Study of the $F^{19}(p,\alpha_0)O^{16}$ Reaction with 3- to 12-MeV Protons*†

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The reaction $F^{19}(p,\alpha_0)O^{16}$ was studied with 3- to 12-MeV protons. Angular distributions were measured at 23 energies. Excitation curves were measured at 70°and 165° over wide energy ranges. The angular distributions show a great variety of shapes, with combinations of forward and backward peaking. The excitation curves have considerable structure, but the structure is not fine enough to be interpreted as individual compound-nucleus levels. Direct-reaction analysis of the angular distributions was only partially successful, indicating that the reaction mechanism is more complicated.

INTRODUCTION

A NUMBER of studies have been performed on the $F^{19}(p,\alpha_0)O^{16}$ reaction with protons above 3 MeV.[1–8] Angular distributions show a wide variation of shapes in this region and the angular distribution at 11 MeV shows large backward peaking.[6] In this study we covered the range from 3- to 12-MeV proton energy (tandem precision) and measured 23 angular distributions as well as several excitation curves.

Because of the forward and backward peakings observed in the angular distributions, it was felt that a direct-reaction analysis should be attempted; the only complete theory that might explain such pronounced peakings would have to consider the coherent mixing of pickup and heavy-particle-stripping reaction mechanisms.[9,10]

We were aware from the outset that such a triton pickup reaction would be inherently more complicated than single-nucleon transfer reactions such as (d,p) and (p,d), because of additional degrees of freedom and generally less available nuclear structure information. Conversely, this type of reaction needs clearly to be tested as a spectroscopic tool before it can yield trustworthy information on nuclear models, especially the cluster model.

The case of F^{19} seemed particularly suited to such a study because of its clear doubly closed-shell plus triton structure, on the one hand, and its N^{15} plus alpha nature, on the other hand, the latter indicated by the nearness of the $\frac{1}{2}^-$ excited state to the ground state of F^{19}. Hence, the necessary ingredients for both direct-reaction modes are present in this target nucleus.

Unfortunately, the excitation function for the reaction is not at all smoothly varying with energy, a criterion which is usually applied when deciding to make a direct reaction interpretation for a given reaction. In fact, many of the strongly fluctuating features observed as a function of the bombarding energy at a fixed angle persist when integrating over angles, thus strongly indicating some compound-nucleus formation. Some recent work on the $F^{19}(p,n)Ne^{19}$ reaction in the same energy region,[11] measuring residual activity and, hence, total cross sections, shows these fluctuations in even greater detail. Ericson[12] has recently given considerable attention to the situation of high compound-nuclear level densities and its implications as to fluctuations in cross section, departures from fore-and-aft symmetry for angular distributions, etc. It is not clear whether a

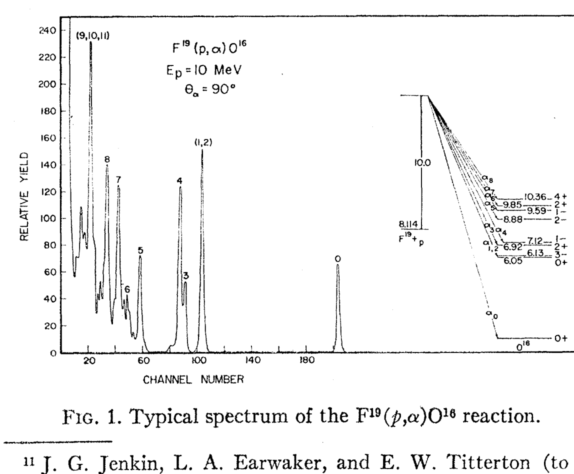

FIG. 1. Typical spectrum of the $F^{19}(p,\alpha)O^{16}$ reaction.

