12 | 3.790 | 1, 2, 3 | 31 | 6.376 | |
| 13 | 3.839 | $2^{(+)}$ | 32 | 6.472 | |
| 14 | 4.115 | 1, 2, 3 | 33 | 6.548 | $3^+, 4^+, 5^+$ |
| 15 | 4.231 | 1, 2 | 34 | 6.634 | |
| 16 | 4.361 | $\leq 3$ | 35 | 6.765 | |
| 17 | 4.400 | $\geq 2$ | 36 | 6.790 | $2^-$ |
| 18 | 4.651 | $\geq 3(4^+; T=1)$ | 37 | 6.859 | |

[a] Levels 1–15 are ±1 keV taken from Ref. 4. Levels 16–37 are ±10 keV taken from Ref. 15.

[b] Except for level 9, spins, parities, and isospins of levels 0–20 are taken from Ref. 4. Evidence for a negative-parity assignment to level 9 is given in Ref. 17. The assignments to level 22 are taken from Ref. 9 and those to levels 24 and 25 are taken from Ref. 16. All other assignments are from *Nuclear Data Sheets* (Ref. 15).

obtained in the first two reactions, and the results were analyzed using the distorted-wave Born approximation (DWBA). The isospin-selective $Ne^{20}(d, \alpha)F^{18}$ reaction aided the identification of five $T=1$ analogs of $O^{18}$ states.

Single-stripping spectroscopic factors and double-stripping nuclear-structure factors calculated from the Kuo and Brown[14] wave functions were compared to the experimental data on the $O^{17}(He^3, d)F^{18}$ and $O^{16}(He^3, p)F^{18}$ reactions. The comparison aided in the identification of states formed of $(sd)^2$ configurations, and the over-all agreement obtained supports the validity of the Kuo and Brown predictions.

## II. EXPERIMENTAL PROCEDURE

The three reactions studied were induced with beams from the University of Pennsylvania tandem electrostatic accelerator, and in all cases the outgoing particles were magnetically analyzed in a 65-cm Browne-Buechner magnetic spectrograph and recorded on Ilford $K2$ or $K$-1 emulsions. Mylar absorbers were used when needed to stop unwanted particles from striking the emulsions.

### A. Targets

The $O^{16}(He^3, p)F^{18}$ reaction was studied with an oxygen gas target and a rotating gas cell apparatus.[18] The cell was filled to a pressure of 20 Torr with research grade (99.999 volume % purity) oxygen with natural isotopic abundance and the targets therefore were essentially pure $O^{16}$.

For the neon target, gas enriched to 99.70 volume % in $Ne^{20}$ was used, and again the rotating gas cell was filled to a pressure of 20 Torr.

The target for the $O^{17}(He^3, d)F^{18}$ reaction was tungsten oxide enriched in $O^{17}$. The oxide was made by burning tungsten wire in oxygen gas enriched to 53.8 atomic % $O^{17}$ and 16.3 atomic % $O^{18}$. This technique, developed by Muggleton,[19] yields a mixture of the oxides $WO_2$, $WO_3$, $W_2O_3$ and $W_3O_4$. The oxide powder then was evaporated from a platinum boat onto carbon foils mounted on target holders.

The $O^{17}$ content of a typical target was estimated at 14 $\mu g/cm^2$ by comparing the $O^{17}(He^3, He^3)O^{17}$ elastic cross section experimentally measured at eight laboratory angles from 22.5° to 40° with values predicted from the optical model portion of the distorted-wave code JULIE. The parameters used for this calculation are discussed below.

### B. Data Collection

In the study of the $O^{16}(He^3, p)F^{18}$ reaction, 20 exposures were made at 14 laboratory angles from 10° to 60° with a 15.000-MeV beam of doubly ionized $He^3$. Exposure lengths, measured by the integrated beam current, varied from 200 $\mu$C for the smallest angles to 1000 $\mu$C at the largest angles. During the exposures gas pressure in the cell was monitored by a mechanical gauge. A solid-state detector fixed at a laboratory angle of 45° monitored the He ions elastically scattered from $O^{16}$ and provided the normalization for the angular distributions.

[18] The rotating gas cell was patterned after the design of A. M. Hoogenboom, Rev. Sci. Instr. **32**, 1395 (1961).

[19] A. H. F. Muggleton and F. A. Howe, Nucl. Instr. Methods **12**, 192 (1961).

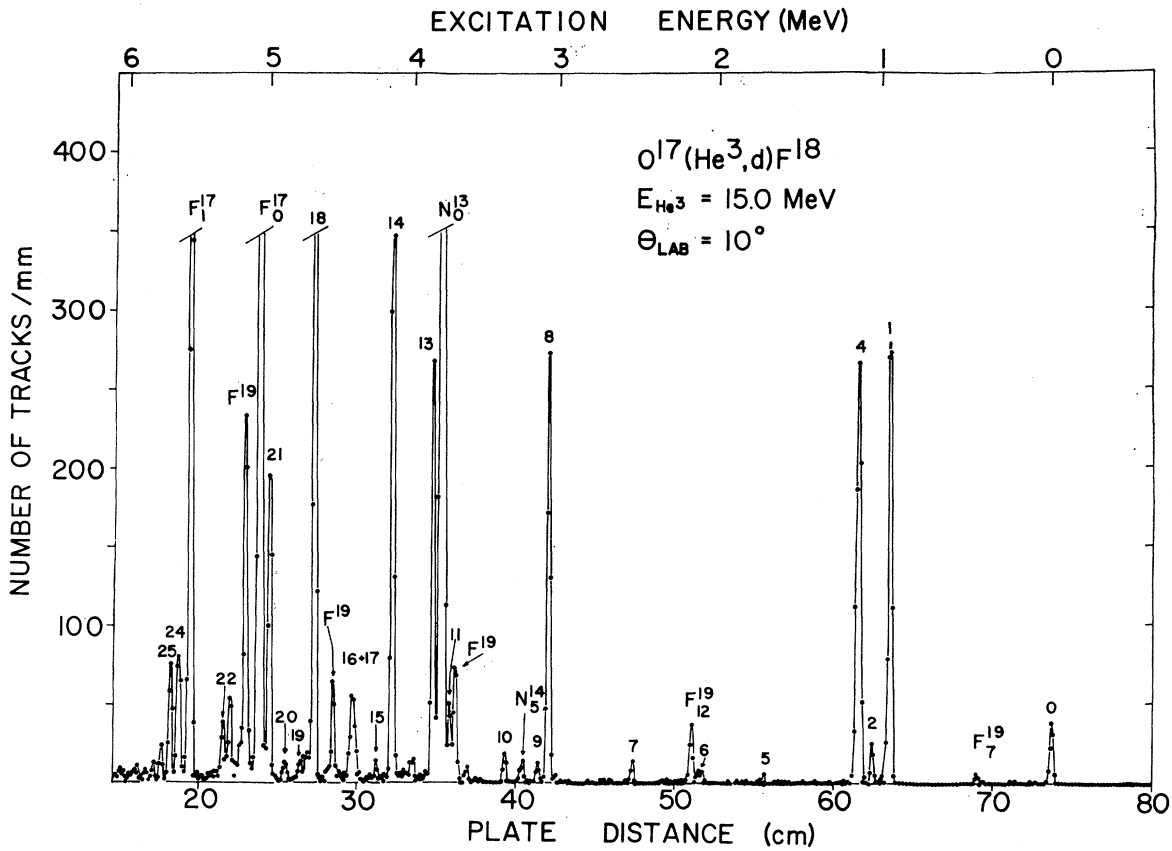


FIG. 1. $O^{17}(He^3, d)F^{18}$ spectrum. Levels of $F^{18}$ are numbered 0–25 and correspond to the excitation energies given in Table I. Impurity groups that could be definitely identified are indicated by the appropriate residual nucleus. Such groups arose from $O^{16}$, $O^{18}$, and $C^{12}$ contaminants in the target.

