Reaction Mechanism in $F^{19}(\alpha,p)Ne^{22}$ at 6 Mev

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Angular distributions of protons corresponding to the ground-state and first excited-state transitions in the reaction $F^{19}(\alpha,p)Ne^{22}$ have been measured for five bombarding energies in the region of 6.0 to 6.55 Mev. Angular correlations of the de-excitation gamma ray from the first excited state of Ne^{22} with the alpha-particle and proton directions have been measured for six different combinations of bombarding energy and proton detection direction. Some, but not all, of the results show striking agreements with predictions based on simple direct-interaction mechanisms.

INTRODUCTION

THE study of (α,α') and (α,p) reactions at bombarding energies in the region of a few tens of Mev has given strong evidence[1] for a direct interaction mechanism.[2,3] At lower bombarding energies, it is not expected that such clear-cut indications of direct mechanisms will be observed because of the increased contribution of compound-nucleus processes. However, results interpretable in terms of a direct mechanism have been obtained at energies between 5 and 10 Mev, especially in the $B^{10}(\alpha,p)C^{13}$ reaction.[4] In the present paper we wish to report the results of an investigation of the mechanism of the reaction $F^{19}(\alpha,p)Ne^{22}$ in the region of 6.0 to 6.5 Mev bombarding energy.

EXPERIMENTAL DETAILS

Our experiments consisted of measuring the angular distributions of proton groups p_0 and p_1 corresponding to the ground-state and first excited-state transitions in $F^{19}(\alpha,p)Ne^{22}$ as a function of bombarding energy, and of measuring several correlations between the alpha beam, the protons p_1, and the 1.28-Mev gamma ray from the de-excitation of the first excited state of Ne^{22}.

The doubly-charged helium ion beam was produced by our Van de Graaff generator. Beam currents of up to 0.1 microampere were available in the region of 6 Mev; the spread in beam energy was about 12 kev.

Several targets were used; they were obtained by evaporating CaF_2 onto thin nickel foils. Various target thicknesses were used; for intensity reasons we used mostly targets about 50 kev thick to 6-Mev alpha particles. The targets were placed in the center of a cylindrical scattering chamber 3 in. high and $4\frac{1}{2}$ in. in diameter. Protons emerged through a 0.0005-in. Mylar window which covered a $\frac{3}{8}$-in. slot in the cylindrical wall. Protons could be observed at angles from -20 to $+150$ degrees and were detected in a thin NaI(Tl) crystal, the p_0 and p_1 groups being adequately separated by pulse-height analysis. In the angular distribution work we used two different solid angles for the proton detector, corresponding to linear opening (full cone) angles of 2.0° and 4.2°. A somewhat larger solid angle (linear opening angle 11.4°) was used in the angular correlation experiments in order to obtain increased counting rates.

The gamma rays were detected in a 2 in.×2 in. NaI(Tl) crystal mounted with its front face 10 cm from the target. All gamma-ray observations were made in the plane defined by the alpha-particle and proton directions. Here angles from -135 to $+135$ degrees were usable, except that the angle between the two counters could not be reduced below 50 degrees. Gamma rays emerged either through the Mylar window or the thin brass wall of the bombardment chamber. A Co^{60} source was used to examine the effects of these different absorbing materials and possible target decentering; the maximum observed variation in counting rate with angle was 3%.

For the correlation experiments a "slow-fast" coincidence circuit[5] was employed. The proton group p_1 was selected with a single-channel analyzer for coincidence with the gamma-ray counter. The resolving time of 80 millimicroseconds and the available beam current, target thickness, etc., kept the accidental coincidence rate to about 5% of the true coincidence rate. The slow-fast circuit simultaneously monitored the accidental counts. The coincidence yield was obtained by dividing the number of true coincidences by the number of single protons observed in each run. The spectrum of gamma rays from the alpha-particle bombardment of fluorine contains contributions from Coulomb excitation, inelastic scattering, and the (α,n) processes, as well as the (α,p) reaction. By gating the multichannel analyzer with the output of the coincidence circuit, only the 1.28-Mev gamma ray, resulting from the decay of the first excited state of Ne^{22}, was observed.

In addition to the above, we also measured excitation functions for the production of p_0 and p_1 protons in the region of 6.0 to 6.5 Mev bombarding energy at

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[1] H. J. Watters, Phys. Rev. **103**, 1763 (1956); R. Sherr and M. Rickey, Bull. Am. Phys. Soc. Ser. II, **2**, 29 (1957); C. E. Hunting and N. S. Wall, Bull. Am. Phys. Soc. Ser. II, **2**, 181 (1957).
[2] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).
[3] S. T. Butler, Phys. Rev. **106**, 272 (1957).
[4] P. von Herrmann and G. F. Pieper, Phys. Rev. **105**, 1556 (1957).
[5] G. S. Stanford and G. F. Pieper, Rev. Sci. Instr. **26**, 847 (1955).

laboratory observation angles of 0, 45, 90, and 135 degrees. The same geometry was used as for the angular distribution work (the larger solid angle); points were obtained at 25- or 50-kev intervals with a target 20 kev thick to 6-Mev alpha particles. Although this target thickness precluded the possibility of finding narrow resonances, it was essentially required by our beam conditions. We believe our excitation data are of some value for comparison with the angular distribution information, in spite of their failure to show detailed structure.