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[1] E. B. Teplov, O. P. Shevchenko, and E. K. Ruuge, Zh. Eksperim. i Teor. Fiz. **39**, 923 (1960) [translation: Soviet Phys.—JETP **12**, 640 (1961)].
[2] S. Yamashita, J. Phys. Soc. Japan **16**, 2378 (1959).
[3] J. G. Likely and F. P. Brady, Phys. Rev. **104**, 118 (1956).
[4] W. A. Ranken, T. W. Bonner, and J. H. McCrary, Phys. Rev. **109**, 1646 (1958).
[5] H. D. Holmgren and C. B. Fulmer, Bull. Am. Phys. Soc. **8**, 26 (1963).
[6] H. Ogata, J. Phys. Soc. Japan **14**, 707 (1959).
[7] K. L. Warsh, H. R. Blieden, and G. M. Temmer, Bull. Am. Phys. Soc. **7**, 300 (1962).
[8] G. M. Temmer, in *Proceedings of the International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padua, 1962* (to be published).
[9] L. Madansky and G. E. Owen, Phys. Rev. **99**, 1608 (1955); G. E. Owen and L. Madansky, *ibid.* **105**, 1766 (1957).
[10] S. Edwards, in Proceedings of the International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padua, 1962 (to be published).
[11] J. G. Jenkin, L. A. Earwaker, and E. W. Titterton (to be published).
[12] T. Ericson, Advan. Phys. **9**, 425 (1960).

nucleus as light as ours appropriately lends itself to his interpretation. We have tried to go as far as it is possible with a less complete theory, namely, one which deals only with the direct reaction aspects of the process. Details of an extensive plane-wave analysis will be published at a later date.

EXPERIMENTAL TECHNIQUES

The beam of protons from our Tandem Van de Graaff generator[13] passed through a thin carbon foil coated by evaporation of CaF_2, and stopped in a Faraday cup. The presence of carbon and calcium did not affect the spectrum since the Q values for the (p,α) reactions on calcium and carbon are large and negative. The alpha particles were detected with p-type silicon junction counters of resistivity and bias chosen in such a way that alpha particles left pulses proportional to their full energy, while protons produced pulses much smaller than those corresponding to their energy.

Figure 1 shows a typical pulse-height spectrum of the reaction. The large peak at the left corresponds to the protons. The true zero of this spectrum is 64 channels to the left of the indicated zero. The first and second excited state groups are unresolved since they differ by only 80 keV in excitation energy. The third and fourth excited state groups are only partially resolved, there being only 200-keV excitation energy difference between them. The limit of resolution shown here is about 60 keV, limited mostly by the detector and electronics. The intrinsic beam-energy spread and target thickness account for only a few kilovolts. The fifth, sixth, seventh, and eighth excited states are seen partially resolved. The remaining small peaks are unidentified and may be due to inelastic proton groups. Because of the problem of resolution, yield data were obtained only for the ground-state group. No new levels in O^{16} were seen; the known level scheme is shown at the right of Fig. 1.

The absolute cross sections were measured in a gas cell at known pressure with CF_4 (Freon 12). The geometry of the cell was calibrated using the $He^4(p,p)He^4$ absolute cross sections of Miller and Phillips.[14] Our absolute cross-section scale is believed known to at least $\pm 20\%$.

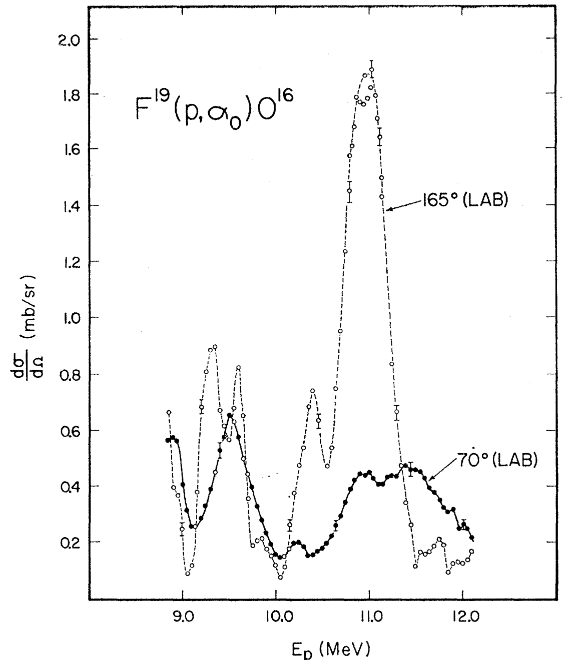

FIG. 3. Comparison of the excitation functions of $F^{19}(p,\alpha_0)O^{16}$ at 70° (lab) and 165° (lab) between 8.8- and 12.2-MeV proton energy.

