The $l_p=1$ assignment is in agreement with the assumed spin and parity of the ground state of N^{13}.[7] The zeros of the theoretical curve are in good agreement with the minima of the experimental curve and the amplitude of the strong forward peak is accounted for reasonably well.

In Fig. 11 these data are compared with the data of Wegner and Hall[4] at 21.0 and 24.0 Mev. As seen, the angular distributions do not change radically in this energy interval and the minima show a systematic shift toward smaller angles as the bombarding energy is increased. If, as is true for most simple direct-interaction theories, the angular dependence is contained in some function of Qr_0, then, assuming that r_0 is constant, the value of Q for a given minimum should be independent of energy. Inspection of Table I shows that the values of Q for a given minimum are nearly independent of energy in this energy range. This leads one to believe that the reaction does indeed proceed by a simple direct process and that the angular distributions will be explained in more detail by a more sophisticated expression.

SUMMARY

Using a crude theory for the $C^{12}(He^3,p_i)N^{14}$ reaction, the angular distributions were fitted by simple $[j_L(Qr_0)]^2$ functions. In fitting these data an effort was made to correlate the minima in the experimental angular distributions with the zeros of $j_L(Qr_0)$ and to keep the interaction radius reasonably constant. This was done with good success using interaction radii of 6.0, 5.7, and 5.7 fermis and $L=2$, 0, and 0 for the p_0, p_1, and p_2 angular distributions, respectively. The theoretical curves, however, grossly underestimate the experimental intensity in the forward angles of the p_1 and p_2 angular distributions. If more freedom is allowed for the value of the interaction radius, the forward part of these experimental curves can be accounted for, but the over-all agreement is vastly reduced.

The $C^{12}(He^3,d_0)N^{13}$ data were compared with Butler's theory[8] for the stripping of a proton from the He^3 nucleus. Good agreement between the zeros of the theoretical curve and the minima of the experimental curve was obtained, though the latter were not always well defined, and the shape of the experimental curve was accounted for reasonably well.

It is expected that just as for (d,p) and (d,n) stripping reactions, more detailed analyses, especially the distorted wave calculations, will remedy some of the deficiencies of the simple stripping theories used here.

ACKNOWLEDGMENTS

The authors take pleasure in expressing their appreciation to Mr. F. Hobaugh and Mr. K. Runck for the cyclotron bombardments, to Mr. J. Moore for his advice and help on the mechanical problems, and to Mr. W. D. Ploughe for his aid in the planning and execution of these experiments.

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Angular Distributions for $C^{12}(\alpha,p)N^{15}$ at 16.1–19.0 Mev and $F^{19}(\alpha,p)Ne^{22}$ at 18.9 Mev*

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Angular distributions have been measured for the reactions $C^{12}(\alpha,p)N^{15}$ and $F^{19}(\alpha,p)Ne^{22}$ using the cyclotron 19-Mev alpha-particle beam. The $C^{12}(\alpha,p_0)N^{15}$ data at 18.0, 17.1, and 16.1 Mev differ markedly from the 19.0-, 18.7-, and 18.3-Mev data; the latter three are very similar to each other. The differential excitation function at 31.8° (lab) shows a resonance at 17.5 Mev with a width at half-maximum of ~2 Mev. Steep backward peaking is observed in the 16.1-Mev data. Some of the features of the 17.1- and 18.0-Mev data can be represented by Butler's formula for (α,p) reactions using $l=1$ and $r_0=5.9$ and 5.5f, respectively. For the $F^{19}(\alpha,p)Ne^{22}$ data the cross sections for the transition to the ground state of Ne^{22} are factors of 10 to 20 less than the cross sections for the transition to the first excited state of Ne^{22}. This inhibition, together with the $F^{19}(n,d)O^{18}$ data, may be explained by assuming that the two last neutrons of F^{19} are not disturbed in the direct interactions and that they are in a $(d_{5/2}{}^2)_0$ configuration in Ne^{22}, in a $(d_{5/2}{}^2)_2$ or $(s_{1/2}{}^2)_0$ configuration in F^{19}. Using $r_0=5.1$f, Butler's formula accounts reasonably well for the forward peak and the location of the minima of all three angular distributions for the region of angles less than 90°. The angular distributions are all peaked in the backward angles.

INTRODUCTION

THE proton angular distributions to be reported here are the first of a series of measurements using low and medium Z target nuclei and the 19-Mev alpha-particle beam from the Purdue cyclotron in which an endeavor is being made to determine the magnitude

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of direct-interaction contributions at this energy. Efforts are being made to establish some systematics over a fairly wide range of target nuclei and to analyze the angular distributions in the light of current direct-interaction theories. Attempts are also being made to correlate the data with the predictions of the shell model for the configurations of the nuclei involved.

