$F^{19}(p,t)F^{17}$ and $F^{19}(p,\alpha)O^{16}$ Reactions at 22.8 MeV*

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The differential cross sections for the $F^{19}(p,t)F^{17}$ reactions leading to the ground state and first excited state of F^{17}, and for the ground-state α-particle group and the composite α-particle groups corresponding to the two unresolved doublets at 6 MeV (6.05 and 6.13) and at 7 MeV (6.92 and 7.12) of excitation in O^{16} from the $F^{19}(p,\alpha)O^{16}$ reaction, were measured as functions of angle at an incident energy of 22.8 MeV. Data were also obtained for higher excited-state groups from both reactions at several forward angles. The angular distributions for all groups exhibit typical oscillatory variations with angles, to the largest angles observed, 170°. The amplitude of the variations is most pronounced for the α_0 group. The total cross sections, obtained by numerical integration of the differential cross sections, are 1.84, 1.45, 0.53, 0.43, and 0.45 mb for the t_0, $t_{0.5}$, α_0, α_6 and α_7 groups, respectively. The angular distributions of the t_0, $t_{0.5}$, and α_0 groups have been fitted with distorted-wave Born approximation calculations. Exchange interactions do not appear to be required in order to fit these data, although the possibility of knockout processes cannot be eliminated on the basis of the present calculations.

INTRODUCTION

THE object of the work reported here was to study the nature of the mechanisms for (p,t) and (p,α) reactions in light nuclei. F^{19} was selected as an interesting nucleus for such investigations; its structure has been extensively studied. The low-lying levels of F^{19} have been the subject of numerous experimental investigations[1] in which the character of many of these levels have been determined. The possibility of performing numerical calculations by treating F^{19} as three nucleons bound to the doubly magic inert-core O^{16} lead to considerable theoretical interest in the structure of the F^{19} nucleus. More recent calculations have also taken into account the effects of the core in explaining the existence of the low-lying negative parity states.

It is interesting to note that many of the qualitative spectroscopic features of the low-lying levels of F^{19} can be accounted for almost equally well on the basis of several of the currently popular nuclear models. Elliott and Flowers[2] have been able to account for the spectroscopic properties of the low-lying positive-parity levels on the basis of an intermediate coupling shell-model calculation. Recently, Harvey[3] has interpreted the existence of the negative parity levels as well as some of the collective properties of these states. Finally, Wildermuth[4] was able to account for the existence, as well as the spectroscopic properties, of both positive- and negative-parity low-lying states on the basis of the cluster model. In this latter work it was assumed that the negative-parity states are predominately of the cluster configuration $(N^{15}+\alpha)$ and that the positive-parity states are mainly $(O^{16}+t)$ configurations. However, since cluster-model wave functions are not orthogonal in this formulation, it is possible that the positive-parity states also contain admixtures of the $(N^{15}+\alpha)$ configuration, in which the clusters have a relative angular momentum of $L=1$.

This latter model is helpful for allowing one to visualize qualitatively the possible reaction mechanisms. The pickup and exchange reactions for the $F^{19}(p,t)F^{17}$ reaction can be expressed as:

$$(F^{17}+2n)+p \rightarrow F^{17}+(p+2n) \quad \text{(pickup)},$$
$$(O^{16}+t)+p \rightarrow (O^{16}+p)+t \quad \text{(exchange)};$$

and for the $F^{19}(p,\alpha)O^{16}$ reaction as:

$$(O^{16}+t)+p \rightarrow O^{16}+(t+p) \quad \text{(pickup)},$$
$$(N^{15}+\alpha)+p \rightarrow (N^{15}+p)+\alpha \quad \text{(exchange)}.$$

It is interesting to note that the same configuration of $F^{19}(O^{16}+t)$ which leads to the exchange interaction for the (p,t) reaction is responsible for the pickup interaction in the (p,α) reaction.

Warsh *et al.*[5] have studied the $F^{19}(p,\alpha_0)O^{16}$ reaction as a function of energy and angle, and have found that the cross section exhibits pronounced resonances in the energy region between 3 and 12 MeV. To fit their data in the region of these resonances it was necessary to include the effects of compound nucleus processes.[6] At higher energies, Likely and Brady[7] also found that the total cross section increased by about 50% between

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16.0 and 18.5 MeV. However, the shapes of the angular distributions which they observed at these two energies were essentially the same. In addition, they were successful in fitting the shapes of these angular distributions with plane-wave pickup calculations.