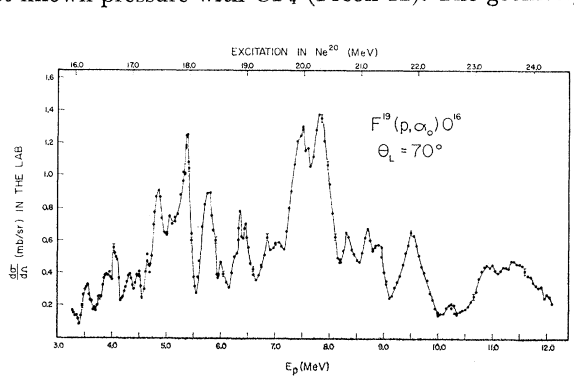

FIG. 2. Excitation function of $F^{19}(p,\alpha_0)O^{16}$ at 70° (lab) between 3.3- and 12.2-MeV proton energy.

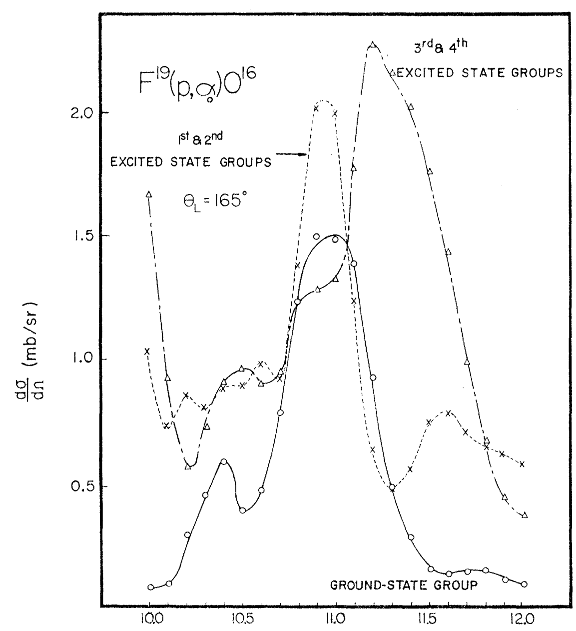

FIG. 4. Relative yields of the ground-state group and excited state groups at 165° (lab) for $F^{19}(p,\alpha)O^{16}$ between 10- and 12-MeV proton energy.

[13] High Voltage Engineering Corporation, Burlington, Massachusetts.

[14] P. D. Miller and G. C. Phillips, Phys. Rev. **112**, 2043 (1958).

EXPERIMENTAL RESULTS

The excitation curve for the $F^{19}(p,\alpha_0)O^{16}$ reaction at 70° (lab) from 3.2 to 12.2 MeV is shown in Fig. 2. Because of the interest in the large backward peaking at 11 MeV an excitation curve at 165° (lab) was measured from 9 to 12 MeV and is shown in Fig. 3. The peaking at the backward angle is centered about 11 MeV with about 700-keV width at half-height. There is no sign of a resonance in the 70° excitation curve at this energy. In order to determine if this is a compound-nucleus reaction the excitation curves for the first and second excited states (unresolved) and the third and fourth excited states are shown in Fig. 4. A peak is seen in the first and second excited states group which corresponds in energy to the ground-state group peak.

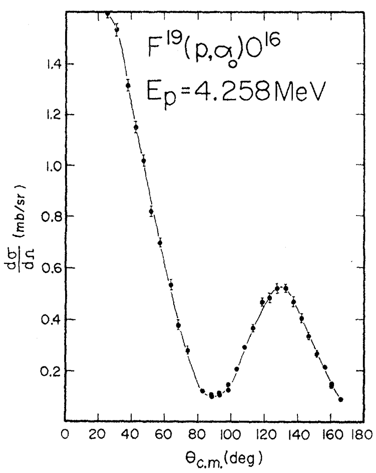

FIG. 5. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 4.258-MeV proton energy. The excitation of the compound system at this energy corresponds to the excitation of the compound system of the $O^{16}(\alpha,\alpha)O^{16}$ angular distribution at 15.20-MeV alpha energy of Mehta (see Ref. 15).

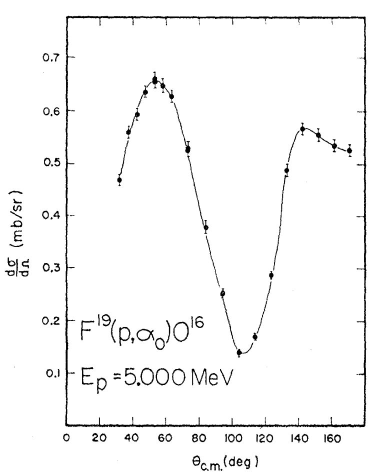

FIG. 6. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 5.000-MeV proton energy.