The angular distributions of the ground-state proton group (p_0) from the reaction $C^{12}(\alpha,p)N^{15}$ for alpha-particle energies between 30 and 40 Mev[1–4] (Fig. 4) have given strong evidence for the direct-interaction mechanism. For energies between 25 and 30 Mev[1] (Fig. 4) some of the direct-interaction character seen at the higher energies is still present but the angular distributions become more energy dependent. The most significant departure from the simple direct-interaction mechanism as visualized, for example, by Butler,[4] is the steep backward peaking which is observed from about 25 to 31 Mev. In order to study the trend of the angular distributions and the direct-interaction contribution at lower energies, we have measured the angular distribution for alpha-particle energies of 19.0, 18.7, 18.3, 18.0, 17.1, and 16.1 Mev.

The $F^{19}(\alpha,p)Ne^{22}$ reaction has been studied by Pieper and Heydenburg[5] for five alpha-particle energies between 6.0 and 6.55 Mev. The angular distributions of the p_0 and p_1 groups, the latter leaving Ne^{22} in its first excited state, were found to be very energy dependent. At some energies the angular distributions showed striking agreement with predictions based on simple direct-interaction mechanisms, whereas there was no resemblance at certain other energies. For a higher bombarding energy one might expect that the direct-interaction character which was observed by Pieper and Heydenburg at selected energies would be better represented. Thus we have measured the angular distributions of the p_0, p_1, and p_2 groups for an energy of 18.9 Mev.

Where feasible, the theory of (α,p) reactions as derived by Butler[4] has been applied to the data presented here. The theoretical curves are calculated from Eq. (40) of reference 4. The form of the Wronskian function used is that given by Butler.[6]

EXPERIMENTAL METHODS

The experimental setup and proton detection technique have been described previously.[7] The rms energy deviation from the nominal alpha-particle energy due to finite geometry and imperfect focusing was 50 kev. Commercial targets of Teflon,[8] $(CF_2)_n$, 2.7 mg/cm^2 thick and polyethylene,[9] $[(CH_2)(CH_2)]_n$, 1.3 mg/cm^2 thick were used as the F^{19} and C^{12} targets, respectively. The Teflon and polyethylene targets were, respectively, 0.73 Mev and 0.48 Mev thick for 19-Mev alpha particles.

The proton groups for the transitions studied were, in general, clearly resolved. There were two exceptions. 1. For the $F^{19}(\alpha,p_i)Ne^{22}$ reaction it was difficult to resolve the p_0 group because of its very weak intensity and the fact that the first excited state of Ne^{22} is only 1.275 Mev above the ground state. 2. For the $C^{12}(\alpha,p_0)N^{15}$ reaction, a gamma-ray background which comes from the very intense gamma-ray flux near the collimator interfered with the low-energy protons which emerge in the backward angles. For each measurement where it was necessary to correct for the gamma-ray background, a run was made with sufficient aluminum in front of the crystal to absorb out all reaction products. The gamma-ray background recorded was then subtracted from the proton spectrum.

A preliminary proton energy scale was determined by calculating the mean energy of the proton groups using the Q values for the reaction as taken from Ajzenberg-

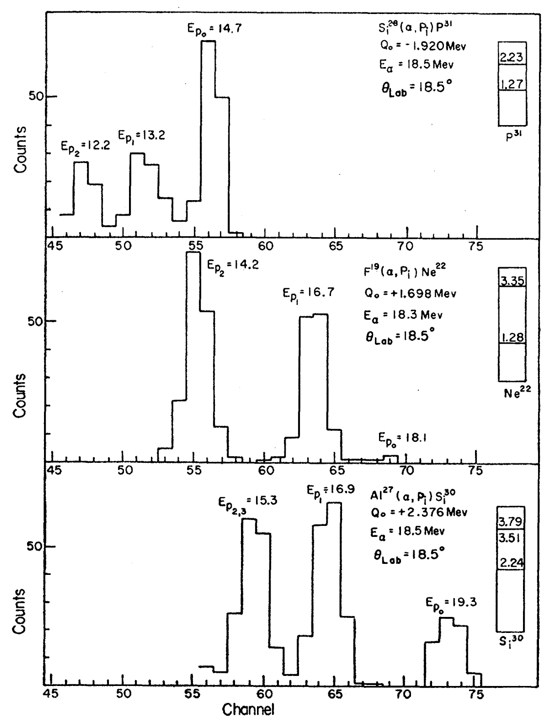

FIG. 1. Energy calibration for the reaction $F^{19}(\alpha,p)Ne^{22}$.