ANGULAR DISTRIBUTIONS

Theory

Although any detailed considerations of noncompound-nucleus mechanisms for the (α,p) reaction must be oversimplified, they are nonetheless of some interest. Previously,[4] we have discussed (α,p) angular distributions solely in terms of the mechanism envisioned by Austern, Butler, and McManus,[2] in which it is suggested that the reaction takes place by a surface scattering or knockout process. The differential cross section for such an interaction in the reaction $X(\alpha,p)Y$ is

$$\frac{d\sigma}{d\Omega}\propto\Big[\sum_l j_l(QR)\Big]^2F(\theta). \tag{1}$$

Here j_l is the spherical Bessel function of order l. The allowed orders are found from the selection rule

$$|\mathbf{J}_x+\mathbf{J}_y+\mathbf{i}|_{\min}\leqslant l\leqslant J_x+J_y+i, \tag{2}$$

where $\mathbf{J}_x$ is the spin of the target nucleus, $\mathbf{J}_y$ is the spin of the residual nucleus, and $\mathbf{i}$ is the vector sum of the spins of the entering and emerging particles. l must be *odd* if the parity of the residual nucleus differs from that of the target nucleus, and *even* if it is the same. Frequently this selection rule limits an actual case to just a single allowed value of l; the ground-state and first excited-state transitions in $F^{19}(\alpha,p)Ne^{22}$ are cases in point. The argument of the spherical Bessel function in (1) is the product of the interaction radius, R, and the absolute value of the momentum transfer vector, $\mathbf{Q}$. In the surface scattering process (center-of-mass system),

$$\mathbf{Q}=\left(\frac{M_x-M_p}{M_x}\right)\left(\mathbf{k}_\alpha-\frac{M_x}{M_y}\mathbf{k}_p\right), \tag{3}$$

where the $\mathbf{k}$'s are the wave vectors of the alpha particle and proton. The Bessel function term in (1) is multiplied by $F(\theta)$, a form factor dependent primarily on the free scattering amplitude. The work of Austern, Butler, and McManus has been revised recently by Butler in a paper[3] on direct nuclear reactions. This results in a somewhat more complicated expression than (1) for the expected cross section in an (α,p) reaction; however, the primary angular dependence is still given essentially by a Bessel function term, as in (1). The momentum transfer vector, of course, is still given by Eq. (3).

Although the strong binding of the alpha particle argues against the probability of an alpha stripping mechanism, it might be considered in analogy to the familiar deuteron stripping. In such an (α,p) process, the alpha particle would dissociate into a triton and a proton, the former being captured by the target nucleus while the latter escapes. Neglecting the internal motion of the triton, the angular distributions from the process would be analogous to those from deuteron stripping. Although these distributions have a somewhat different form[6] from Eq. (1), they too are governed primarily by the square of the spherical Bessel function of appropriate order. Since the argument of the Bessel function is again the product QR, where Q now has the value

$$\mathbf{Q}=\mathbf{k}_\alpha-\frac{M_x}{M_y}\mathbf{k}_p, \tag{4}$$

the angular distributions resulting from an alpha stripping mechanism would be experimentally indistinguishable from the distributions from a knockout process.

In still another mechanism for the reaction $X(\alpha,p)Y$, the incident alpha particle would be captured by the core of the target nucleus while an outer shell proton from the latter is stripped off. In principle such a heavy-particle stripping[7] process can be included, along with normal alpha stripping, in a Born-approximation calculation by using a final-state wave function for the outgoing proton which is antisymmetric in the exchange of a proton from the alpha particle and the outer shell protons from the target nucleus.[8] The exchange wave function also introduces interference between the alpha stripping and heavy-particle stripping, an effect which may be large below the Coulomb barrier. The differential cross section for the heavy-particle stripping process alone would be expressible in the form of Eq. (1), with the significant difference that the momentum transfer vector in this case is given by

$$\mathbf{Q}=-\left(\mathbf{k}_\alpha+\frac{M_\alpha}{M_y}\mathbf{k}_p\right). \tag{5}$$

Thus the heavy-particle stripping process favors the backward direction, and one may thus hope to identify the process experimentally. In all three of these direct interaction mechanisms, one would not expect any considerable change in distribution shape with a small change in bombarding energy.

[6] S. T. Butler and O. Hittmair, *Nuclear Stripping Reactions* (John Wiley and Sons, Inc., New York, 1957).
[7] G. E. Owen and L. Madansky, Phys. Rev. **99**, 1608 (1955).
[8] G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957); T. Fulton and G. E. Owen, Phys. Rev. **108**, 789 (1957). See also A. P. French, Phys. Rev. **107**, 1655 (1957), in which it is shown that exchange effects may also be interpreted in such a way as to give rise to a forward rather than a backward peaking.