Angular distributions were measured at 23 energies from 4.258 to 12.250 MeV. Some energies were selected to correspond to those of other studies, and some to correspond in excitation of the compound system to the $O^{16}(\alpha,\alpha)O^{16}$ angular distribution data of Mehta.[15]

Figures 5 through 18 show some of the angular distributions of the $F^{19}(p,\alpha_0)O^{16}$ reaction, between

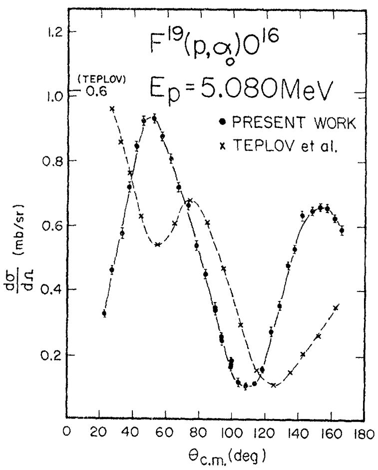

FIG. 7. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 5.080-MeV proton energy. Comparison is shown to the angular distribution of Teplov *et al.* (see Ref. 1) at this energy. The scale has been adjusted to give a better comparison of the shapes of curves.

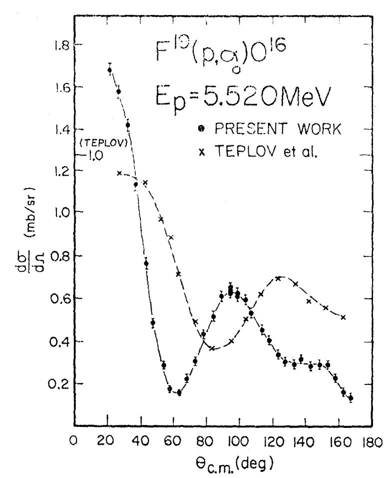

FIG. 8. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 5.520-MeV proton energy. Comparison is shown to the angular distribution of Teplov *et al.* (see Ref. 1) at this energy. The scale has been adjusted to give a better comparison of the shapes of the curves.

4.258-MeV and 12.000-MeV proton energy. Figures 7, 8, and 9 contain comparisons with the data of Teplov *et al.*[1] The absolute scales in the work of other authors have been adjusted to facilitate comparison of the curve shapes. We note large discrepancies from the work of

[15] M. K. Mehta, Ph.D. dissertation, Florida State University, 1962 (unpublished).

Teplov *et al.*, which was carried out with a cyclotron beam and beam-energy degrading foils; better agreement could be obtained if it is assumed that the nominal energies used by Teplov *et al.* were about 300 keV too low.

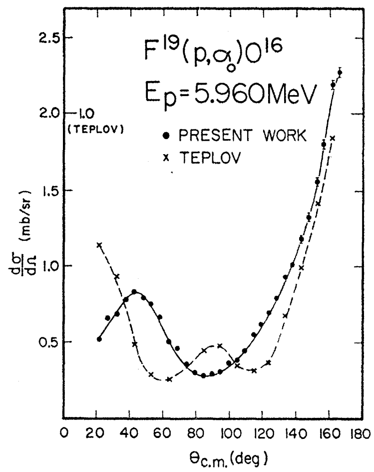

FIG. 9. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 5.960-MeV proton energy. Comparison is shown to the angular distribution of Teplov *et al.* (see Ref. 1) at this energy. The scale has been adjusted to give a better comparison of the shapes of the curves. The excitation of the compound system at this energy corresponds to the excitation of the $O^{16}(\alpha,\alpha)O^{16}$ angular distribution at 17.22-MeV alpha energy of Mehta (see Ref. 15).

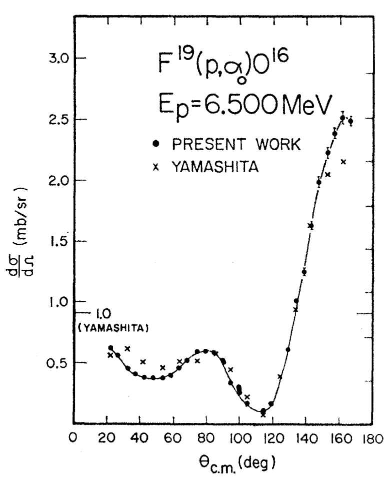

FIG. 10. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 6.500-MeV proton energy. Comparison is shown to the angular distribution of Yamashita (see Ref. 2) at this energy. The scale has been adjusted to give a better comparison of the shapes of the curves.