[1] I. Nonaka, H. Yamaguchi, T. Mikumo, I. Umeda, T. Tabata, and S. Hitaka, J. Phys. Soc. (Japan) **14**, 1260 (1959).
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[4] S. T. Butler, Phys. Rev. **106**, 272 (1957).
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[6] S. T. Butler and O. H. Hittmair, *Nuclear Stripping Reactions* (John Wiley & Sons, Inc., 1957), p. 30.
[7] J. R. Priest, D. J. Tendam, and E. Bleuler, preceding paper [Phys. Rev. **119**, 1295 (1960)].
[8] Purchased from the Dielectrix Corporation, Farmingdale, Long Island, New York.
[9] Kindly supplied by the Bakelite Corporation, Division of Union Carbide, Bound Brook, New Jersey.

Selove and Lauritsen[10] and then comparing these energies with the mean pulse heights for the groups. The energy scale was cross-checked by comparing these proton energies with calculated proton energies from other (α,p) reactions with known Q values.[10] For the $F^{19}(\alpha,p)Ne^{22}$ calibration, the protons from the reactions $Al^{27}(\alpha,p)Si^{30}$ and $Si^{28}(\alpha,p)P^{31}$ were used for the cross-check. These results are shown in Fig. 1. The p_0 group from the reaction $C^{12}(\alpha,p)N^{15}$ was identified by comparing its pulse height with the knock-on proton pulse height.

RESULTS AND DISCUSSION

$C^{12}(\alpha,p_0)N^{15}$

The angular distributions of the p_0 group from the $C^{12}(\alpha,p)N^{15}$ reaction measured for alpha-particle energies of 19.0, 18.7, 18.3, 18.0, 17.1, and 16.1 Mev (lab) are shown in Figs. 2 and 3. For illustration purposes, these data along with the data at 25 to 39 Mev[1] are shown in Fig. 4. The energies of 19.0 and 18.7 Mev were those for which maximum beam intensities were available for two different operating conditions of the cyclotron. The 18.3-Mev energy was obtained by selecting an energy somewhat lower than the maximum-beam energy. To obtain energies of 18.0, 17.1, and 16.1 Mev, the beam energy was degraded by using combinations of 0.0005-inch and 0.001-inch beryllium foils placed in front of the entrance slit to the analyzing magnet. 16.1 Mev represents the lower limit that could be used while still retaining reasonable beam intensity. For the three higher energies the counting statistics are better than 6%. For the three lower energies, where the beam intensity was low, the counting statistics are usually better than 8%. Because of the high intensity of the knock-on protons from the hydrogenic content of the targets used, it was impossible to obtain any data for angles less than about 25°.

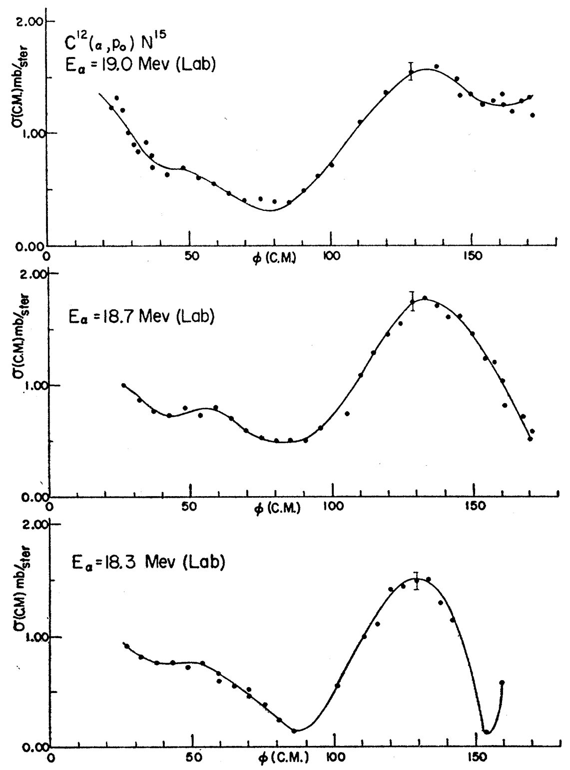

FIG. 2. Angular distributions of the p_0 group from the reaction $C^{12}(\alpha,p)N^{15}$ at 19.0, 18.7, and 18.3 Mev.