The present experiment was performed only at a bombarding energy of 22.8 MeV. Although there is always the danger that resonance effects are overlooked when measurements are made at only one energy, it was hoped that the effects of such resonances would be less at this higher energy than at lower energies and that the interpretation of the results in terms of a direct interaction would be more reliable. It is also expected that both strong coupling effects[8] and distortion effects would be somewhat less important at this energy than at lower energies; hence, the approximations of the distorted-wave Born approximation calculations (DWBA) should be better satisfied, and the interpretation of the results in terms of such calculations more meaningful.

In the present experiment we have measured the differential cross sections at a bombarding energy of 22.8 MeV for the $F^{19}(p,t)F^{17}$ reaction leading to the ground state and first excited state and for three triton groups corresponding to higher excited states at 3.10, 3.86, and 4.69 MeV in F^{17}; and for α-particle groups from the $F^{19}(p,\alpha)O^{16}$ reaction corresponding to the ground state, the two unresolved doublets at 6 MeV (6.05 and 6.13) and at 7 MeV (6.92 and 7.12), as well as levels at 8.88, 9.85, and 11 MeV of excitation energy in O^{16}.

PROCEDURE

The 22.8-MeV external beam of protons from the ORNL 86-in. Cyclotron was used to bombard target foils located on the axis of a 24-in.-diam scattering chamber. The beam was collected in a Faraday cup at the end of the chamber. The reaction particles were detected with a counter telescope which consisted of a 2-in.-thick gas proportional counter (dE/dx counter) and a 0.16-in.-thick totally depleted silicon surface-barrier counter (E counter).

The pulses from the dE/dx counter and the E counter were fed into an analog computer. The magnitude of the output pulses from this circuit is proportional to the mass of the detected particles. These pulses were used to route the residual energy pulses from the E counter to the appropriate section of the memory of the 400-channel pulse-height analyzer, in a manner such that pulses from different types of particles were recorded in different sectors of the storage unit. For this experiment, triton pulses were recorded in one half of the analyzer memory and α-particle pulses in the other half.

The charge collected by the Faraday cup was measured with a current integrator and the number of re-

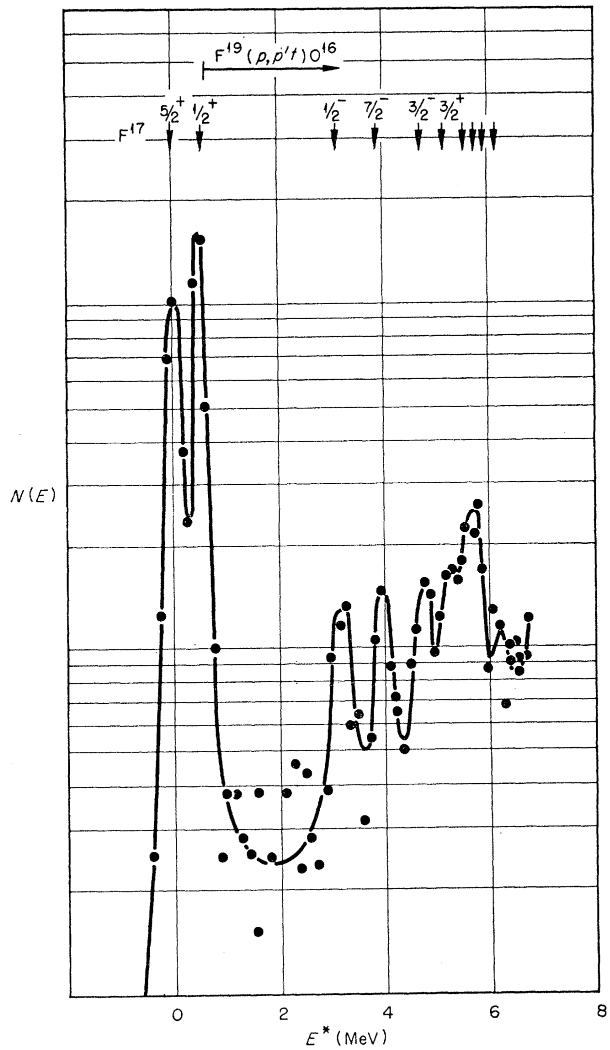

FIG. 1. Excitation energy spectrum for the $F^{19}(p,t)F^{17}$ reaction.