An 11.000-MeV deuteron beam was used for the $Ne^{20}(d, \alpha)F^{18}$ reaction and two exposures were made at laboratory angles of 15° and 30°. Exposure lengths were 4000 and 6000 $\mu$C, respectively, and gas cell pressure was monitored as described above.

For the $O^{17}(He^3, d)F^{18}$ reaction twenty spectra were recorded at 14 laboratory angles between 2.5° and 40°, using a doubly ionized 15.040-MeV $He^3$ beam. Exposure lengths varied from 200 to 1000 $\mu$C. The elastic scattering, recorded by a solid-state detector fixed at 135°, was used for normalization, and each time the target was changed, at least one previous angle was repeated so that appropriate corrections for variations in target thickness could be made.

For the exposures at 2.5° and 5.0°, beam current could not be integrated because it was necessary to remove the beam stop, and exposure lengths were determined by the integrated number of counts in the elastic peak recorded by the solid-state counter.

## III. RESULTS AND ANALYSIS

### A. $O^{17}(He^3, d)F^{18}$ Reaction

A typical deuteron spectrum is shown in Fig. 1, and angular distributions in the c.m. system of deuteron groups leading to 10 excited states in $F^{18}$ are shown in Fig. 2. The error bars show a statistical uncertainty of one standard deviation. Also shown in the figures are the angular distributions predicted by the DWBA code JULIE.[20] In those cases where the distributions indicated a mixture of $l$ values for the transferred proton, the individual components are shown as broken lines and the sum distribution is the solid line.

The absolute cross sections shown were calculated with the target thickness determined by normalization of measured elastic scattering to the optical-model predictions.

#### *Distorted-Wave Calculations*

Optical-model parameters needed for DWBA calculations were not available for either the incident $He^3+O^{17}$ or outgoing $d+F^{18}$ channels, and the $O^{17}(He^3, He^3)O^{17}$ scattering data obtained in this study did not cover a large enough angular range to permit the extraction of these parameters with the standard

[20] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. 3240 (unpublished) and supplement.

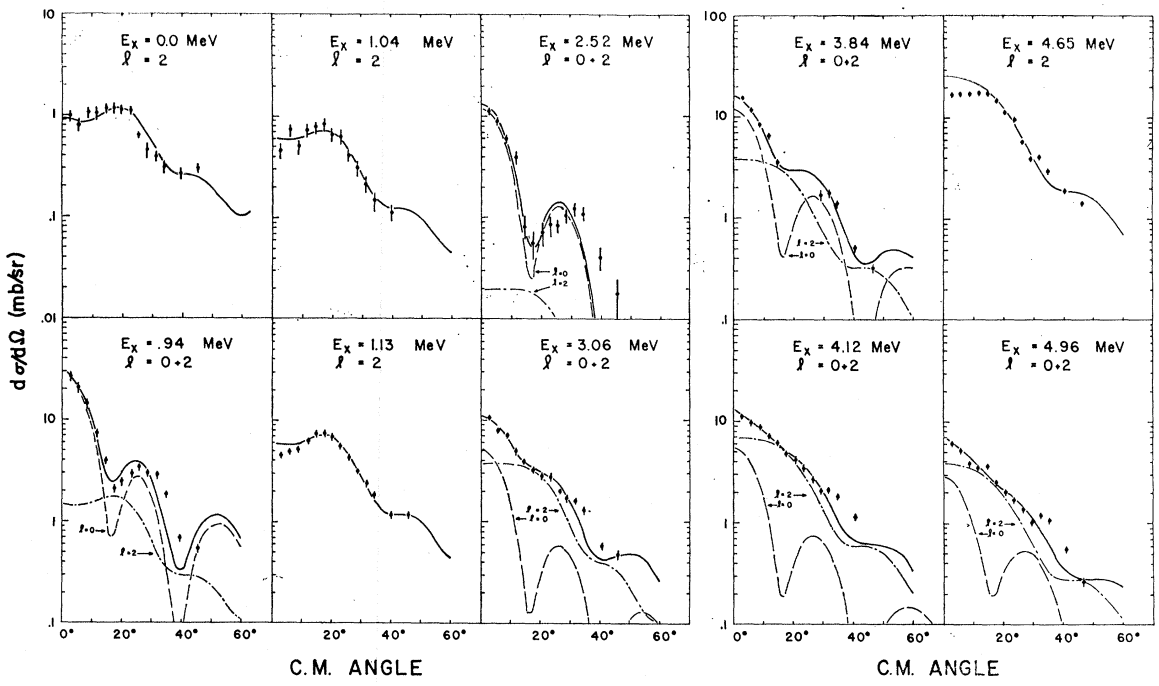


FIG. 2. Angular distributions of ten deuteron groups leading to final states in $F^{18}$ excited by the $O^{17}(He^3, d)F^{18}$ reaction. The solid lines are DWBA predictions. Where the distributions required a mixture of $l=0$ and $l=2$, the experimental data were fitted with a $\chi^2$-minimization program and the individual components are shown as broken lines. The error bars represent 1 standard deviation due to statistics. The estimated error in the absolute cross sections is $\pm 25\%$.

search codes. Therefore, the exit-channel parameters were taken to be those used by Siemssen, Lee, and Cline[21] to describe the $d+Ne^{20}$ channel in an analysis of the $F^{19}(He^3, d)Ne^{20}$ reaction, and an appropriate set of entrance-channel parameters was then found by varying $He^3$ parameters known to work well in this mass region.[21,22]

The well parameters for $He^3$ were varied until the $l=2$ angular distribution calculated with JULIE agreed with the experimental angular distribution for the $J^\pi=5^+$ state at 1.13-MeV excitation. This state was chosen because it can be excited only with an angular momentum transfer of 2 since it is composed only of the $(d_{5/2})_5^2$ configuration, as is discussed later. The parameters indicated in Table II were selected as giving the best over-all match, and were used to calculate the angular distributions given in Fig. 2.

### *Spectroscopic Analysis*

Spectroscopic factors were extracted from the data using the relation

$$(d\sigma/d\Omega)_{\text{expt}}=N[(2J_f+1)/(2J_i+1)]\sum_l C^2S(l)\sigma(l,\Theta),$$

where $\sigma(l,\Theta)$ is the JULIE cross section and the normalization $N$ was taken equal to 4.4, as calculated by Bassel.[23] $J_i$ and $J_f$ are the initial and final spins and $C$ is the isospin Clebsch-Gordan coefficient. The results of the analysis are summarized in Table III.

Since at low excitation energies we expect that this reaction will directly excite only those states with $(sd)^2$ configurations, we have analyzed the data only with $l=0$ and $l=2$ DWBA predictions. The angular distributions shown in Fig. 2 can be divided into three classes by comparison with the shapes of the DWBA predictions: pure $l=2$, dominant $l=0$ with a possible small admixture of $l=2$, and a mixture of $l=0$ and $l=2$ in approximately equal amounts.