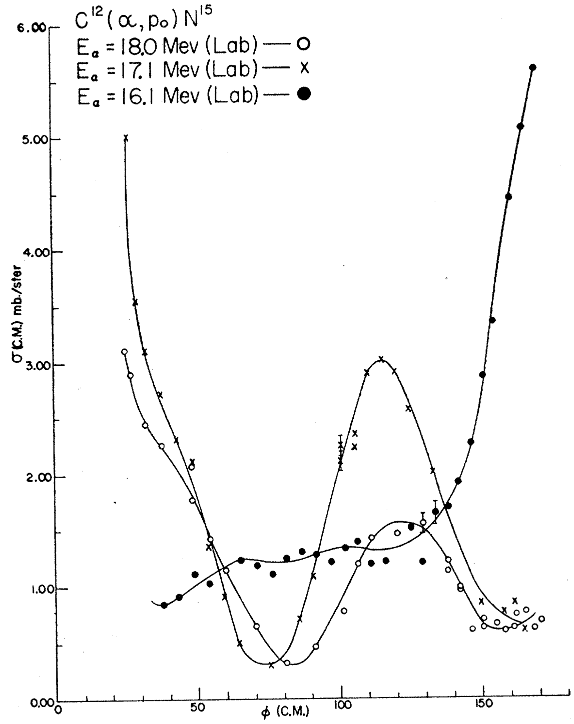

FIG. 3. Angular distributions of the p_0 group from the reaction $C^{12}(\alpha,p)N^{15}$ at 18.0, 17.1, and 16.1 Mev.

The angular distributions are seen to be very energy dependent, especially in the region of angles less than about 50° and greater than about 130°. The cross section at around 130°, where a pronounced maximum occurs at all energies except 16.1 Mev, is fairly constant except at 17.1 Mev where it is a factor of two larger. In all cases there is a minimum at around 80°, as there is at higher energies.[1] The sharp rise beyond 130° at 16.1 Mev is a characteristic which has been observed elsewhere[1–3] at higher energies. Similar effects have been recorded in this laboratory for the reactions $F^{19}(\alpha,p)Ne^{22}$ (to be presented later) and $Si^{28}(\alpha,p)P^{31}$,[11] and at other laboratories for the reactions $Al^{27}(p,\alpha)Mg^{24}$,[12] $F^{19}(p,\alpha)O^{16}$,[13] and $O^{16}(p,\alpha)N^{13}$.[14]

[10] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

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[13] H. Ogata, J. Phys. Soc. (Japan) **14**, 707 (1959).

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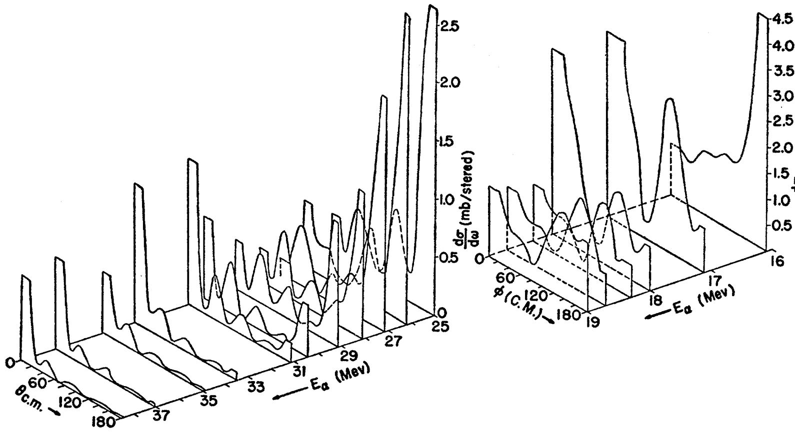

FIG. 4. Comparison of the Purdue data at 16.1–19.0 Mev with the data of the University of Tokyo at 25–39 Mev.

Because of the rapid changes in the cross section in the forward angles, the differential excitation function was measured at 31.8° (lab). The energy was varied in steps which were consistent with the energy spread of the incident beam before striking the target. The results (Fig. 5) show a pronounced resonance at about 17.5 Mev. The width of the resonance is about 2 Mev at half-maximum. Similar resonances have also been observed for this reaction at 27 and 34 Mev.[1] At the higher bombarding energies,[1] attempts were made to correlate these resonances with resonances in the total cross section. However, the total cross section varies quite smoothly and increases as the energy is decreased. Only slight bumps, if at all, appear in the total cross section versus energy curve at 27 and 34 Mev