action particles was monitored with a fixed-angle counter at 45°. Thin Teflon foils were used as targets. The Q values for the (p,t) and (p,α) reactions on C^{12} are sufficiently negative, so that these reactions on C^{12} did not interfere with the measurements on F^{19}.

The incident beam was varied in intensity from about 10^9 to about 10^{10} protons per second, depending on the detector angle. Visible radiation effects on the target film were observed after an integrated beam of approximately 10^{14} protons. A comparison of the 45°-monitor counts and the charge collected by the Faraday cup indicated that the Teflon foil decreased in thickness with bombardment, and that the decrease was proportional to the total number of incident protons. The target thickness was reduced about 20% by 10^{15} incident protons. Further investigations showed that the ratio of carbon to fluorine did not change significantly during this process. The targets were changed after a bom-

[8] R. M. Drisko (private communication).

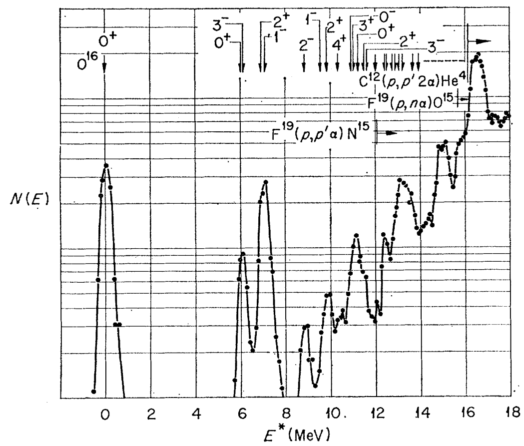

FIG. 2. Excitation energy spectrum for the $F^{19}(p,\alpha)O^{16}$ reaction.

bardment of about 10^{15} protons (i.e., approximately 6×10^{8} rad).

A correction was made for the effect of the beam on the target thickness by using the monitored counter to normalize the data and by repeating standard runs frequently at 30°. The relative yields for various targets were normalized by a similar procedure. Data from a fresh target that had been weighed were used for determining the absolute cross sections.

RESULTS

Figures 1 and 2 illustrate the excitation spectra of the residual nuclei F^{17} and O^{16} from the $F^{19}(p,t)F^{17}$ and $F^{19}(p,\alpha)O^{16}$ reactions. These curves were obtained at an angle of 30° for a bombarding energy of 22.8 MeV. For these figures the raw pulse-height data were transformed to corrected energy spectra with the aid of a program called NEWDAC[9] and an IBM-7090 computer. The points in these figures represent the numbers of α-particle or triton counts per energy interval plotted as a function of corresponding energy of excitation in the residual nuclei O^{16} and F^{17}, respectively. Thus, the ground-state α-particle group and the ground-state triton group lie at the same position in these spectra even though the Q value of the $F^{19}(p,\alpha)$ reaction is $+8.11$ MeV and that for the $F^{19}(p,t)$ reaction is -11.1 MeV. The known energy levels of each nucleus are also indicated on the figures as well as the points beyond which the $F^{19}(p,p't)O^{16}$, $F^{19}(p,p'\alpha)N^{15}$, $F^{19}(p,n\alpha)O^{15}$, and $C^{12}(p,p'2\alpha)He^{4}$ reactions may contribute to the observed spectra.

The ground-state α-particle group and the two α-particle groups corresponding to the unresolved doublets near 6 and 7 MeV in O^{16} are clearly seen. Weak groups corresponding to the 2^- state at 8.8 MeV and possibly the 2^+ state at 9.85 MeV, as well as the broad group due to the levels in the region of 11 MeV, are also seen. The structure corresponding to higher excitation energies becomes more difficult to identify.