The first class includes the transitions to the ground state, 1.04-, 1.13-, and 4.65-MeV levels, and in these cases the $l=2$ DWBA predictions were normalized to the experimental data at the forward maximum.

The distributions for the 0.94- and 2.52-MeV levels are predominantly $l=0$, but the depths of the minima and positions of the secondary maxima are not well predicted by the pure $l=0$ DWBA calculations. Therefore, a mixture of $l=0$ and $l=2$ was fitted to the experimental points with a $\chi^2$-minimization computer program. The indicated ratios of $l=0$ and $l=2$ give a better fit to the data than pure $l=0$, but the admixture of $l=2$ is quite small. However, at small angles $\sigma(l=0)$ (JULIE) is approximately 25 times greater

[21] R. H. Siemssen, L. L. Lee, Jr., and D. Cline, Phys. Rev. **140**, B1258 (1965).

[22] E. M. Kellogg and R. W. Zurmuhle, Phys. Rev. **152**, 890 (1966).

[23] R. H. Bassel, Phys. Rev. **149**, 791 (1966).

TABLE II. Optical-model parameters used in the $O^{17}(He^3, d)F^{18}$ and $O^{16}(He^3, p)F^{18}$ DWBA analyses. All potentials are of the Woods-Saxon form except the imaginary proton and deuteron potentials which are surface Gaussian and surface derivative, respectively.

| Channel | $V$ (MeV) | $W$ (MeV) | $r_0$ (F) | $a$ (F) | $r_c$ (F) | $r_W$ (F) | $a_W$ (F) | $W'$ (MeV) |
|---|---|---|---|---|---|---|---|---|
| $\binom{He^3+O^{17}}{He^3+O^{16}}$ | 156.0 | 6.00 | 1.05 | 0.829 | 1.40 | 2.40 | 0.592 | 0 |
| $p+F^{18}$ | 47.5 | 28.00 | 1.25 | 0.600 | 1.40 | 1.25 | 0.20 | 0 |
| $d+F^{18}$ | 100.0 | 0 | 1.00 | 0.900 | 1.40 | 1.85 | 0.500 | 10.0 |
| Bound state | ...[a] | ... | 1.25 | 0.650 | 1.25 | | | |

[a] Depth of the bound-state well was adjusted to give a binding energy equal to the proton or deuteron separation energy minus the excitation energy of the particular state.

than $\sigma(l=2)$ (JULIE), and a relatively small admixture of $l=2$ in the cross section yields corresponding spectroscopic factors comparable to those for the $l=0$ components. Since the effect on the composite angular distributions of the $l=2$ admixture is not great, it is unreasonable to accept the relatively large $l=2$ spectroscopic factors at face value, and therefore they were taken as upper limits.

The third class of distributions comprises the transitions to the 3.06-, 3.84-, 4.12-, and 4.96-MeV levels, none of which can be identified as being dominantly $l=0$ or $l=2$. In the case of the 3.84-MeV level, the uncertainty exists because three data points between 15° and 30° are missing due to interference from the $N^{13}$ ground-state impurity group. The four transitions were fitted with mixtures of $l=0$ and $l=2$ distributions by means of the above-mentioned $\chi^2$-minimization program, and good fits were obtained in each case.

The 3.84-MeV transition presents a problem because the three missing data points are at angles where the $l=0$ distribution is near its first minimum and the $l=2$ distribution is near its principal maximum—precisely the region where the distribution is most sensitive to the $l=2$ admixture. The $\chi^2$ minimization has most probably overestimated the strength of the $l=2$ component, and, therefore, its associated spectroscopic factor was taken as an upper limit.

The absolute spectroscopic factors derived from the above procedure are given in the third and fourth columns of Table III. The values are quoted as the product $(2J_f+1)C^2S(l)$, which does not require assignment of the final-state spin, and in those cases where a range of values is indicated, the maximum of $C^2S(0)$ is to be associated with $C^2S(2)=0$ and the lower limit on $C^2S(0)$ corresponds to the indicated maximum of $C^2S(2)$.

TABLE III. Experimental spectroscopic information for the $O^{17}(He^3, d)F^{18}$ reaction.

| $E_x$ (MeV) | $l$ | $(2J_f+1)C^2S_{abs}$ $l=0$ | $l=2$ | $(2J_f+1)C^2S_{rel}$ $l=0$ | $l=2$ | $J^\pi$ Previous | Final[a] | $C^2S_{rel}$ $l=0$ | $l=2$ | $2C^2S(0)+C^2S(2)$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 2 | | 1.86 | | 2.24 | $1^+$ | $1^+$ | | 0.75 | 0.75 |
| 0.94 | 0(+2) | <1.95<br>>1.77 | <2.10 | <2.35<br>>2.13 | <2.53 | $3^+$ | $3^+$ | <0.34<br>>0.30 | <0.36 | <0.96<br>>0.68 |
| 1.04 | 2 | | 0.96 | | 1.16 | $0^+$ | $0^+$ | | 1.16 | 1.16 |
| 1.13 | 2 | | 9.12 | | 11.00 | $5^+$ | $5^+$ | | 1.00 | 1.00 |
| 2.53 | 0(+2) | <0.106<br>>0.096 | <0.020 | <0.128<br>>0.116 | <0.024 | $2^+$ | $2^+$ | <0.026<br>>0.023 | <0.005 | <0.052<br>>0.051 |
| 3.06 | 0+2 | 0.66 | 3.06 | 0.80 | 3.69 | $2^{(+)}$ | $2^+$ | 0.16 | 0.74 | 1.06 |
| 3.84 | 0(+2) | <2.40<br>>1.74 | <2.34 | <2.90<br>>2.10 | <2.82 | $2^{(+)}$ | $2^+$ | <0.58<br>>0.42 | <0.56 | <1.40<br>>1.16 |
| 4.12 | 0+2 | 0.78 | 4.38 | 0.94 | 5.28 | 1, 2, 3 | $2^+$<br>$3^+$ | 0.19<br>0.13 | 1.06<br>0.75 | 1.44<br>1.01 |
| 4.65 | 2 | | 7.32 | | 8.82 | $\geq 3(4^+)$ | $3^+$<br>$4^+$ | | 1.26<br>0.98 | 1.26<br>0.98 |
| 4.96 | 0+2 | 0.90 | 2.04 | 1.09 | 2.46 | $(2^+)$ | $2^+$<br>$3^+$ | 0.22<br>0.16 | 0.49<br>0.35 | 0.93<br>0.67 |

[a] When two $J^\pi$ values are consistent with existing spin-parity assignments and the angular momentum transfer observed here, both values and their corresponding spectroscopic information are given.