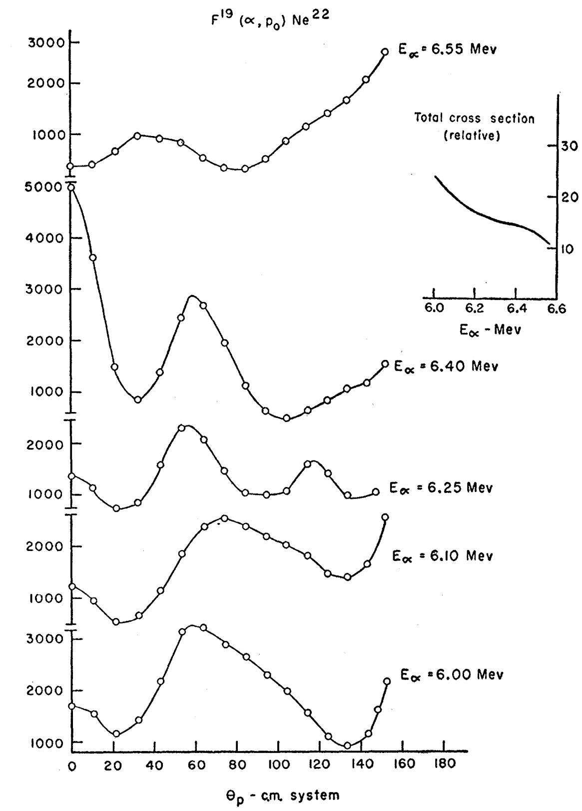

FIG. 1. Angular distributions of protons from $F^{19}(\alpha,p_0)Ne^{22}$. On the ordinate scale, 1000 units correspond approximately to 1.5 millibarns per steradian. Insert shows approximate behavior of total cross section as a function of bombarding energy.

Concerning the possibility of compound nucleus formation, at the bombarding energies employed, the excitation of the compound nucleus Na^{23} would be between 15.5 and 16 Mev. Although no detailed excitation data are available for this region, data at lower excitations[9] indicate that the average level spacing here would be of the order of 50 kev or less. For this reason we would not expect to observe the usual compound-nucleus fore-and-aft symmetry, since it is quite likely that levels of opposite parity will interfere and destroy this symmetry. However, if the analysis of the distributions requires high powers of $\cos\theta$ to fit the data, penetrability arguments may rule out compound-nucleus formation.

Results

The results of five angular-distribution measurements on proton group p_0 at various bombarding energies between 6.00 and 6.55 Mev are shown in Fig. 1. If we were to employ only the criteria used before[4] concerning the change in distribution shape with bombarding energy, we should certainly conclude that compound-nucleus effects are important in this reaction. This conclusion may well be correct, but in addition we note the rather striking agreement of the shapes of certain of the distributions with predictions based on direct-interaction mechanisms. Figures 2 and 3 illustrate this point, showing the distributions at 6.25 and 6.40 Mev bombarding energy and theoretical curves based on Eq. (1), with Q given by Eq. (3). l is uniquely zero for the $F^{19}(\alpha,p_0)Ne^{22}$ reaction, and we take $F(\theta)$ to be constant, so the curves are simply $[j_0(QR)]^2$. While better fits could be obtained in these cases if an isotropic background were assumed, it is clear that the main features of the distributions are reproduced by the theoretical curves. The radius parameter R required to obtain the theoretical curve of Fig. 2 is 6.6×10^{-13} cm, while that for Fig. 3 is 5.8×10^{-13} cm. We are inclined to pass over the problem of the difference between these values, and mention only that a fit to the data of Fig. 3 using a radius of 5.2×10^{-13} cm in Eq. (40) of reference 3 produced a curve very nearly identical to the $[j_0(QR)]^2$ curve shown. We cannot, however, ignore the problem of why the three other distributions shown in Fig. 1 should have shapes more or less different from the two singled out in Figs. 2 and 3. The distributions at 6.00- and 6.10-Mev bombarding energy do show some similarities to those at 6.25 and 6.40 Mev, especially in the forward direction, but the one at 6.55 Mev is qualitatively different from all the others. The general increase in the backward direction shown by nearly all the cross sections may appear to be indicative of the existence of a heavy-particle stripping process. However, estimates based on Eqs. (5) and (1) above indicate that (with the partial exception of the 6.55-Mev case) the yields change too rapidly with angle to be accounted for by the heavy-particle stripping process alone. Although a fair fit could

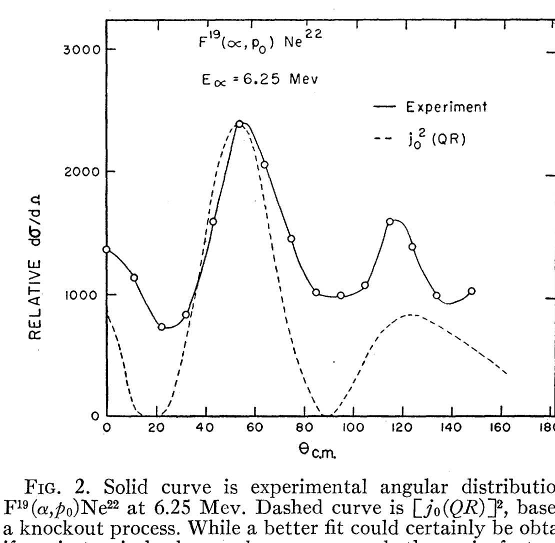

FIG. 2. Solid curve is experimental angular distribution in $F^{19}(\alpha,p_0)Ne^{22}$ at 6.25 Mev. Dashed curve is $[j_0(QR)]^2$, based on a knockout process. While a better fit could certainly be obtained if an isotropic background were assumed, the main features of the distribution do appear to be given quite well by the theoretical curve.