Triton groups corresponding to the ground state, 0.500-, 3.10-, 3.86-, and 4.69-MeV states of F^{17}, as well as possibly higher unresolved states, are seen. At angles above 30° it becomes impossible to resolve the low-energy (corresponding to excitation energy greater than 8 MeV) α-particle groups from the continuum; and in the case of tritons only the ground state and first excited state groups could be identified above 70°. This difficulty was in part due to the loss of energy resolution resulting from the increasing spread in the energy loss of the lower energy particles in the target with increasing angle. In addition, slight drifts in the particle identification system occasionally allowed deuterons from the apparently copious $F^{19}(p,d)F^{18}$ reaction to be recorded in the triton sector of the analyzer memory. The particle identification system was adjusted to minimize this effect for the ground-state and 0.500-MeV-state triton groups; however, the data for the higher excited state groups became rather unreliable at large angles where longer runs were required because of smaller cross sections.

The differential cross sections for the various α-particle groups from $F^{19}(p,\alpha)O^{16}$ reaction are plotted in Fig. 3 as functions of the angle. The subscripts on the α's indicate the corresponding energy of excitation in the residual nucleus for each group. The uncertainties in the relative cross sections for each group range from approximately 3% in the forward direction for the ground-state group to as large as 30% for the α_6 and α_7 groups at large angles, where the low yield and poor resolution made it difficult to separate these groups. The uncertainties in the absolute cross sections are estimated to be about 20% at forward angles. The

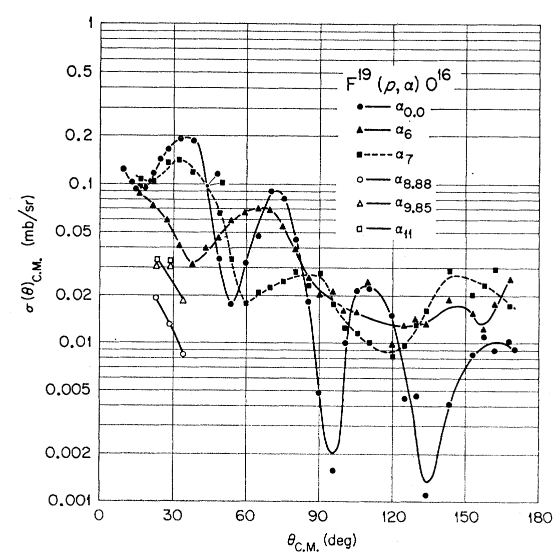

FIG. 3. Differential cross section for the $F^{19}(p,\alpha)O^{16}$ reaction to several final states.

[9] J. B. Ball, ORNL Report 3405, 1963 (unpublished).

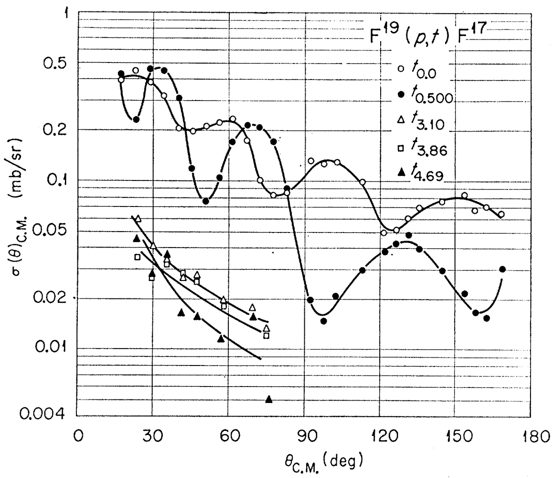

FIG. 4. Differential cross section for the $F^{19}(p,t)F^{17}$ reaction to several final states.

angular distributions of the three highest energy α-particle groups exhibit typical oscillatory behavior. However, the amplitudes of the oscillations are more pronounced for the ground-state group; the cross section for this group also oscillates more rapidly with angle than the others.

The total cross sections of the α_0, α_6, and α_7 groups have been determined by numerical integration of differential cross sections over angle and are 0.53 ± 0.11, 0.43 ± 0.09, and 0.45 ± 0.09 mb, respectively. At forward angles the cross sections for the $\alpha_{8.88}$, $\alpha_{9.85}$, and α_{11} groups are factors of 5 to 10 smaller than those for the other three groups. It is difficult, however, to draw any conclusions about the ratios of the total cross sections because of the very limited angular range of data available for these latter groups.