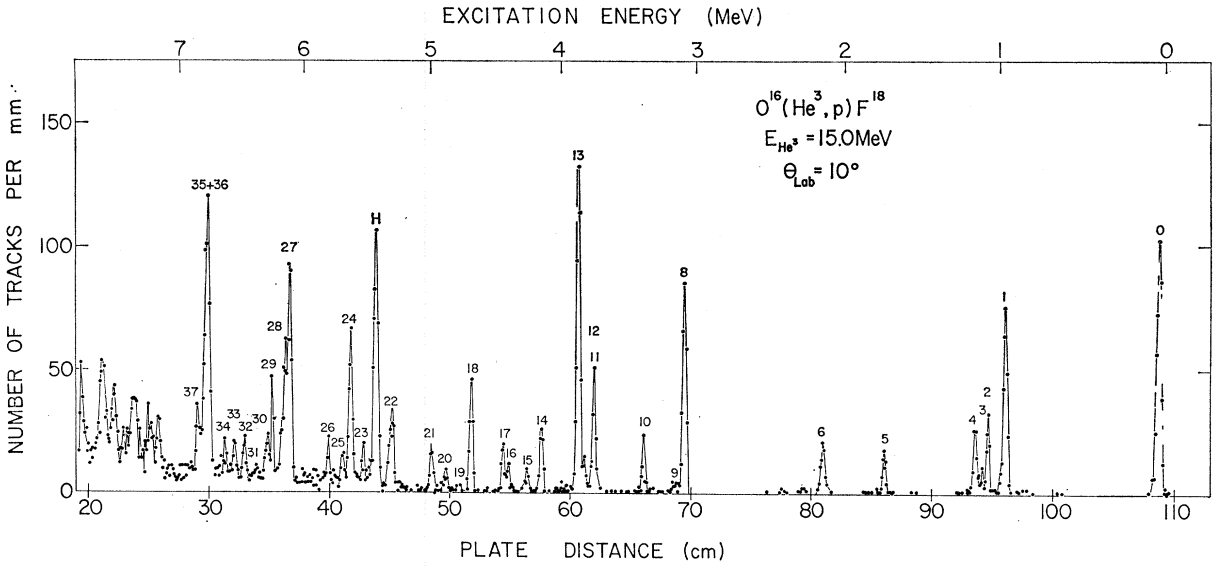


FIG. 3. $O^{16}(He^3, p)F^{18}$ spectrum. Levels of $F^{18}$ are numbered 0–37 and correspond to the excitation energies given in Table I. The group labeled *H* is recoil protons from the small hydrogen contaminant in the target gas.

The absolute spectroscopic factors depend directly on the target thickness measurement which enters as an over-all normalization. However, there are reasons to doubt the reliability of the target thickness obtained by normalizing the measured to the predicted elastic scattering because there may be other sets of optical-model parameters which would fit the elastic scattering over the limited angular range of the experimental data, but which would predict different absolute cross sections. Therefore, it is desirable to eliminate this uncertainty before attempting to draw any further conclusions. For this reason the spectroscopic factors were renormalized to yield the expected value for the $5^+$ state of the $(d_{5/2})^2$ configuration. If only $(sd)$-shell final-state configurations are considered, this state must be pure $(d_{5/2})^2$ since no other configuration can couple to $J^\pi=5^+$, and $C^2S$ for it must be 1. This state has been identified[8] as the level at 1.13 MeV. In addition, its measured *g* factor[7] agrees well with the theoretical value for a pure $(d_{5/2})^2$ configuration.

If $C^2S$ for the 1.13-MeV level is normalized to unity [that is, $(2J_f+1)C^2S=11$], the relative spectroscopic factors given in the fifth and sixth columns of Table III are obtained. The latter differ from the absolute values by less than 20%, supporting the validity of the target-thickness normalization and the choice of incident-channel optical-model parameters used in the DWBA calculations.

### *Spin and Parity Assignments*

The $(sd)^2$ configurations with parentage in $O^{17}$ accessible directly by this reaction are $d_{5/2}s_{1/2}$, $(d_{5/2})^2$, and $d_{5/2}d_{3/2}$. The first will be excited with $l=0$, and the ohters with $l=2$. The single-stripping selection rules[24] are

$$\pi_f=\pi_i(-1)^l, \qquad \mathbf{J}_f=\mathbf{J}_i+\mathbf{J}.$$

Therefore, the presence of an $l=0$ component limits the final state $J$ to 2 or 3, and a pure $l=2$ excitation allows $0\leq J\leq 5$. Only positive parity states can be excited with these angular momentum transfers.

As noted before, the large reduced cross section for *s*-wave transfer makes this reaction extremely sensitive to any admixture of the $d_{5/2}s_{1/2}$ configuration in the final-state wave function. Consequently, it is likely that there is no $d_{5/2}s_{1/2}$ component in the wave functions of states excited with a pure $l=2$ transition. If such states had $J^\pi=2^+$ or $3^+$, at least a small $l=0$ component would be expected, and therefore neither of these assignments is favored for states so excited.

The observed angular momentum transfers in the excitation of the ground-state, 0.94-, 1.04-, 1.13-, 2.52-, 3.06-, and 3.84-MeV levels are consistent with the previous unique spin assignments to these levels. In addition, the uncertainties in the positive parity assignments to the levels at 3.06 and 3.84 MeV are removed. The 4.12-MeV level may be assigned positive parity and the possibility of its having $J=1$ is excluded.

The spin of the 4.65-MeV level was previously limited to $\geq 3$, and the level has been tentatively identified[16] as the $4^+$, $T=1$ analog of the $O^{18}$ state at 3.55 MeV. The observation of a pure $l=2$ transition establishes the positive parity and limits $J\leq 5$. The possibility of $J=5$ is doubful because we expect only $(sd)^2$ configurations to be excited directly at this ex-

[24] N. K. Glendenning, in *Annual Reviews of Nuclear Science*, edited by E. Segrè (Annual Reviews, Inc., Palo Alto, Calif., 1963), Vol. 13.