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[9] N. P. Heydenburg and G. M. Temmer, Phys. Rev. 94, 1252 (1954); Sherr, Li, and Christy, Phys. Rev. 96, 1258 (1954).

probably be obtained, we have not tried to fit the 6.55-Mev data to a heavy-particle stripping process.

We have attempted to determine whether there is any relation between the behavior of the angular distributions and the excitation curve for the reaction. An indication of the behavior of the total cross section was first obtained by integrating the five angular distributions; a more or less monotonic decrease of total cross section by about a factor of two was observed with increasing energy between 6.00 and 6.55 Mev. In addition, we have measured four differential excitation curves, as described above. When a small energy shift due to carbon buildup on the target was accounted for, the results of the excitation measurements were, at common points, consistent with the angular-distribution measurements. The shape of the relative total cross section is indicated in the insert in Fig. 1. There seems to be no simple correlation between the shapes of the various angular distributions and the total cross section for the process.

The angular distributions of the proton group p_1 at the same five bombarding energies between 6.00 and 6.55 Mev are shown in Fig. 4. In this case, from Eq. (2) l is uniquely 2. Some of the five distributions have shapes which show certain resemblances to predictions of direct mechanisms, *viz.*, those at 6.10 and 6.40 Mev; but on the whole, the changes in distribution shape with bombarding energy are even more striking than

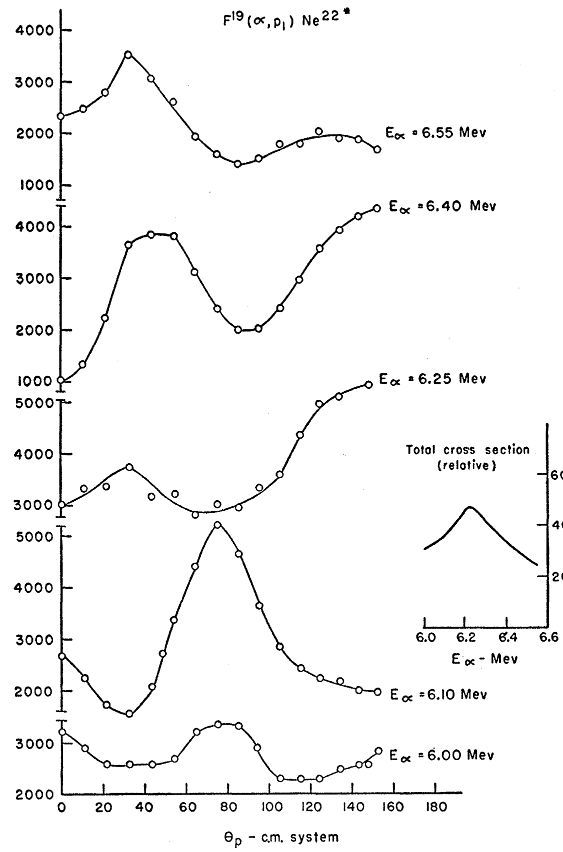

FIG. 4. Angular distributions of protons from $F^{19}(\alpha,p_1)Ne^{22*}$. On the ordinate scale, 1000 units corresponds approximately to 1.5 millibarns per steradian. Insert shows approximate behavior of total cross section as a function of bombarding energy.

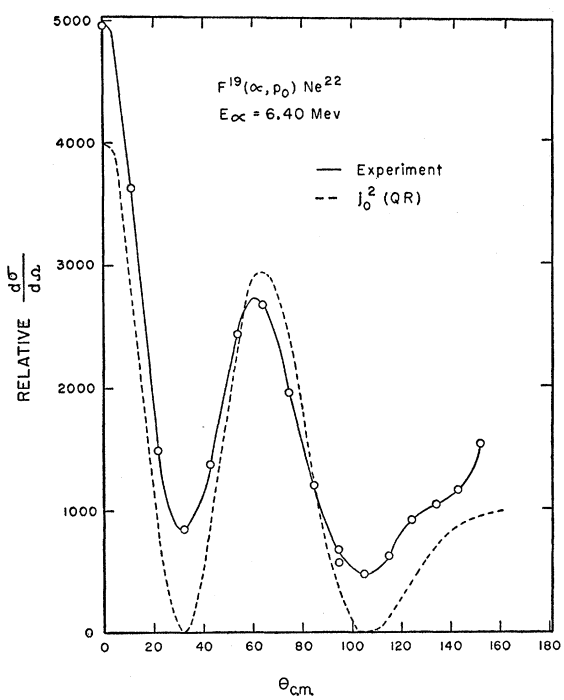

FIG. 3. Solid curve is experimental angular distribution in $F^{19}(\alpha,p_0)Ne^{22}$ at 6.40 Mev. Dashed curve is $[j_0(QR)]^2$, based on a knockout process. A nearly identical theoretical prediction is made by the latest Butler theory, reference 3. The agreement between prediction and experiment in this case is better than in any other in this work.

in the case of the p_0 group. In this case, the integrated angular distributions and the excitation data show one rather broad increase in the total cross section centered at about 6.20 Mev, as indicated in the insert in Fig. 4.