The differential cross sections for the various triton groups from the $F^{19}(p,t)F^{17}$ reaction are given in Fig. 4 as a function of the angle. The relative uncertainties in the values for the ground-state and 0.500-MeV-state groups were determined mainly by the statistical uncertainties of the measurements, except at large angles where poor resolution introduced additional uncertainties in the separation of these groups. The statistical uncertainties range from 2% at small angles to a maximum of about 7% at large angles. The uncertainties for the other groups are considerably larger due to the lower yield of these groups and the greater difficulty in resolving these groups. In addition it was necessary to make background subtractions due to the continuum of tritons in the case of the groups corresponding to higher energy levels.

Again the angular distributions for both the ground-state and 0.500-MeV-state groups exhibit typical oscillatory behavior. The total cross sections for these groups are 1.8 ± 0.4 and 1.5 ± 0.3 mb, respectively. Sufficient data are not available for the group corresponding to higher excited states of F^{17} to determine either their characteristic angular distributions or their total cross sections. However, the available data suggests the total cross sections for each of these groups may be less than 10% of that for the ground-state groups.

CALCULATIONS

The angular distributions for the ground-state α-particle group from the $F^{19}(p,\alpha)O^{16}$ reaction and those for the ground-state and 0.500-MeV-state triton groups from the $F^{19}(p,t)F^{17}$ reactions were fitted with DWBA pickup calculations. These calculations were carried out in the zero-range approximation with a lower cutoff radius using the ORNL code "SALLY."[10] The values of the optical-model parameters suggested by Hodgson[11] were used in the initial calculations, since no elastic scattering data were available. These parameters were then varied in an attempt to determine if it might be possible to fit the data with a reasonable choice of the parameters. However, an extensive search was not made; the parameters were varied only until sufficiently good fits were obtained to establish the feasibility of fitting the data reasonably well with such calculations. (In view of the known limitations of such calculations further "curve fitting" did not seem justified.)

The parameters were varied only in the calculations for the ground-state groups from both reactions. The calculations for the $t_{0.5}$ group were carried out only for

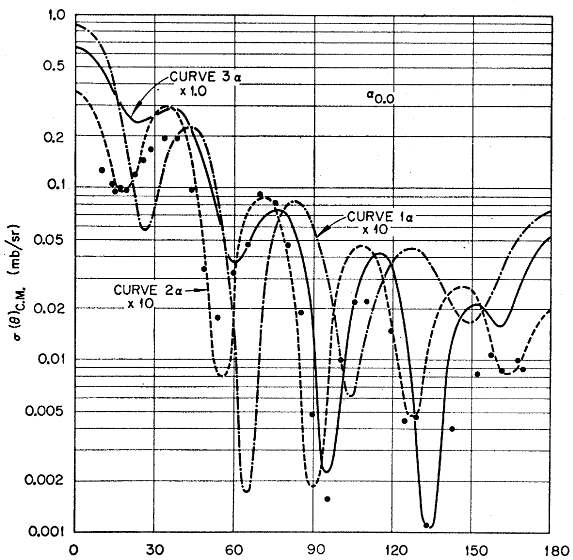

FIG. 5. Comparisons of the DWBA calculated angular; distributions with experimental data for ground-state α-particle group from the $F^{19}(p,\alpha)O^{16}$ reaction.

[10] R. H. Bassel, R. M. Drisko, and G. R. Satchler, ORNL Report 3240, 1962 (unpublished).

[11] P. E. Hodgson, *Proceedings of the International Symposium of Direct Interactions and Nuclear Reaction Mechanisms, 1962* (to be published).

TABLE I. Values of optical model parameters and integration controls for the theoretical curves shown in Figs. 5, 6, and 7.