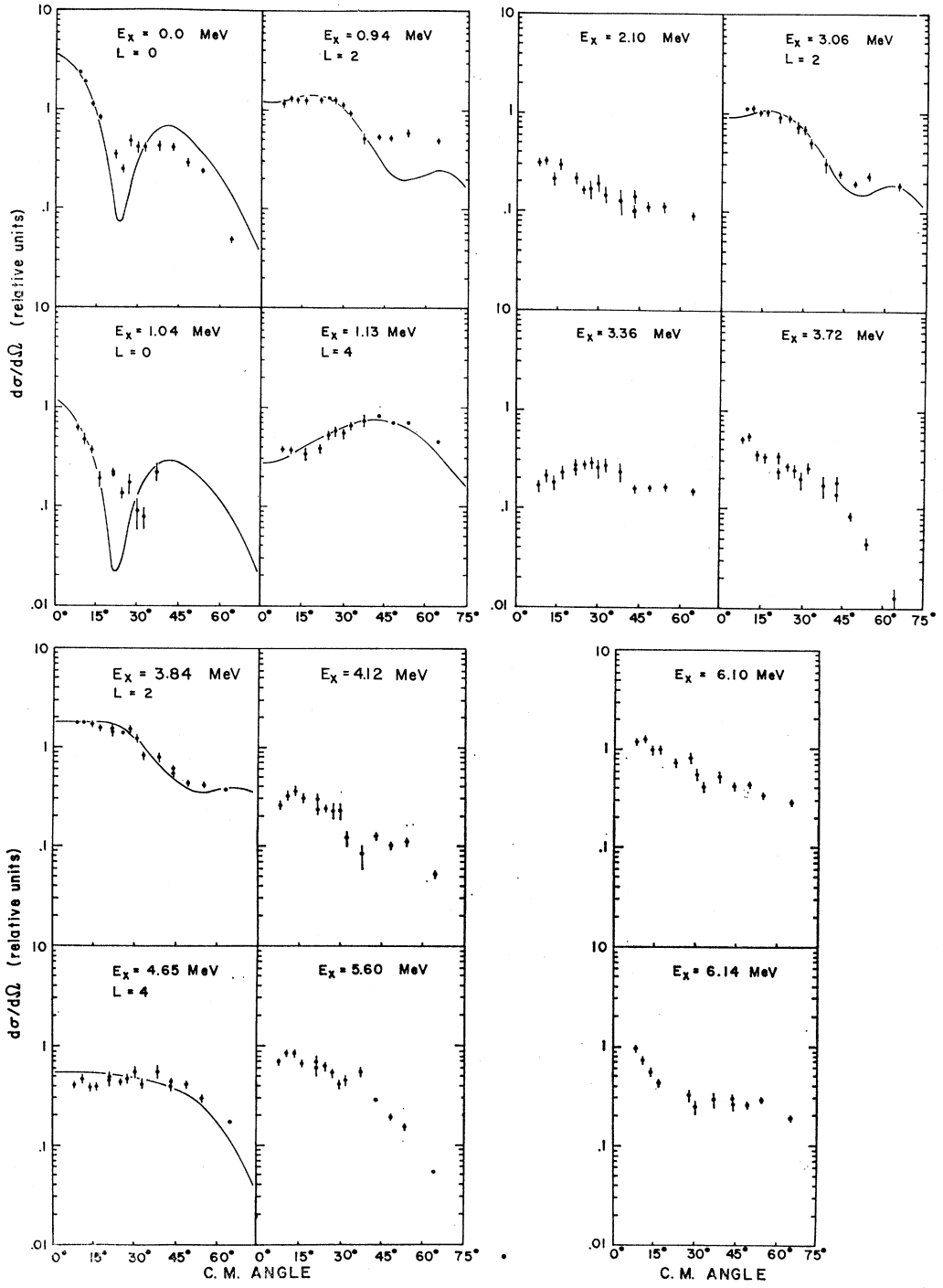


FIG. 4. Angular distributions of 14 proton groups leading to final states of $F^{18}$ excited by the $O^{16}(He^3, p)F^{18}$ reaction. The solid lines are DWBA calculations performed as explained in the text.

citation energy. They can give rise to only one $5^+$ state, and it has been shown to be the 1.13-MeV level.[8] For these reasons the possible quantum numbers of the 4.65-MeV level are reduced to $3^+$ or $4^+$ with the $3^+$ assignment not favored because of the pure $l=2$ excitation.

The 4.96-MeV level was tentatively assigned $J^\pi = 2^+$.[16] The observation of an $l=0+2$ excitation in this reaction is consistent with $2^+$ but also allows $3^+$.

The values of $C^2S_{rel}$ derived from these data with the spin and parity assignments assumed above are given in Table III, and a quantitative examination

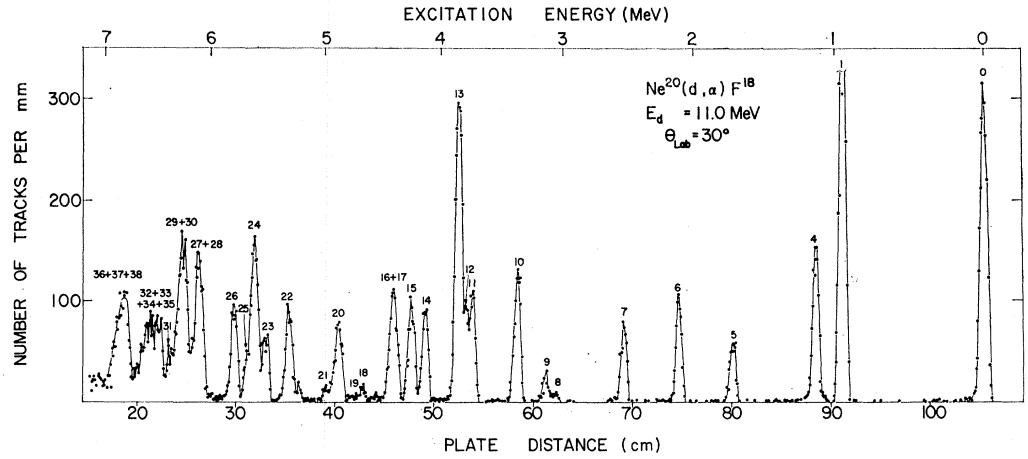


FIG. 5. $Ne^{20}(d, \alpha)F^{18}$ spectrum. Levels of $F^{18}$ are numbered 0 through 38 and correspond to the excitation energies given in Table I. Levels 2, 8, 18, 19, and 21 have been assigned $T=1$. Level 2 was not seen in this exposure.

of them provides further limitations on two of the three ambiguous spin-parity assignments. The wave functions for final states excited in this reaction can be expressed as

$$\Psi_f = a(d_{5/2})^2 + b(d_{5/2}d_{3/2}) + c(d_{5/2}s_{1/2}) + \Phi,$$

where those configurations not having parentage in $O^{17}$ are grouped into $\Phi$. Normalization requires that

$$a^2+b^2+c^2 \leq 1,$$

and, in addition, the definition of the spectroscopic factors yields

$$c^2 = 2C^2S(0), \qquad a^2+b^2/2 = C^2S(2).$$

Therefore, the spectroscopic factors must satisfy the relation

$$2C^2S(0)+C^2S(2) \leq 1.$$

The quantity of the left is tabulated as the last column of Table III, and with the proper choices of final-state spins, the condition is reasonably met for all but two states. For the 1.04-MeV level there is a 16% violation which can be attributed to uncertainty in the spectroscopic factor. A large violation occurs if the upper limit of 0.56 is taken for the $l=2$ spectroscopic factor of the 3.84-MeV level, supporting the earlier conclusion that the $\chi^2$ minimization overestimated the $l=2$ contribution to this angular distribution. Similarly, support is given to $J^\pi = 3^+$ for the 4.12-MeV level and $4^+$ for the 4.65-MeV level. The limitation on the spectroscopic factors is satisfied for either choice of spin and parity of the 4.96-MeV state, and in this case the ambiguity cannot be resolved by these considerations.

### B. $O^{16}(He^3, p)F^{18}$ Reaction

Angular distributions of 14 proton groups from the $O^{16}(He^3, p)F^{18}$ reaction have been analyzed, and the angular momentum transferred in seven of the transitions was identified by comparison with DWBA calculations. A typical proton spectrum is shown in Fig. 3 and the angular distributions are shown in Fig. 4.

The DWBA calculations were performed with the code JULIE by treating the reaction as pseudo-single-stripping of a mass-2 particle. This procedure is equivalent to assuming that the two stripped nucleons are transferred to the target in a relative $1s$ state. The bound-state quantum numbers were taken to be $(N, L) = (3, 0)$, $(2, 2)$, or $(1, 4)$, consistent with the Talmi transformation and the assumption that both nucleons enter the $(sd)$ shell. With these quantum numbers the data were successfully interpreted using the optical-model parameters given in Table II. The $O^{17}+He^3$ parameters arrived at in the analysis of the $O^{17}(He^3, d)F^{18}$ reaction were used for the incident channel, and the parameters given by Duke[25] for the scattering of 17-MeV protons by $O^{18}$ were used for the exit channel.