In order to determine whether the compound-nucleus theory can provide a satisfactory explanation of our results we have resorted to penetrability arguments. The ten angular distributions shown in Figs. 1 and 4 have been analyzed by the method of least squares in terms of a power series in $\cos\theta$; the number of points per yield curve made it reasonable to go only to the sixth power of $\cos\theta$. In all cases, the analyses showed large coefficients for the high-power terms. Calculation of penetrability factors shows that while an angular momentum of $L=3$ is not at all unreasonable between the incoming alpha particle and the fluorine nucleus, it is not so likely between the outgoing proton and the residual neon nucleus. Thus, the consistent prominence of high-angular-momentum components in the outgoing proton wave argues to some extent against a compound-nucleus interpretation for our results.

To conclude concerning angular distributions: we have observed some angular distributions whose oscilla-

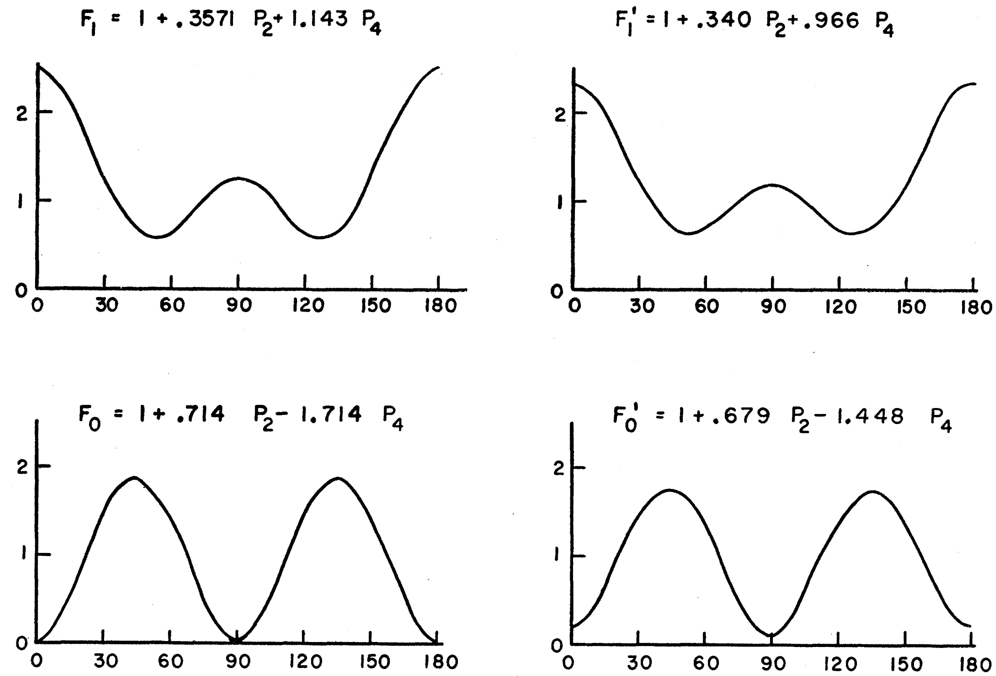

FIG. 5. Correlation functions for the F^{19}-$(\alpha,p_1)Ne^{22*}(\gamma)Ne^{22}$ reaction based on an alpha stripping mechanism. The abscissas of all graphs are the angle λ_γ and the arguments of the Legendre functions are $\cos\lambda_\gamma$. For other details, see text.

tory nature is quite strikingly fitted by an appropriate order spherical Bessel function. These distributions provide *prima facie* evidence for a direct (surface) interaction, although it is not possible to distinguish which of several detailed mechanisms is involved. Concerning those angular distributions which do not show such oscillatory behavior, it has been suggested by Butler[3] that at low energies contributions to the direct reaction from the interior of the nucleus would tend to smear out the maxima in the angular distributions, and that consequently such distributions might not show the oscillatory behavior characteristic of surface reactions. One can also expect that modifications to the simple direct-reaction theory will arise due to Coulomb effects, and to the initial- and final-state interactions, as well as, in certain cases, to interference effects. We should be more inclined to accept some of these suggestions in the present case, were it not for the considerable change in distribution shape which occurred in some instances with a very small change in bombarding energy. Such an effect is difficult to account for without invoking compound-nucleus processes. This sort of result in our proton angular distributions led us to investigate the $(\alpha,p\gamma)$ angular correlations in the hope that they might throw some light on the nature of the reaction mechanism.