Curve	Lower Cutoff Radius (F)	α-particle or triton V (MeV)	W (MeV)	r_0 (F)	r_c (F)	a (F)	Proton V (MeV)	r_0 (F)	r_c (F)	a (F)	W' (MeV)	a (F)	r_0' (F)
1α	5.04	50	10	1.85	1.50	0.60	55	1.30	1.30	0.65	30	0.47	1.50
2α	5.04	50	10	1.85	1.50	0.60	70	1.50	1.30	0.65	30	0.47	1.50
3α	4.00	50	10	1.85	1.50	0.60	90	1.50	1.30	0.65	30	0.47	1.50
$1t$	5.04	50	8	1.85	1.50	0.65	55	1.3	1.3	0.65	30	0.47	1.3
$2t$	4.00	50	8	1.85	1.50	0.65	70	1.5	1.3	0.65	30	0.47	1.5
$3t$	6.02	50	8	1.85	1.50	0.65	55	1.3	1.3	0.65	30	0.47	1.3
$4t$	5.00	50	8	1.85	1.50	0.65	70	1.5	1.3	0.65	30	0.47	1.5

several sets of parameters which gave reasonable fits for the ground-state triton group. The results of several of these calculations are shown in Figs. 5, 6, and 7 for the α_0, t_0, and $t_{0.5}$ groups, respectively. The curves in these figures have been arbitrarily normalized to the experimental data in the region of the second maximima; the normalization factors are indicated in the figures. The values of the optical model parameters and the integration controls for each of the curves are given in Table I. Oscillator wave functions with appropriate quantum numbers matched to bound-state Coulomb wave functions at a radius of 4 Fermis were used for the bound-state wave functions of the respective clusters in the target nucleus. The separation energies of the clusters were used as the binding energies in the bound-state Coulomb wave functions.

On the basis of the known spin and parities of the levels involved in the $F^{19}(p,\alpha_0)O^{16}$ and the $F^{19}(p,t)F^{17}$ reaction to the ground-state and 0.500-MeV state, only one value of the transfer angular momenta is allowed for each of these three reactions: 0, 2, and 0 for the α_0, t_0, and $t_{0.5}$ groups, respectively. These values of the angular momentum transfer were used in the calculations. Calculations were not performed for the α_6 and α_7 groups because of the composite nature of these groups and the corresponding ambiguity in the choice of transfer angular momenta.

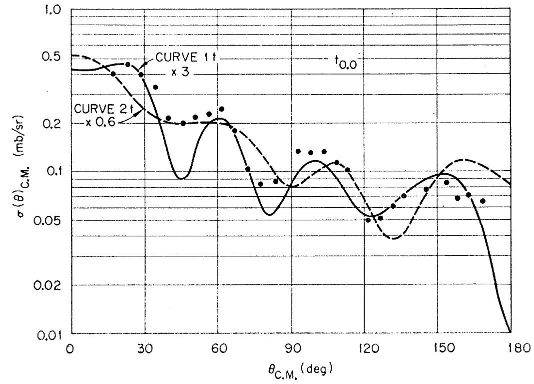

FIG. 6. Comparisons of the DWBA calculated angular distributions with the experimental data for the ground-state triton group from the $F^{19}(p,t)F^{17}$ reactions.

DISCUSSION

It was previously pointed out that the $F^{19}(p,\alpha)O^{16}$ reaction exhibits resonances in the energy region between 3 and 12 MeV,[5] and that significant variations in the total cross section are observed for energies up to 18 MeV.[7] Since the present measurements were made at only one energy, one cannot be certain that compound nucleus processes did not affect the observed angular distributions (even at 22.8 MeV). However, the rapid variation of the differential cross sections with angle, even at large angles, certainly indicates that both the $F^{19}(p,\alpha)O^{16}$ and the $F^{19}(p,t)F^{17}$ reactions leading to the low-lying levels in the residual nuclei proceed predominately by direct processes at this energy.