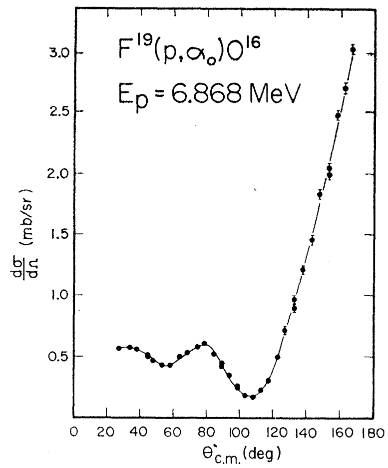

FIG. 11. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 6.868-MeV proton energy. The excitation of the compound system at this energy corresponds to the excitation of the compound system of the $O^{16}(\alpha,\alpha)O^{16}$ angular distribution at 18.30-MeV alpha energy of Mehta (see Ref. 16). The $F^{19}(p,\alpha_0)O^{16}$ angular distribution of Yamashita (see Ref. 2) at 6.9 MeV is comparable since his energy is only known to within 100 keV.

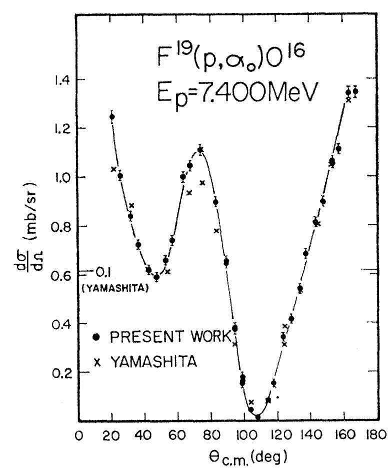

FIG. 12. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 7.400-MeV proton energy. Comparison is shown to the angular distribution of Yamashita (see Ref. 2) at this energy. The scale has been adjusted to give a better comparison of the shapes of the curves. Within the limit of his experimental error the excitation of the compound system at this energy corresponds to the excitation of the compound system of the $O^{16}(\alpha,\alpha)O^{16}$ angular distribution at 18.90-MeV alpha energy of Mehta (see Ref. 15).

Figures 10 and 12 show comparisons to the data of Yamashita[2]; the agreement is quite good. Figure 19 shows a three-dimensional plot of the angular distributions from 9.000 to 12.250 MeV. Our angular distributions at 8.000, 9.000, 10.000, 11.000, and 12.000 MeV are compared to those of Ogata[6] at these energies. Excellent agreement is found for all of these energies except 12.000 MeV, where discrepancies exist at the forward angles. Table I shows the normalization factors used to adjust the scales of these angular distributions for comparison. The absolute scales of Teplov *et al.*, Yamashita, and Ogata were all obtained using polytetrafluoroethylene foils of supposedly known thickness, and measurements of geometry and absolute charge. Ogata has reported a correction to his original scale owing to a remeasurement of his solid angle.[16]

[16] H. Ogata, H. Itoh, Y. Matsuda, K. Takamatsu, M. Kawashima, A. Masaike, and I. Kumabe, J. Phys. Soc. Japan **15**, 1719 (1960).

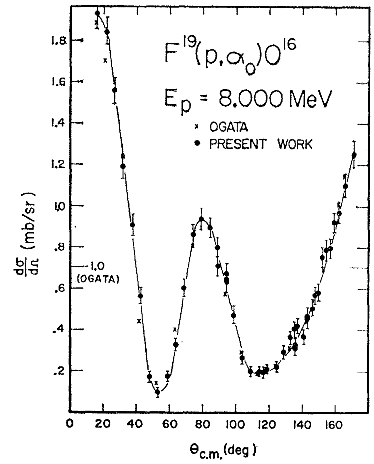

FIG. 13. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 8.000-MeV proton energy. Comparison is shown to the $F^{19}(p,\alpha_0)O^{16}$ angular distribution of Ogata (see Ref. 6) at this energy. The scale has been adjusted to give a better comparison of the shapes of the curves.