ANGULAR CORRELATIONS

Theory

If one considers that the $F^{19}(\alpha,p_1)Ne^{22*}(\gamma)Ne^{22}$ reaction takes place by an alpha stripping process, then the analysis of the $(\alpha,p_1\gamma)$ angular correlation is straightforward, since the corresponding $(d,p\gamma)$ correlation has been treated in detail by Satchler,[10] and others.[11] It is shown that one should observe a correlation azimuthally symmetric about the direction of momentum transfer, **Q**, as given (in the center-of-mass system) by Eq. (4). In the laboratory **Q** becomes just $(M_x/M_y)(\mathbf{k}_\alpha-\mathbf{k}_p)$, so it is clear that its direction corresponds simply to the direction of the recoiling Ne^{22*}. The situation is the same as if one were investigating a (t,γ) capture reaction, except here the direction of the "triton beam" is specified by the directions of the alpha beam and the observed protons. Since all the necessary quantum numbers for the $F^{19}(t,\gamma)Ne^{22}$ are known in our case, the correlation function, $W(\lambda_\gamma)$, is directly obtainable: the spins of the triton and the fluorine nucleus are each $\frac{1}{2}^+$ and that of the intermediate Ne^{22*} is known to be 2^+; thus the relative orbital angular momentum between the captured triton and the fluorine nucleus must be 2 regardless of whether the incoming channel spin is 0 or 1. The outgoing gamma ray is of the $E2$ type and the final Ne^{22} state has spin 0^+. Therefore, since incoming channel spins add incoherently, the correlation function is given simply by[12]

$$W(\lambda_\gamma)=AF_0(\lambda_\gamma)+BF_1(\lambda_\gamma), \qquad (6)$$

where F_0 is the correlation function for channel spin 0 and F_1 that for channel spin 1; A and B measure the formation probability of channel spins 0 and 1, respec-

[10] G. R. Satchler and J. A. Spiers, Proc. Phys. Soc. (London) **A65**, 980 (1952); G. R. Satchler, Proc. Phys. Soc. (London) **A66**, 1081 (1953).
[11] Biedenharn, Boyer, and Charpie, Phys. Rev. **88**, 517 (1952); L. J. Gallaher and W. B. Cheston, Phys. Rev. **88**, 684 (1952).
[12] Kraus, Schiffer, Prosser, and Biedenharn, Phys. Rev. **104**, 1667 (1956).

tively. The angle λ_γ is that between the direction of the observed gamma ray and $\mathbf{Q}$. The correlation functions F_0 and F_1 are given explicitly and graphically in Fig. 5. Also given in Fig. 5 are functions F_0' and F_1'; these are the smeared[13] correlation functions appropriate to the solid angles subtended by the detectors used in our experiment. Thus if the alpha stripping process correctly describes our experiment, our observed correlations should then be given by

$$W'(\lambda_\gamma)=AF_0'+BF_1', \tag{7}$$

with A and B as adjustable parameters.

The angular correlation to be expected in the event that the reaction proceeds by an (α,p) knockout process may be treated following the approach of Satchler[14] to the problem of gamma radiation following the surface scattering of nucleons. In the present case, the problem is complicated by interferences, since the proton can be ejected from an $s_{\frac{1}{2}}$ orbital with the alpha particle entering as a d wave, or from a $d_{\frac{3}{2}}$ or $d_{\frac{5}{2}}$ orbital with the alpha particle being captured in an s state. Furthermore, the work of Elliott and Flowers[15] has shown that there is a good deal of configuration mixing in the ground state of F^{19}, and thus the correlation function can neglect none of these three possibilities for the proton; it must contain appropriate amplitudes for each orbital, including the probability that the alpha particle can knock the proton out of the orbital. Although these considerable complications are sufficient to prevent our determining the correlation explicitly in the knockout case, we may still make use of certain characteristic symmetries which Satchler has shown to be exhibited in the general case, namely, that the angle dependence consists of even powers of $\cos\lambda_\gamma$, where λ_γ is the angle between the gamma ray and the momentum transfer axis, $\mathbf{Q}$. [$\mathbf{Q}$ is given in this case by Eq. (3); its direction is again that of the recoiling Ne^{22*}.] Thus, if the knockout process correctly describes our experiment, we may expect the correlation to show symmetry about the plane perpendicular to