In view of the possible cluster configurations of the nuclei involved in both reactions, it is possible for these reactions to proceed by exchange processes, as well as a pickup process. Although the knockout component of the exchange interactions might be difficult to distinguish from the pickup component on the basis of angular distribution measurements alone, the heavy-particle stripping component would be expected to lead

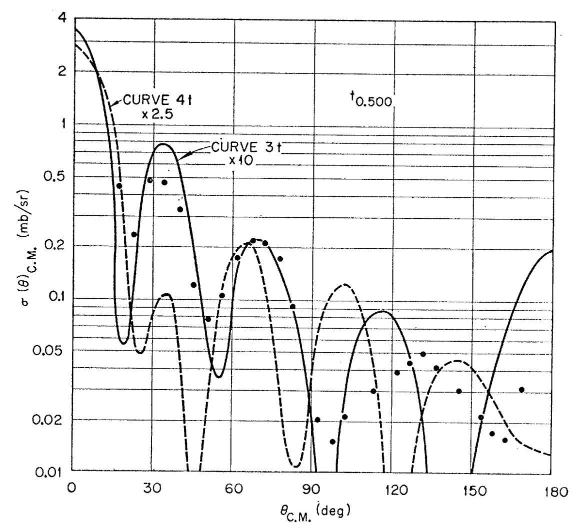

FIG. 7. Comparisons of the DWBA calculated angular distributions with the experimental data for the first excited state triton group from the $F^{19}(p,t)F^{17}$ reaction.

to structure at large angles and thus might be more easily identified.

Since none of the observed angular distributions (Figs. 3 or 4) exhibit pronounced peaks at large angles, it appears that the heavy-particle stripping contribution is small. Hence, an attempt was made to fit these data with DWBA calculations by using only a pickup process. The curves in Fig. 5 suggest that the angular distribution for the $F^{19}(p,\alpha_0)O^{16}$ reaction could very likely be fitted with such calculations if a more thorough search of the parameters were made.[12] The calculated curves in Fig. 6 fit the experimental data for the $F^{19}(p,t_0)F^{17}$ reaction rather well, even at large angles; in spite of the limited number of calculations performed for the $F^{19}(p,t_{0.5})F^{17}$ reaction, the curves in Fig. 7 seem to reproduce some of the general features of the data.

In almost every case the normalized, calculated angular distributions have greater yields at large angles than the experimental data. Thus, on the basis of the present experiment, there is no indication of heavy-particle stripping for either the $F^{19}(p,\alpha)O^{16}$ or $F^{19}(p,t)F^{17}$ reactions.

Warsh and Edwards[13] have been able to fit the present data for the $F^{19}(p,\alpha_0)O^{16}$ reaction rather well with a plane-wave calculation by using an exchange interaction model which includes pickup and heavy-particle stripping (the knockout contribution is not taken into account in their calculations). However, they find that the best fits to the data are obtained with only a very small contribution from the heavy-particle stripping component and that plane-wave pickup calculations by themselves fit the data almost as well as the exchange calculations.

In spite of the possible cluster configurations of F^{19}, it may not be surprising to find a negligible heavy-particle stripping contribution for the $F^{19}(p,\alpha)O^{16}$ and $F^{19}(p,t)F^{17}$ reactions, particularly for reactions leading to low-lying levels of the residual nuclei with an incident-proton energy of 22.8 MeV. At this energy, however, it is possible that the knockout interaction is important, even though heavy-particle stripping is not, because of the difference in the interaction mechanisms of these two processes.[8] (In this connection it is noted that rather large cross sections have been observed for the $F^{19}(d,Li^6)N^{15}$ reaction[14] which suggest a large reduced width for α-clusters in F^{19}.) More detailed calculations with less variation of parameters will be required to differentiate between pickup and knockout processes in the $F^{19}(p,\alpha)O^{16}$ and $F^{17}(p,t)F^{17}$ reactions. Since these processes involve different cluster configurations of the target nucleus, one, of course, cannot obtain reliable information about the structure of the nuclei from such reactions until the question of the mechanism has been answered.

It is hoped that the finite range calculations[15] now in progress will allow one to distinguish between knockout and pickup; however, it may be necessary to include more detailed information about the internal wave functions of the particles.

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[12] Very recent calculations have shown that finite range effects are particularly significant for reactions such as the $F^{19}(p,\alpha_0)O^{16}$ reaction where the momentum transfer is very large. R. M. Drisko (private communication).

[13] K. L. Warsh and S. Edwards (private communication).

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[15] N. Austern, E. C. Halbert, R. M. Drisko, and G. R. Satchler, Phys. Rev. (to be published).