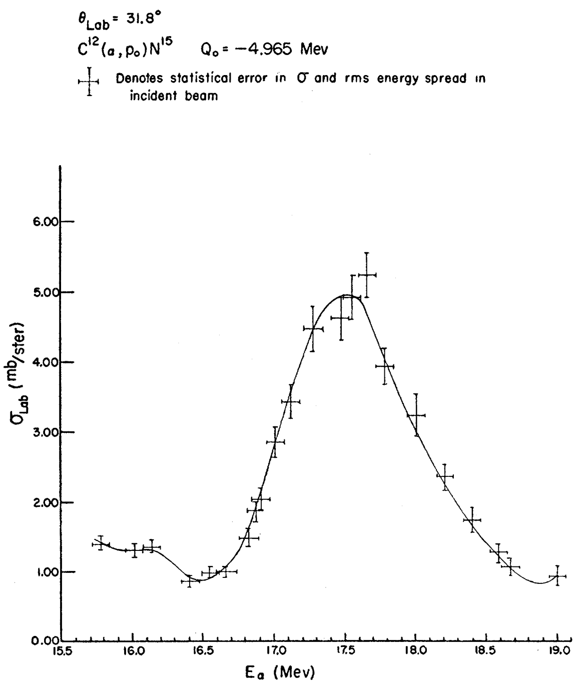

FIG. 5. Differential excitation function for the reaction $C^{12}(\alpha,p)N^{15}$ at $\theta_{lab}=31.8°$.

where the resonances in the differential cross section are in the forward angles. The data at 16.1 to 19.0 Mev were integrated over solid angle from 20° to 170°. The results are shown in Table I. To within the errors involved in excluding the contributions from angles less than 20° and greater than 170° and uncertainties in the measured differential cross sections, the systematics observed in the higher energy data are also true for this energy region. The integrated cross section increases with decreasing energy and there is a small increase at 17.1 Mev, which is near the energy for the resonance in the differential excitation function at $\theta_{lab}=31.8°$. It seems difficult to attribute these resonances to compound-nucleus formation if large resonances do not occur in the total cross section. Resonances in the differential cross section in the forward angles have also been noted for (d,p) reactions where the stripping-type character of the angular distributions was well represented.[15,16] The resonant structure for the $Si^{28}(d,p)Si^{29}$ data[16] has been interpreted as "reflecting direct interaction-compound nucleus interference effects with a dominant direct reaction amplitude." Although the direct-interaction character, as visualized in the simple theories,[4] is not as well represented in (α,p) reactions as in (d,p) reactions, the resonant structure observed in the differential cross section in the forward angles for $C^{12}(\alpha,p_0)N^{15}$ may also be due to direct interaction-compound nucleus interference or to unknown resonant processes within the direct-interaction formalism.

Butler's formula[4] for the direct knock-out of the least bound proton has been applied to the data at

TABLE I. Integrated $C^{12}(\alpha,p_0)N^{15}$ differential cross sections. The range of integration was from 20° to 170°.

E_α (Mev)	19.0	18.7	18.3	18.0	17.1	16.1
σ (mb)	7.0	7.2	5.5	9.3	13.3	11.3

[15] T. W. Bonner, J. T. Eisinger, A. A. Kraus, Jr., and J. B. Marion, Phys. Rev. **101**, 209 (1956).

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17.1 and 18.0 Mev. The theoretical curves (Figs. 6 and 7) were calculated from Eq. (40) of reference 4. The interaction radii of 5.9f for the 17.1-Mev data and 5.5f for the 18.0-Mev data compare favorably with a radius of 5.5f which was used in the analysis of the $C^{12}(\alpha,\alpha')C^{12*}$, $Q=-4.43$ Mev (2^+) data at 18.0[17] and 31.5 Mev.[18] As seen, the theoretical curves for both energies have minima in the forward angles while the experimental curves have maxima. However, the bumps in the experimental curves at $\sim 45°$ coincide with the first peaks of the theoretical curves and the positions of the second experimental and theoretical peaks coincide. If the theoretical curves are normalized to the experimental curves at $\sim 45°$ the heights of the second theoretical peaks fall below the experimental peaks. If the theoretical curves are normalized to the experimental curves at $\sim 120°$, an excellent fit is obtained beyond 90° but the theoretical curves are much too high in the forward angles. Qualitatively, the peaks which appear in both cases at $\sim 120°$ and the bumps at $\sim 45°$ can be accounted for by the simple knock-out process. However, the formula does not explain at all the forward parts of the angular distributions. The distinct difference in the theoretical and experimental curves in the very forward angles that was observed here at 17.1 and 18.0 Mev is very similar to that which was observed in this laboratory for $C^{12}(\alpha,\alpha')C^{12*}$, $Q=-4.43$ Mev (2^+) at 18.0 Mev.[17]