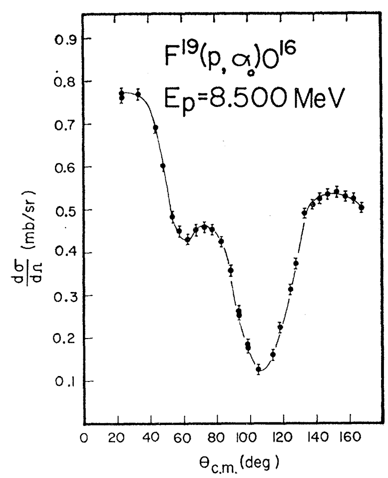

FIG. 14. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 8.500-MeV proton energy.

Figure 20 shows a plot of the positions of maxima and minima in the angular distributions as a function of energy. The present work is compared to the work of Holmgren,[5] Likely and Brady,[3] Ogata,[6] Clarke and Paul,[17] and Isoya *et al.*[18] It may be seen that there are certain regularities in the positions of the maxima and minima at the higher energies. The angular distributions were integrated to obtain total (p,α_0) cross sections and a plot is shown in Fig. 21. Resonances are seen to occur at 9.5 and 11.0 MeV.

It has been asserted[12] that if angular distributions from a compound nucleus reaction including many states show lack of symmetry about 90° (c.m.) then by averaging these angular distributions over a wide range of energies, the symmetry can be reestablished. To this end, we averaged 12 angular distributions over a 2.5-MeV interval. The result is shown in Fig. 22; there is no symmetry about 90°.

DISCUSSION OF RESULTS

The following general observations can be made concerning these 23 angular distributions: (1) The number of maxima and minima increases with increasing energy. (2) The positions of the maxima and minima become more clearly defined with increasing energy. (3) Angular distributions at minima in the total cross sections show forward peaking. (4) Backward

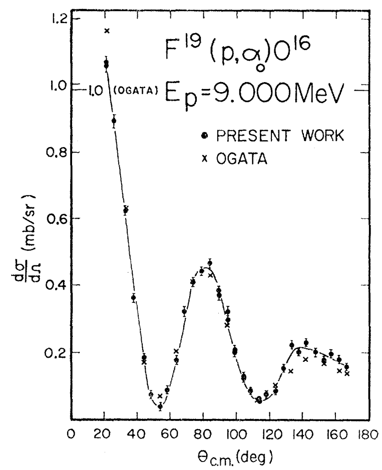

FIG. 15. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 9.000-MeV proton energy. Comparison is shown to the $F^{19}(p,\alpha_0)O^{16}$ angular distribution of Ogata (see Ref. 6) at this energy. The scale has been adjusted to give a better comparison of the shapes of the curves.

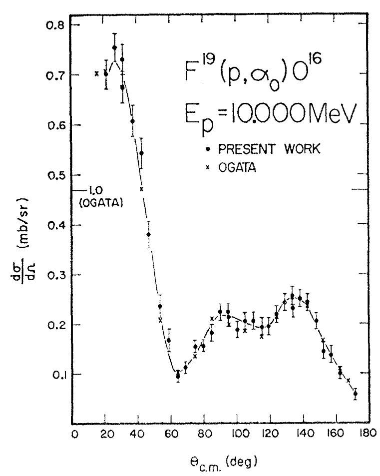

FIG. 16. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 10.000-MeV proton energy. Comparison is shown to the $F^{19}(p,\alpha_0)O^{16}$ angular distribution of Ogata (see Ref. 6) at this energy. The scale has been adjusted to give a better comparison of the shapes of the curves.

[17] R. L. Clarke and E. B. Paul, Can. J. Phys. **35**, 155 (1957).
[18] A. Isoya, H. Ohmura, and T. Momoto, Nucl. Phys. **7**, 116 (1958).

peaking in the angular distributions is associated with maxima in the total cross section. Item 4 above can be cited as evidence for the hypothesis that backward peaking can be produced by a compound-nucleus mechanism.[19] Also since the excitation curve for the first and second excited state groups exhibits a resonance at the same place as the resonance with the largest backward peaking in the ground-state group, there is further evidence for a compound-nucleus mechanism.