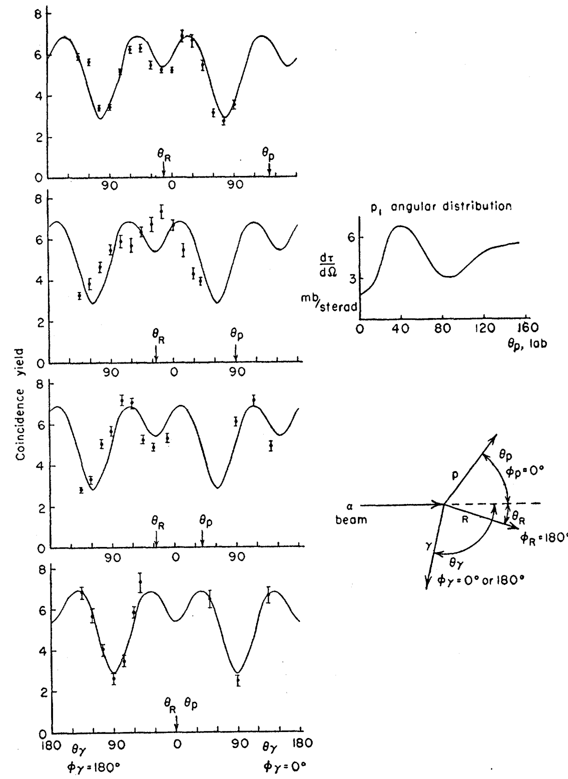

FIG. 6. $F^{19}(\alpha,p_1)Ne^{22*}(\gamma)Ne^{22}$ angular correlations at 6.40 Mev bombarding energy, for proton detection angles, θ_p, of 0°, 40°, 90°, and 140°. The solid curve in each correlation represents one particular (not unique) prediction of the alpha stripping mechanism [$A/B=1.5$ in Eq. (7)]; it is included to show that the results at $\theta_p=0°$, 40°, and 140° show the symmetries with respect to θ_R predicted by the alpha stripping and knockout mechanisms, while the data at $\theta_p=90°$ do not show these symmetries. The inserts are the p_1 proton angular distribution (laboratory system) at 6.40-Mev bombarding energy and a diagram of some of the directions involved in the reaction and its analysis.

the recoil direction as well as azimuthal symmetry about this direction. These, of course, are the very symmetries shown in Eq. (7) so we shall be unable to distinguish between the knockout and alpha stripping mechanisms on this basis.

In the case of a heavy-particle stripping process, the $(\alpha,p_1\gamma)$ correlation can be shown to be azimuthally symmetric about the direction of momentum transfer, just as in the two other surface interaction mechanisms. In the heavy-particle case, however, this direction is not that of the recoil Ne^{22*}, since $\mathbf{Q}$ is now given by Eq. (5). In the laboratory, the direction is given by $\mathbf{k}_\alpha+[M_\alpha/(M_x-M_p)]\mathbf{k}_p$. The explicit correlations have not been determined for the heavy-particle process; however, the unique symmetry direction should help to distinguish the mechanism.

The angular correlation to be expected in the event that the reaction proceeds entirely by compound-nucleus formation can in principle be determined from the summary of Kraus *et al.*[12] The situation is made difficult in the present case by a lack of knowledge of

TABLE I. Directions of momentum transfer (in the laboratory system) for various direct-interaction mechanisms. All directions are specified in terms of a polar angle θ with respect to the beam direction and an azimuthal angle ϕ. The proton direction always lies in the $\phi_p=0°$ plane.

E Mev	Proton direction θ_p	ϕ_p	Alpha stripping and knockout process θ_R	ϕ_R	Heavy-particle stripping θ_H	ϕ_H
6.40	0°	0°	0°	0°	0°	0°
6.40	40°	0°	28°	180°	3.7°	0°
6.40	90°	0°	25°	180°	5.8°	0°
6.40	140°	0°	12°	180°	3.8°	0°
6.10	0°	0°	0°	0°	0°	0°
6.10	70°	0°	27°	180°	5.5°	0°

[13] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[14] G. R. Satchler, Proc. Phys. Soc. (London) **A68**, 1037 (1955).
[15] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955).

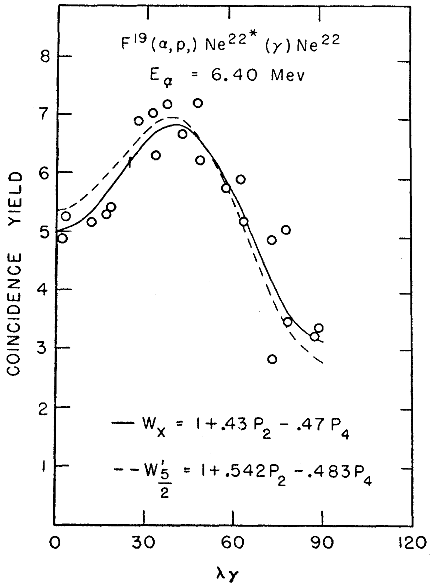

FIG. 7. Comparison of some of the angular correlation data shown in Fig. 6 to the prediction of the alpha stripping mechanism with pure $j=\frac{5}{2}$ triton capture. The experimental points are taken from the correlations at $\theta_p=40°$ and 140°; W_x is the least-squares fit to these data. $W_{\frac{5}{2}}'$ is the theoretical prediction, adjusted for the detector geometry used in the experiment. The angle λ_γ is measured between the direction of the gamma ray and the direction of momentum transfer (in this case the direction of the recoil nucleus Ne^{22*}). The data have been compressed into one quadrant by making use of the symmetry about the plane $\lambda_\gamma=90°$.

the properties of the compound state or states in Na^{23}. However, whatever symmetries might result in the compound-nucleus case would be with respect to the incoming and/or outgoing particle directions; it has been emphasized by Biedenharn[11] and Satchler[14] that the momentum transfer axis **Q** has no special significance in compound-nucleus processes.

Results

We have measured six $(\alpha,p_1\gamma)$ correlations, four at a bombarding energy of 6.40 Mev, for proton detection angles of 0°, 40°, 90°, and 140°, and two at 6.10 Mev, for proton detection angles of 0° and 70°. The directions of momentum transfer for these six cases for the various direct interaction processes are summarized in Table I.