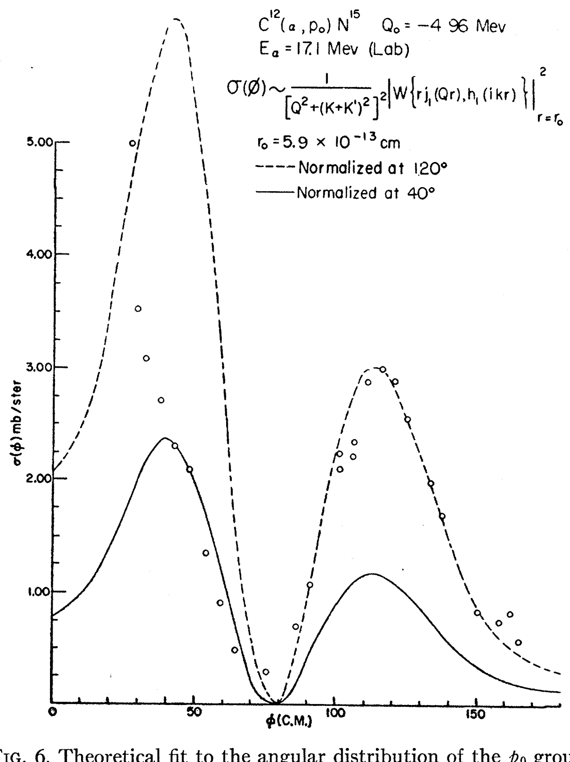

FIG. 6. Theoretical fit to the angular distribution of the p_0 group from the reaction $C^{12}(\alpha,p)N^{15}$ at 17.1 Mev.

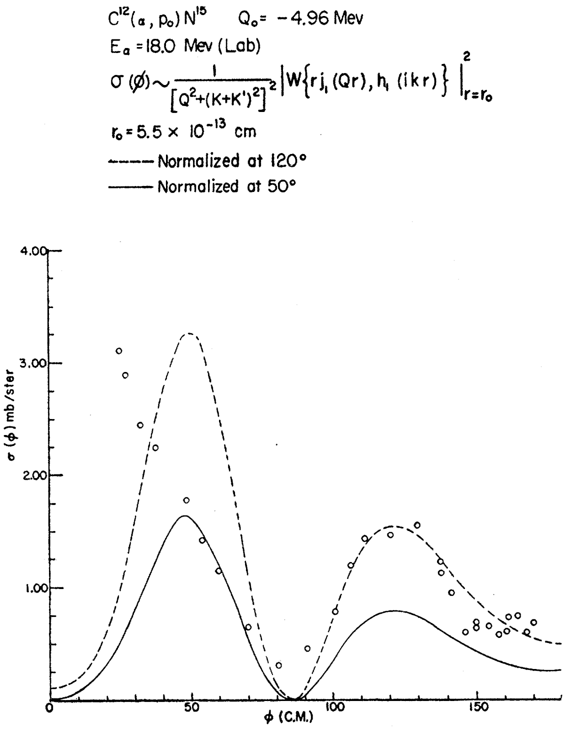

FIG. 7. Theoretical fit to the angular distribution of the p_0 group from the reaction $C^{12}(\alpha,p)N^{15}$ at 18.0 Mev.

The sharp rise in the cross section beyond $\sim 130°$ for the 16.1-Mev data (Fig. 3) is reminiscent of the heavy-particle stripping process as proposed by Madansky and Owen.[19–21] However, the steepness of the peaking cannot be accounted for in a simple manner.

$F^{19}(\alpha,p_i)Ne^{22}$

The angular distributions of the p_0, p_1, and p_2 groups from the reaction $F^{19}(\alpha,p_i)Ne^{22}$ are shown in Figs. 8, 9, and 10. The mean alpha-particle energy was 18.9 Mev. Representative errors, which include those due to counting statistics and an estimation of errors due to unfolding the peaks, are indicated on each angular distribution.

With the exception of the extreme backward angles, the transition to the 0^+ ground state is easily a factor of ten and at some angles a factor of twenty less probable than the transition to the 2^+ first excited state of Ne^{22}. Even though the statistical factor can account for a factor of five, the ground-state transition is still weak. A similar inhibition of the ground-state transition was observed in the $F^{19}(d,n)Ne^{20}$ stripping