Because of the forward- and backward-peaking features of the angular distributions a direct-reaction analysis was attempted. First, a distorted-wave Born-approximation analysis in terms of triton pickup, using "reasonable" optical-potential distortions, was unable

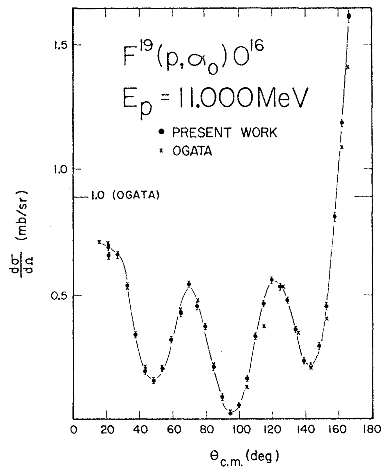

FIG. 17. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 11.000-MeV proton energy. Comparison is shown to the $F^{19}(p,\alpha_0)O^{16}$ angular distribution of Ogata (see Ref. 6) at this energy. The scale has been adjusted to give a better comparison of the shapes of the curves.

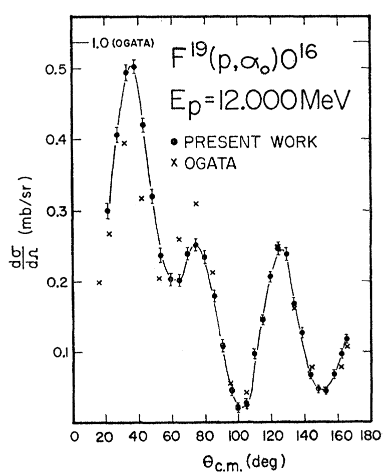

FIG. 18. Angular distribution of $F^{19}(p,\alpha_0)O^{16}$ at 12.000-MeV proton energy. Comparison is shown to the $F^{19}(p,\alpha_0)O^{16}$ angular distribution of Ogata (see Ref. 6) at this energy. The scale has been adjusted to give a better comparison of the shapes of the curves.

[19] H. R. Blieden, Phys. Letters 3, 257 (1963).

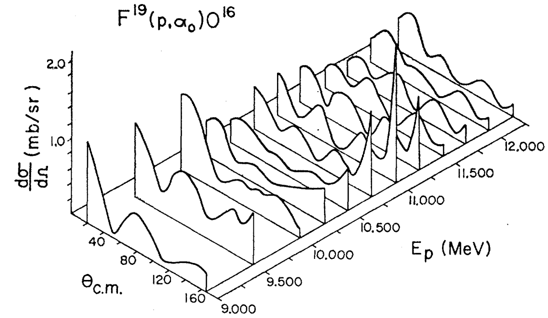

FIG. 19. Cross section of $F^{19}(p,\alpha_0)O^{16}$ as a function of proton energy and angle between 9.000 and 12.250 MeV.

TABLE I. Ratio of average absolute cross sections measured by others to present work.

Proton energy (MeV)	Ogata[a]	Yamashita[b]	Teplov *et al.*[c]
12.000	1.86		
11.000	1.21		
10.000	2.11		
9.000	1.01		
8.000	1.40		
7.400		1.61	
6.500		1.09	
5.960			0.50
5.520			0.80
5.080			0.60

[a] See Ref. 6.
[b] See Ref. 2.
[c] See Ref. 1.

to account for our results even in crude, qualitative fashion, especially with respect to reproducing the large backward peaks.[20] The heavy-particle-stripping mechanism, where the projectile proton is not part of the outgoing alpha, was considered to be the only direct mechanism which might produce such a large backward peak. Since there was also forward peaking it was necessary to use a more complete direct reaction theory incorporating coherent mixing of both pickup and heavy-particle-stripping modes. This theory has only been formulated with plane waves to date, and is called the plane-wave Born approximation with exchange (PWBAE).[10]

The expression for the differential cross section in the PWBAE theory contains three additive parts which correspond to the pickup, exchange or heavy-particle-stripping (HPS), and interference terms. The analysis is carried out by the simultaneous adjustment of five free parameters (or six if the scale factor is included). The scale factor is not predicted in this theory. The five parameters are the mixing ratio for the two modes of reaction, and interaction radii for the particles and nuclei involved. Because of this large number of parameters a search program for a computer was difficult to write, and indeed, a good one was never

[20] We are indebted to G. R. Satchler and co-workers for this private communication.