The rather striking agreement of some of our 6.40-Mev data with the symmetry predictions of the alpha stripping and knockout mechanisms will be clear from Fig. 6. The failure of all the data (except the trivial case of $\theta_p=0°$) to fit the symmetry predictions of the heavy-particle stripping mechanism or the limiting possibilities for the compound-nucleus process is also evident. The same theoretical curve has been drawn in each of the four correlations in order to facilitate comparison between them; it was obtained from Eq. (7) by taking the ratio $A/B=1.5$. The results for $\theta_p=0°$, 40°, and 140° all fit the curve fairly well, although when considered individually they can be made to fit theoretical curves based on somewhat different A/B ratios even better (e.g., at $\theta_p=40°$, an A/B of 1.9 gives a notably better fit). The ratio $A/B=1.5$, when translated from the channel-spin formalism into a "j formulation,"[10] corresponds to pure $j=\frac{5}{2}$ triton capture. How well *some* of our data fit this possibility is shown in Fig. 7 in which a least-squares fit to the data taken at $\theta_p=40°$ and 140° is compared to the $j=\frac{5}{2}$ triton capture prediction. Thus if one were to place credence in this *prima-facie* evidence for the alpha stripping process, the result shown in Fig. 7 would be of significance with regard to the j-j coupling shell model. It is perhaps superfluous to add that we do not necessarily interpret these results as indicative of the existence of an alpha stripping mechanism as opposed to a knockout process. We have simply compared our experimental results to whatever theoretical predictions we could obtain. It is unfortunate that the complications of the reaction chosen have prevented a more detailed comparison of our results to the predictions of the knockout process.

The correlation observed at $\theta_p=90°$ is interesting because it apparently is the only one which does not fit the same general shape as the others at 6.40 Mev. It may be possible to relate this effect to the fact that the proton angular distribution has a minimum at 90°; possibly the forward peak (at 40°) in the p_1 distribution is due to one interaction mechanism and the backward peak to another mechanism; we observe normal correlations when we take protons corresponding to the one or the other mechanism, while interference effects destroy the correlation in between.

The results of our two angular correlation measurements at 6.10 Mev bombarding energy are shown in Fig. 8. Here the symmetry with respect to θ_R shown by much of the 6.40-Mev data is definitely absent in

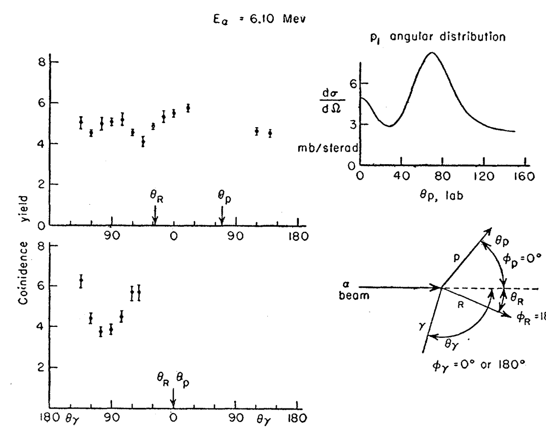

FIG. 8. $F^{19}(\alpha,p_1)Ne^{22*}(\gamma)Ne^{22}$ angular correlations at 6.10-Mev bombarding energy, for proton detection angles, θ_p, of 0° and 70°. The inserts are the p_1 proton angular distribution (laboratory system) at 6.10 Mev bombarding energy, and a diagram of some of the directions involved in the reaction and its analysis.

the $\theta_p=70°$ case and probably absent at $\theta_p=0°$. Furthermore, in the case of the 70° data, there is no evidence for any symmetry with respect to the beam direction, θ_p, or θ_H. It appears from this result that compound-nucleus processes play a predominant part in the reaction at 6.10 Mev; in any event, the character of the correlations at 6.10 Mev is quite different from that of the 6.40-Mev results.

CONCLUSIONS

The results of our $(\alpha,p\gamma)$ angular correlation experiments have not decided the issue of the reaction mechanism in $F^{19}(\alpha,p)Ne^{22}$ in favor of any single one of the processes we have considered. They have, in fact, presented the same sort of conflicting evidence as the proton angular distributions, in that both experiments show in some cases striking agreements with the predictions of quite simple direct-interaction mechanisms, while in other cases there are evident disagreements with these predictions. We are unable to explain this behavior in detail; our inability to relate the apparent rapid changes with energy of the reaction mechanism to the total cross section is especially puzzling. Further angular correlation experiments, especially as a function of bombarding energy, should throw additional light on this problem. It seems clear, however, that both direct-reaction mechanisms and compound-nucleus processes are needed to explain our results. This is hardly surprising, since, as many authors[16] have pointed out, we may expect to observe features of both the extremes of compound-nucleus formation and direct interaction in an actual reaction. The present cases are perhaps distinguished for the clarity with which evidences for direct interactions appear, at a somewhat lower bombarding energy than usual.

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[16] D. C. Peaslee, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1955), Vol. 5, p. 99; V. F. Weisskopf, Revs. Modern Phys. **29**, 174 (1957); A. M. Lane, Revs. Modern Phys. **29**, 191 (1957).