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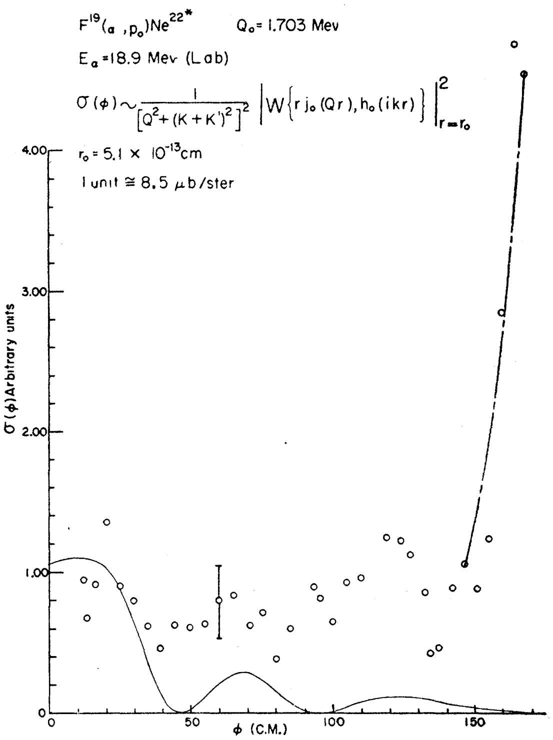

FIG. 8. Angular distribution of the p_0 group from the reaction $F^{19}(\alpha,p)Ne^{22}$ at 18.9 Mev. The broken curve is drawn to emphasize the trend in the extreme backward angles.

reaction.[22,23] In the $F^{19}(n,d)O^{18}$ pickup process, however, the reduced widths for the transitions to the ground state and the first excited state were found to be about equal.[24] In Table II, an attempt is made to gain information on the structure of F^{19} from these reactions by listing some shell-model configurations for the initial and final nuclei which can be connected by a direct-interaction process. It is assumed that the two last neutrons in F^{19} remain unaffected and that in the (α,p) reaction the alpha particle captured in the final nucleus is in an S state. The angular momentum transfer is then equal to the angular momentum of the proton in F^{19}. The first symbol in each case stands for the last two neutrons, the second for the last proton(s).

TABLE II. Possible direct transitions between some shell-model configurations of the initial and final nuclei for the reactions $F^{19}(n,d)O^{18}$, $F^{19}(\alpha,p)Ne^{22}$, and $F^{19}(d,n)Ne^{20}$. Experimentally inhibited transitions are shown in brackets.

F^{19}		$(d_{5/2}^2)_2 d_{5/2}$	$(d_{5/2}^2)_0 s_{1/2}$	$(s_{1/2}^2)_0 s_{1/2}$
O^{18}	$(d_{5/2}^2)_0$	...	$l_p=0$	...
	$(s_{1/2}^2)_0$	...	...	$l_p=0$
O^{18*}	$(d_{5/2}^2)_2$	$l_p=2$	...	...
Ne^{22}	$(d_{5/2}^2)_0$	...	$(l_p=0)$	...
	$(s_{1/2}^2)_0$	...	...	$(l_p=0)$
Ne^{22*}	$(d_{5/2}^2)_2$	$l_p=2$	...	...
Ne^{20}	$(d_{5/2}^2)_0(d_{5/2}^2)_0$	...	...	...
	$(d_{5/2}^2)_0(s_{1/2}^2)_0$	...	$(l_p=0)$	...
	$(s_{1/2}^2)_0(s_{1/2}^2)_0$	...	...	$(l_p=0)$
Ne^{20*}	$(d_{5/2}^2)_2(d_{5/2}^2)_0$	$l_p=2$	...	...

From the inhibition of the ground-state transitions in the reactions $F^{19}(\alpha,p)Ne^{22}$ and $F^{19}(d,n)Ne^{20}$ alone, one would be tempted to conclude that the $(d_{5/2}^2)_2 d_{5/2}$ term is predominant in F^{19}. The strong ground-state transition in the pickup reaction, however, indicates that one of the other terms must also have a large amplitude. A consistent picture is obtained, for example, if one assumes that only $d_{5/2}$ states contribute in Ne^{20} and Ne^{22}, whereas O^{18} has an $(s_{1/2}^2)$ term and F^{19} is a mixture of $(d_{5/2}^3)$ and $(s_{1/2}^3)$ terms, with only a small $(d_{5/2}^2)s_{1/2}$ part. This would be in contradiction to the calculations by Elliott and Flowers[25] and by Redlich[26] who find essentially equal $(s_{1/2}^3)$ and $(d_{5/2}^2)s_{1/2}$ terms, with the $(d_{5/2}^3)$ intensity being smaller by about a factor 4.