Angular distributions calculated as described above were adequate for identification of transferred angular momenta, but, because of the well-known[24,26] coherence effects in two-nucleon transfer reactions, these calculations cannot be used in a quantitative analysis of the experimental results. Relative magnitudes of the experimentally observed transitions are compared with the predictions of the Glendenning theory[26] in Sec. IV B below.

#### *Spin and Party Assignments*

The double-stripping selection rules[26] become particularly simple for this reaction because the $O^{16}$ ground state has $J^\pi;T = 0^+;0$. There are two pos-

[25] C. B. Duke, Phys. Rev. **129**, 681 (1963).
[26] N. K. Glendenning, Phys. Rev. **137**, B102 (1965).

TABLE IV. Allowed quantum numbers of states excited with $L=0$, 2, or 4 in the $O^{16}(He^3, p)F^{18}$ reaction.

| $L$ | 0 | 2 | 4 |
|---|---|---|---|
| $J^\pi; T$ | $1^+; 0$<br>$0^+; 1$ | $1^+, 2^+, 3^+; 0$<br>$2^+; 1$ | $3^+, 4^+, 5^+; 0$<br>$4^+; 1$ |

sible cases corresponding to the transfer of a deuteron ($S=1$, $T=0$) or a virtual deuteron ($S=0$, $T=1$). In the latter instance, $J$, the final-state spin, equals $L$, and in the former $(L-1)\leq J\leq(L+1)$. In either case, the parity of the final state is $(-1)^{l_1+l_2}$, and the isospin is just that of the transferred pair. The permitted quantum numbers of states excited with a transfer of $L=0$, 2, or 4 are given in Table IV.

The angular momentum transfers observed in the excitation of the ground-state, 0.94-, 1.04-, 1.13-, 3.06-, and 3.84-MeV levels are consistent with the unique spin and parity assignments made or confirmed with the $O^{17}(He^3, d)F^{18}$ reaction.

The 4.65-MeV level ($J^\pi$ either $3^+$ or $4^+$ from the analysis in Sec. III A) is excited with $L=4$, which does not eliminate either spin but does make the unique association of $J=4$ with $T=1$. That is, if the level can be shown to have isospin 1, its spin must be 4. The identification of the $T=1$ levels will be pursued further in the analysis of the $Ne^{20}(d, \alpha)F^{18}$ reaction.

The other angular distributions could not be explained by the DWBA calculations. The unexplained distributions leading to positive-parity states may result from mixtures of different $L$'s; it is also possible that the levels are not being excited by a direct mechanism. Angular distributions for excitation of the negative-parity states at 5.60 and 6.10-MeV were calculated assuming one nucleon entered the ($sd$) shell and the other went into the ($fp$) shell. However, these distributions were rather structureless and lacking in distinctiveness, and it was not possible to use them to determine angular momentum transfers.

### C. $Ne^{20}(d, \alpha)F^{18}$ Reaction; Identification of the $T=1$ States

Because both the deuteron and $\alpha$ particle have $T=0$, the $(d, \alpha)$ reaction is subject to the selection rule $\Delta T=0$. The ground state of $Ne^{20}$ is also $T=0$ and, to the extent that $T$ is a good quantum number, the $T=1$ states of $F^{18}$ should not be excited by the $(d, \alpha)$ reaction.

The spectrum recorded at a laboratory angle of 30° is shown in Fig. 5. Unfortunately, the width of the groups (approximately 60 keV FWHM) prohibited resolution of many of the closely spaced levels at higher excitation energies.

It may be seen from the figure that groups 2, 8, 18, 19, and 21 are either absent or only weakly excited, each taking no more than 0.3% of the yield observed at this angle. These groups are, respectively, the 1.04-, 3.06-, 4.64-, 4.74-, and 4.96-MeV levels, and are the same levels suggested by Ollerhead *et al.*[16] to be $T=1$ analogs of states in $O^{18}$. Our data therefore support $T=1$ assignments to these levels. The proposed alignment of $O^{18}$ levels and their $T=1$ analogs in $F^{18}$ is shown in Fig. 6.

Groups 24 and 25 leading to the 5.60- and 5.67-MeV doublet, although not clearly resolved, do show the latter as a weak shoulder on the side of the former. Ollerhead *et al.*[16] proposed, as a possible explanation of inconsistencies in earlier data, that these levels are both $J^\pi=1^-$ and are of mixed $T$ and share the $T=1$ wave function of the $O^{18}$ 4.45-MeV level. Although the 5.67-MeV level is excited with much less strength than the 5.60-MeV level, it is still much stronger than the lower $T=1$ states. Therefore, our data do not disagree with the above proposal.

Unique spins and parities may now be assigned to the levels at 4.65, 4.74, and 4.96 MeV because of their identification as analogs of $O^{18}$ states. The 4.65-MeV level was assigned $J^\pi=3^+$ or $4^+$ in the $O^{17}(He^3, d)F^{18}$ analysis with $4^+$ preferred, and it was shown that only $4^+$ is possible if the level is $T=1$ because of the

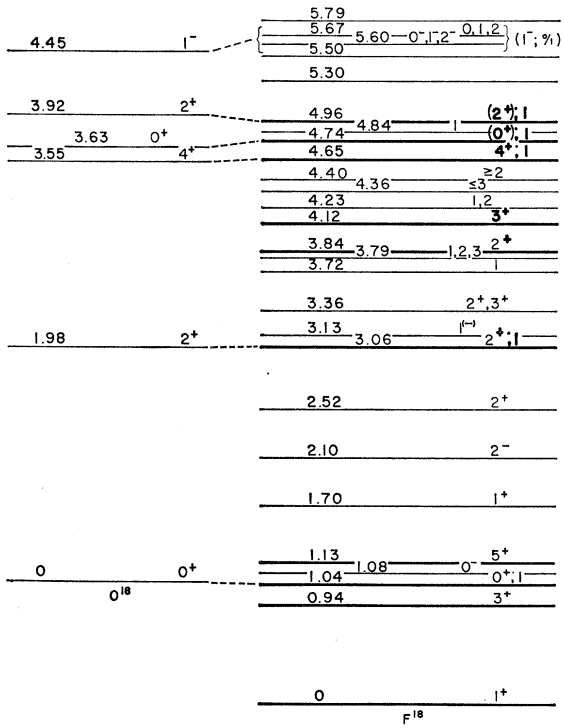


FIG. 6. Summary of information on $F^{18}$ based on a synthesis of the results of the present study and the information given in Table I. Dark lines indicate states formed of $(sd)^2$ configurations; new spin, parity, and isospin assignments made in this work are indicated in bold face. There is some evidence that the 3.72-MeV level is the $1^+(sd)^2$ level predicted to lie at 3.77 MeV. The levels of $O^{18}$ are also shown for comparison with the $T=1$ states of $F^{18}$.