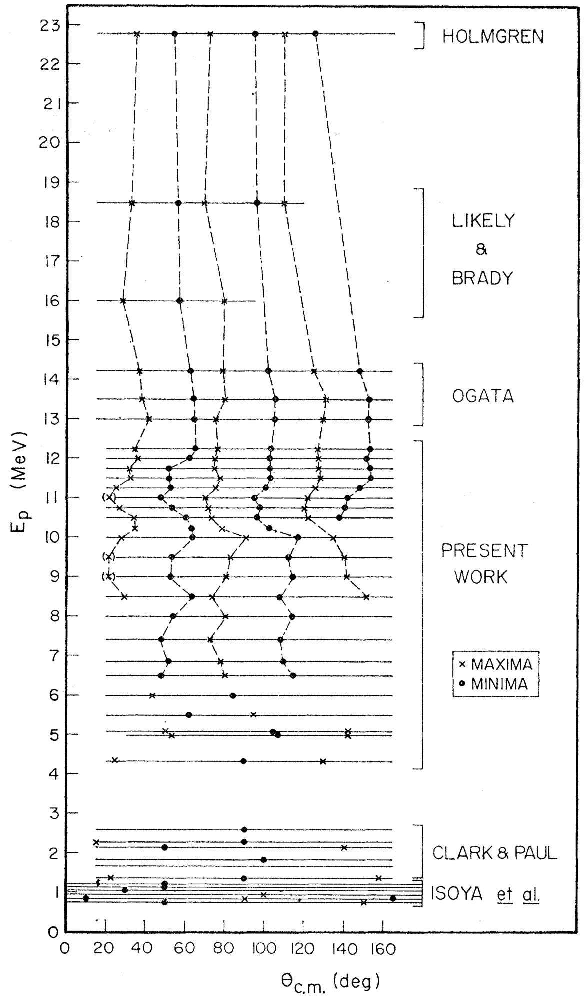

FIG. 20. The positions of the maxima and minima in the angular distributions of $F^{19}(p,\alpha_0)O^{16}$ as a function of proton energy. For work of other authors, see Refs. 3, 5, 6, 17, and 18.

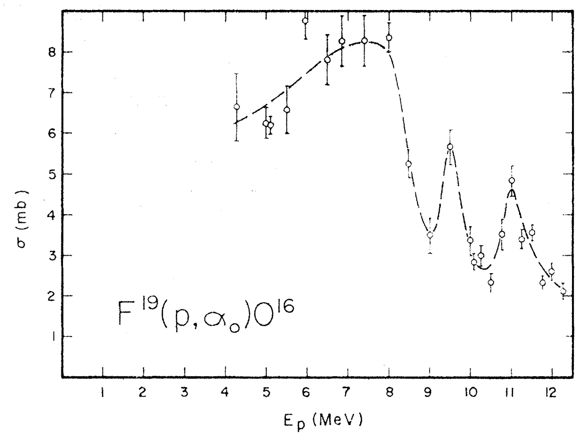

FIG. 21. Total integrated cross section for $F^{19}(p,\alpha_0)O^{16}$.

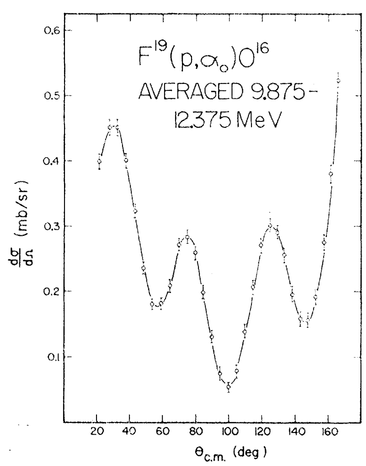

FIG. 22. Averaged $F^{19}(p,\alpha_0)O^{16}$ angular distribution for 9.87- to 12.3-MeV protons.

found. Some partial fits were found but in general no physically meaningful set of parameters could be located that would fit all angular distributions.

The best fits were obtained at energies where the total cross section was at a minimum, and at lower energies where the shapes of the angular distributions are relatively simple and fittings are not so sensitive. The fits found at minima in the cross section are further evidence for the presence of some compound reaction mechanism at maxima in the total cross section.

In a recent publication,[19] Blieden has been successful in specifically accounting for the strongly backward-peaked angular distributions observed in the neighborhood of 11 MeV, invoking two interfering compound-nucleus states of opposite parities, in combination with some direct triton pickup at the forward angles (neglecting interference terms). If this is indeed what actually occurs in this reaction, it illustrates drastically the general complexity of the interpretation of reactions of this type in our energy region.

It is concluded that (1) the reaction mechanism here is probably a complicated mixture of processes, (2) a more accurate distorted-wave Born-approximation direct-reaction theory with exchange would be desirable, and most of all, (3) a direct reaction-compound-nucleus interference calculation should be made when the state of reaction theory permits it.

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