The results of fitting Butler's formula[4] to these data are also shown in Figs. 8, 9, and 10. An interaction radius of 5.1f was used throughout. Pieper and Heydenburg,[5] using the same equation for the analysis of the $F^{19}(\alpha,p_0)Ne^{22}$ angular distribution at 6.40 Mev, used an

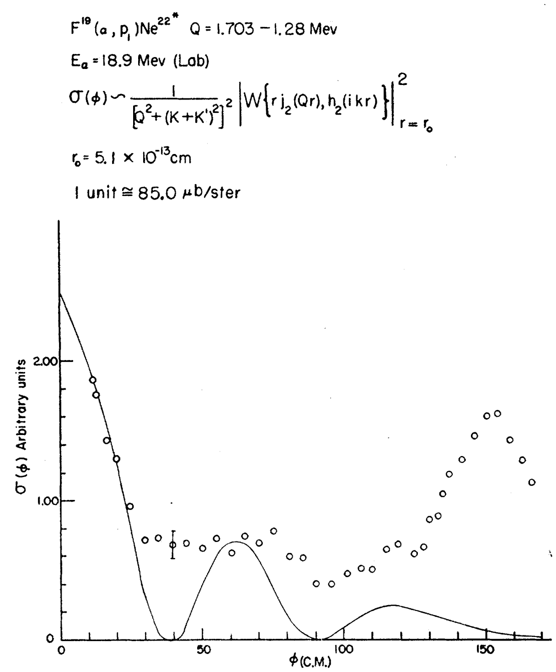

FIG. 9. Angular distribution of the p_1 group from the reaction $F^{19}(\alpha,p)Ne^{22}$ at 18.9 Mev.

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[25] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955).
[26] M. G. Redlich, Phys. Rev. **110**, 468 (1958).

interaction radius of 5.2f. Although the character of the p_0 angular distribution is poor, the zeros of the theoretical curve are not inconsistent with the indications of minima in the experimental data. The formula accounts well for the forward peak and the location of the minima in the p_1 angular distribution. The peak at 150° is not explained at all by the formula but is reminiscent of a heavy-particle stripping process.

Although the spin and parity of the 3.35-Mev level of Ne^{22} are not known for certain,[10,27] the theoretical curve for $l=2$ is not inconsistent with 2^+, the most probable assignment. The theoretical fit in the forward angles is reasonable and the zeros of the theoretical curve are consistent with the minima of the experimental data.

The most significant departure from the predictions of Butler's theory[4] is the backward peaking observed in all three angular distributions. Backward peaking, though much more slowly rising, has been adequately explained in certain (d,n) cases[19] by the heavy-particle stripping process. However, the sharp backward peaking observed here and elsewhere for other (α,p)[1–3,11] and (p,α)[12–14] reactions has thus far defied analysis.

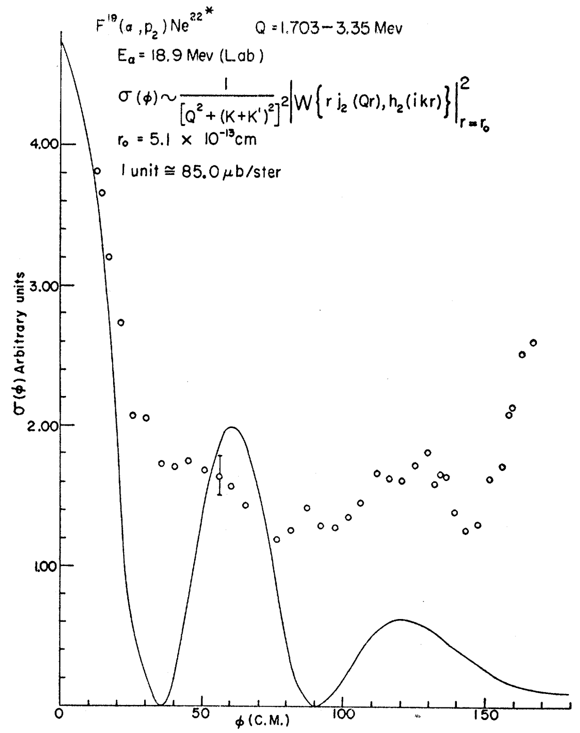

FIG. 10. Angular distribution of the p_2 group from the reaction $F^{19}(\alpha,p)Ne^{22}$ at 18.9 Mev.

SUMMARY

Direct-interaction effects of varying magnitudes have been observed in both reactions studied. The most prominent differences between the measured angular distributions and the predictions of the simple direct-interaction theories were the backward peaking, especially the steep backward peaking at selected energies, the strong energy dependence of the $C^{12}(\alpha,p_0)N^{15}$ reaction, and the lack of definition in the minima. As pointed out, similar behaviors have been observed elsewhere. The interpretation is not at all clear and certainly demands more theoretical attention. It is not known at all whether the more realistic distorted wave calculations will account for the (α,p) data. Perhaps these data will be better explained by the inclusion of another direct process, presumably heavy particle stripping, with appropriate interference between the two.

ACKNOWLEDGMENTS

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