TABLE V. Comparison of spectroscopic factors calculated from the Kuo and Brown wave functions (Refs. 14 and 27) with the relative experimental values of Table III.

| Energy Theory (MeV) | Energy Expt (MeV) | $J^\pi; T$ | $C^2S(l)$ Theory $l=0$ | Theory $l=2$ | Expt $l=0$ | Expt $l=2$ |
|---|---|---|---|---|---|---|
| 0.17 | 0.0 | $1^+; 0$ | | 0.524 | | 0.75 |
| 0.78 | 1.04 | $0^+; 1$ | | 0.812 | | 1.16 |
| 0.96 | 0.94 | $3^+; 0$ | 0.334 | 0.305 | <0.34 >0.30 | <0.36 |
| 1.31 | 1.13 | $5^+; 0$ | | 1.00 | | 1.00 |
| ... | 2.53 | $2^+; 0$ | ... | ... | <0.026 >0.023 | <0.005 |
| 3.11 | 3.06 | $2^+; 1$ | 0.168 | 0.616 | 0.16 | 0.74 |
| 3.41 | 3.84 | $2^+; 0$ | 0.284 | 0.144 | <0.58 >0.42 | <0.56 |
| 3.77 | (3.72) | $1^+; 0$ | | 0.320 | ... | ... |
| 4.73 | 4.12 | $3^+; 0$ | 0.164 | 0.648 | 0.13 | 0.75 |
| 4.73 | 4.65 | $4^+; 1$ | | 0.955 | | 0.98 |
| 4.94 | 4.74 | $0^+; 1$ | | 0.104 | ... | ... |
| 5.23 | 4.96 | $2^+; 1$ | 0.310 | 0.369 | 0.22 | 0.49 |

$L=4$ excitation in the $O^{16}(He^3, p)F^{18}$ reaction. We have seen here that the level is in fact $T=1$ and therefore has $J^\pi=4^+$. It is clearly to be associated with the $4^+$ state at 3.55 MeV in $O^{18}$. Although the evidence is not as strong as in the previous case, the assignments of $J^\pi=2^+$ for the 4.96-MeV level [possible $2^+$ or $3^+$ from the $(He^3, d)$ reaction] and $O^+$ for the 4.74-MeV level are suggested from their identification as analogs of $O^{18}$ states with those spins and parities. These conclusions are given further support by comparisons of the $O^{16}(He^3, p)F^{18}$ and $O^{17}(He^3, d)F^{18}$ results to the predictions of Kuo and Brown presented in the next section.

## IV. DISCUSSION

Kuo and Brown[14] have calculated the wave functions and properties of the low-lying $F^{18}$ levels by assuming the states to be formed of $(sd)^2$ configurations and calculating the residual interactions from the Hamada-Johnston free nucleon-nucleon potential. They predict 11 positive-parity levels below 6-MeV excitation.

All but three of the predicted levels can be identified with experimentally observed $F^{18}$ states on the basis of energy, spin, parity, and isospin. A comparison of spectroscopic factors, calculated from the wave functions of Kuo and Brown with the experimental results of the $O^{17}(He^3, d)F^{18}$ study, serves to identify the three remaining predicted levels. Comparison of the double-stripping structure factors with the results of the $O^{16}(He^3, p)F^{18}$ reaction further tests the validity of the wave functions.

### A. $O^{17}(He^3, d)F^{18}$ Spectroscopic Factors

Spectroscopic factors are given by $S(0)=c^2$ and $S(2)=2a^2+b^2$, where $a$, $b$, and $c$ are the amplitudes of the $(d_{5/2})^2$, $d_{5/2}d_{3/2}$, and $d_{5/2}s_{1/2}$ configurations in the predicted wave function. Spectroscopic factors derived from the Kuo and Brown wave functions[14,27] are given in Table V as the product $C^2S$, where $C^2$ is $\frac{1}{2}$ for both $T=0$ and $T=1$. The results of our $O^{17}(He^3, d)F^{18}$ analysis are also included for comparison.

Except for the predicted 3.41-, 3.77-, and $3^+$, 4.73-MeV levels the associations of the experimental and theoretical levels shown in the table follow directly from the agreement of the quantum numbers and energies. We have associated the predicted $2^+; 0$ level at 3.41 MeV with the level observed experimentally at 3.84 MeV because all other levels in this region of excitation can be eliminated as candidates for this state either because of inadequate strength (see Fig. 1) or spin-parity assignments other than $2^+$ (see Tables I and III).

The $1^+$ level predicted to be at 3.77 MeV should be excited with $l=2$ with about the same strength as the ground state because the reduced $l=2$ cross section increases with excitation energy and compensates for the difference in spectroscopic factors. Again most of the levels in the vicinity of the proper energy can be eliminated because they have spins other than 1 leaving only the two levels at 3.72 and 3.79 MeV

[27] The wave function for the second $3^+$ state predicted to be at 4.73 MeV was not included in Ref. 14 and was supplied by T. T. S. Kuo (private communication). The wave function is $0.790\ (d_{5/2})^2 - 0.572\ (d_{5/2}\ s_{1/2}) - 0.220\ (d_{5/2}d_{3/2}) + 0.008\ (d_{3/2})^2$.

TABLE VI. Double-stripping structure factors for the $O^{16}(He^3, p)F^{18}$ reaction.[a]

| Energy Theory (MeV) | Energy Expt (MeV) | $J^\pi; T$ | $L$ | $G_{NLSJT}$ $N=1$ | $N=2$ | $N=3$ | Expt $L$ | Expt $d\sigma/d\Omega$ Peak[b] |
|---|---|---|---|---|---|---|---|---|
| 0.17 | 0.0 | $1^+; 0$ | 0 | 0.015 | 0.090 | 0.556 | 0 | 100 |
| | | | 2 | 0.008 | 0.097 | | | |
| 0.78 | 1.04 | $0^+; 1$ | 0 | 0.014 | 0.103 | 0.499 | 0 | 24 |
| 0.96 | 0.94 | $3^+; 0$ | 0 | 0.058 | 0.592 | | 2 | 53 |
| | | | 4 | 0.016 | | | | |
| 1.31 | 1.13 | $5^+; 0$ | 4 | 0.603 | | | 4 | 32 |
| 3.11 | 3.06 | $2^+; 1$ | 2 | 0.060 | 0.484 | | 2 | 47 |
| 3.41 | 3.84 | $2^+; 0$ | 2 | 0.056 | 0.563 | | 2 | 76 |
| 3.77 | (3.72) | $1^+; 0$ | 0 | −0.005 | 0.081 | −0.179 | ... | 22 |
| | | | 2 | −0.018 | −0.119 | | | |
| 4.73 | 4.12 | $3^+; 0$ | 2 | 0.048 | −0.091 | | ... | 16 |
| | | | 4 | −0.016 | | | | |
| 4.73 | 4.65 | $4^+; 1$ | 4 | 0.419 | | | 4 | 24 |
| 4.94 | 4.74 | $(0^+); 1$ | 0 | 0.009 | −0.063 | 0.310 | ... | 2 |
| 5.23 | 4.96 | $(2^+); 1$ | 2 | −0.019 | 0.238 | | ... | 7 |

[a] With the exception of the factors for the predicted 4.73-MeV $3^+$ level, values were supplied by N. F. Mangelson (private communication).

[b] Cross sections are given relative to the ground state. Peak cross sections are given except for the ground-state, 1.04-, 4.74-, and 4.96-MeV levels, for which the values at $\Theta_{lab} = 10°$ are quoted.

as candidates. Angular distributions were not obtained for either of the two; however, both have approximately the correct strength at angles where they are not obscured by impurity groups. There is some evidence[28] that the 3.79-MeV level has $J^\pi = 3^-$, and we therefore tentatively associate the predicted 3.77-MeV level with the state observed at 3.72 MeV.

The predicted 4.73-MeV, $3^+$ level has been identified with the level experimentally observed at 4.12 MeV because of the $2^+$ or $3^+$ spin assignment we have made to the latter and the excellent agreement with the predicted spectroscopic factors if $J^\pi = 3^+$ is assumed. We note that this was, in fact, the preferred assignment for the level.

Of the levels for which angular distributions were obtained, only the one at 2.52 MeV cannot be fitted into the Kuo and Brown predictions, and there is in fact no need to because all the predicted levels can be accounted for. Furthermore, the weak excitation and small spectroscopic factors of this level imply that (*sd*) shell configurations contribute little to it and we must look to other configurations such as two holes in the $O^{16}$ core coupled to four valence nucleons.

With the above alignment of the experimental and predicted levels, a consistent explanation of the $O^{17}(He^3, d)F^{18}$ results is achieved. The theoretical and experimental spectroscopic factors are in good agreement, and the average difference between predicted and observed energies is less than 250 keV.

### B. $O^{16}(He^3, p)F^{18}$ Structure Factors

The double-stripping structure factors calculated by Mangelson[29] for the $O^{16}(He^3, p)F^{18}$ reaction are given in Table VI. They were calculated from the Kuo and Brown wave functions using the Glendenning[26] formalism and taking the oscillator parameter $\nu$ to be 0.339 $F^{-2}$. The table also gives the experimentally observed angular-momentum transfers and relative peak cross sections.

The double-stripping cross section as derived by Glendenning[26] depends on a coherent sum over $N$ (the radial quantum number for the motion of the center of mass of the stripped nucleons) of the products $G_{NLSJT}B_{NL}{}^M$. The $G_{NLSJT}$'s are the structure factors and contain the nuclear structure information, and the $B_{NL}{}^M$'s are completely analogous to the similarly denoted quantities in the theory of single-stripping reactions. As shown by Glendenning,[26] an examination of the dominant structure factors (those for $N = N_{max}$) and the magnitudes of the relevant $B_{NL}{}^M$'s can give information on relative magnitudes and dominant $L$'s of transitions that can be compared to the experimental results.

The DWBA calculations that were performed give an indication of the relative magnitudes of the $B_{NL}{}^M$'s, since the pseudo-single-stripping cross sections are proportional to $|B_{NL}{}^M|^2$. It was found that at forward angles and low excitation energy the calculated cross sections were in the approximate ratio of 20:6:1 for $(N, L) = (3, 0)$, $(2, 2)$, and $(1, 4)$. From this fact and the data of Table VI we see that the mixed transitions to the ground-state and predicted 0.96-MeV levels should be dominantly $L=0$ and $L=2$, respectively, as was observed experimentally.

Considering the dominant structure factors, we see that, of the two $1^+$ states, the ground state should be more strongly excited in agreement with the experimental results. Similarly, the intensities of the predicted $2^+$ states should be in the order $I_{3.41} > I_{3.11} > I_{5.23}$, also in agreement with the experimental data. Experimental confirmation of the predicted relative

[28] R. Middleton, L. M. Polsky, C. H. Holbrow, and K. Bethge Phys. Rev. Letters **21**, 1398 (1968).

[29] N. F. Mangelson (private communication); N. F. Mangelson, B. G. Harvey, and N. K. Glendenning, Nucl. Phys. **A119**, 79 (1968).

intensities is also obtained for the two $0^+$ states and the two $3^+$ states.

It must be noted that the above arguments ignore the dependence of the $B_{NL}{}^M$'s on the $Q$ value. However, this dependence was explored with the DWBA code JULIE and we found that it would not affect our conclusions.

To the extent that the theoretical wave functions can be checked by these approximate arguments, our data support the validity of the Kuo and Brown calculations and the proposed association of the predicted and experimental levels.

## V. CONCLUSIONS

This study was undertaken with the dual purposes of confirming or establishing the spins and parities of many of the low-lying $F^{18}$ levels and obtaining information on their wave functions. The specific results are summarized in the level diagram of Fig. 6, where new quantum numbers assigned are in bold lettering and states concluded to be primarily composed of $(sd)$ shell configurations are denoted by heavy lines.

The $O^{17}(He^3, d)F^{18}$ reaction was the most fruitful of the three studied because of its amenability to a detailed DWBA analysis. The $O^{16}(He^3, p)F^{18}$ reaction was successfully interpreted in terms of the DWBA double-stripping predictions, and although it did not yield any new spin-parity assignments, the results were found to be completely consistent with the previous data. Furthermore, the isospin-selective $Ne^{20}(d, \alpha)F^{18}$ reaction supported the identification of the $T=1$ analogs of the five $O^{18}$ states expected to be below 5 MeV in $F^{18}$.

Good correspondences were found between the experimental $F^{18}$ levels and the theoretical predictions of Kuo and Brown, and there was generally good agreement between the $O^{17}(He^3, d)F^{18}$ spectroscopic factors and the values derived from the theoretical wave functions. In addition, double-stripping, nuclear-structure factors calculated from the wave functions, correctly predicted the dominant $L$'s observed experimentally in those cases where the selection rules permitted mixed transitions via the $O^{16}(He^3, p)F^{18}$ reaction. The relative intensity of excitations observed in this reaction was well predicted by the structure factors.

Because of the generally good agreement of the experimental results with the Kuo and Brown predictions, the levels indicated in Fig. 6 have been identified as arising from $(sd)^2$ configurations. Of the remaining states, Poletti[2] has proposed that the low-lying negative-parity states be viewed as formed by promoting a particle from the $1p_{1/2}$ shell to the $(sd)$ shell to form one-hole–three-particle configurations approximated by coupling a $p_{1/2}$ hole to the two lowest positive-parity states of $F^{19}$. This coupling would give rise to levels of spin 0, 1, 2, and 3 and provides a reasonable explanation of the $0^-$ and $2^-$ levels at 1.08 and 2.10 MeV. The suggested negative-parity assignment for the 3.13-MeV level (although somewhat uncertain) makes it a candidate for the $1^-$ state, and our recent study of the $N^{14}(Li^7, t)F^{18}$ reaction[28] yielded evidence that the 3.79-MeV level is the expected $3^-$ state.

The results of the present study also imply that the two positive-parity levels at 1.70 and 2.52 MeV do not have $(sd)^2$ configurations. The first of these is not excited with significant strength in the $O^{17}(He^3, d)F^{18}$ reaction and is excited weakly in the $O^{16}(He^3, p)F^{18}$ reaction. The second is absent in the $O^{16}(He^3, p)F^{18}$ spectrum and its very small spectroscopic factors in the $O^{17}(He^3, d)F^{18}$ analysis indicate that $(sd)$ shell configurations contribute only a small fraction of the total amplitude of this state. The study of the $N^{14}(Li^7, t)F^{18}$ reaction mentioned above has confirmed these conclusions by establishing the two-hole–four-particle configurations of the states at 1.70 and 2.52 MeV and four other states at 3.36, 4.23, 5.30, and 6.55 MeV. With these additional results it is believed that the structure of the 16 levels below 4.3-MeV excitation and several of the higher levels of $F^{18}$ can be fully explained.

## ACKNOWLEDGMENTS

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