Fluorine-plus-Proton Reactions*

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The properties of certain energy levels in O^{16}, F^{19}, and Ne^{20} have been studied by observations on the alpha particles and inelastic protons from the bombardment of fluorine by protons. A high-resolution magnetic analysis of the alpha-particle groups to the 2^+ and 1^- levels in O^{16} from the $F^{19}(p,\alpha)O^{16*}$ reaction failed to reveal any doublet structure in these known levels. The angular distributions of the alpha-particle groups to these levels did not indicate degeneracy with a 2^- level, nor did a search for new excited levels in O^{16} up to 8.7-Mev excitation reveal a 2^- level. These results are not in agreement with the alpha-particle model of the O^{16} nucleus which predicts a 2^- state close in energy to the 2^+ state.

Angular distributions of the alpha particles were measured at proton bombarding energies of 873, 935, 1290, 1355, and 1381 kev. The distributions at 1355 kev indicated that the corresponding Ne^{20} resonance level at 14.16 Mev has spin 2 and odd parity. The spin and parity assignments previously found for the other levels were confirmed.

A study of the inelastic proton groups from the $F^{19}(p,p')F^{19*}$ reaction gave 108.8±0.8 and 196.0±1.4 kev for the excitation energies of the two lowest excited levels of F^{19}. The cross sections at the 1431-kev resonance for these groups in the center-of-mass system were 0.187±0.015 barn for the first group and 0.007 ±0.002 barn for the second group. At 1381 kev the cross section was 0.0427±0.0040 barn for protons to the second excited level.

Angular distributions of the proton groups were measured and, in conjunction with other studies made in this laboratory, resulted in spin and parity assignments of $\frac{1}{2}^-$ and $\frac{5}{2}^+$ for the first and second excited states of F^{19}, respectively.

INTRODUCTION

IN the work reported in this paper the alpha particle and inelastic proton groups from the bombardment of fluorine by protons have been studied in an effort to gain information concerning certain states in O^{16}, F^{19}, and Ne^{20}. In particular, the $F^{19}(p,\alpha)O^{16*}$ reaction has been investigated to determine whether or not there exists an energy level in the O^{16} nucleus in the range of excitation energy 7.1 to 8.7 Mev just above the four known levels[1,2] at 6.05 Mev with spin and parity (0^+), 6.13 Mev (3^-), 6.91 Mev (2^+), and 7.12 Mev (1^-). The alpha-particle model of the O^{16} nucleus[3,4] indicates that levels with these spins and parities could be expected to be the lowest excited states of this nucleus, and that in addition a 2^- state should lie near to the 2^+ state, differing from it only in the "inversion" energy of the tetrahedral structure of the four alpha particles. None of the experiments previous to these studies had been done with high enough resolution to resolve a very narrow doublet in the known level structure, nor had the region just above 7.1 Mev been carefully investigated. Therefore, it appeared worthwhile to use the high resolution equipment available in this laboratory to investigate the region near and above the 2^+ level, the region of lower excitation energy having been covered by Chao *et al.*[2] Special attention was paid to the alpha-particle groups leading to the 2^+ level and the nearby 1^- level in O^{16} to make certain that a 2^- level was not degenerate with one of them. In the first place, the groups were studied with the highest possible energy resolution. Secondly, the angular distributions of these particles relative to the direction of the incident proton beam were studied at various resonance levels of the compound nucleus Ne^{20}. Since these distributions depend in part upon the spin and parity of the final state of the residual nucleus, it was expected that a 2^- state which could not be resolved from either of these levels might be revealed by deviations from the angular distributions expected for either a pure 2^+ or 1^- level. Special high resolution and angular distribution studies of the groups leading to the 3^- and 0^+ states were not made, since it was considered unlikely that the 2^- state would be degenerate with either of these states which lie some 1 Mev lower than the 2^+ state.

In the second part of these studies the inelastic protons from the reaction $F^{19}(p,p')F^{19*}$ were observed in an attempt to find groups corresponding to excited levels in F^{19} reported at 113 and 192 kev by Mileikowsky and Whaling[5] from studies of the $Ne^{21}(d,\alpha)F^{19*}$ reaction. The same two excited levels were also reported by Day,[6] who observed the de-excitation gamma rays following the reaction $F^{19}(n,n')F^{19*}$. The inelastic proton groups leading to these two levels in the bombardment of fluorine by protons had not been previously reported, and our experiment was undertaken to observe these groups and measure their energies. In addition, their angular distributions were studied in order to aid in the determination of the spins and parities of these levels.

The results have been briefly reported in a Letter to the Editor of this journal[7] along with other studies on

* This work was assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

[1] J. Seed and A. P. French, Phys. Rev. 88, 1007 (1952); see also J. M. Freeman, Phil. Mag. 41, 1225 (1950).
[2] Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. 79, 108 (1950); C. Y. Chao, Phys. Rev. 80, 1035 (1950).
[3] J. A. Wheeler, Phys. Rev. 52, 1083 (1937); D. M. Dennison, Phys. Rev. 57, 454 (1940).
[4] D. R. Inglis, Revs. Modern Phys. 25, 390 (1953).
[5] C. Mileikowsky and W. Whaling, Phys. Rev. 88, 1254 (1952).
[6] R. B. Day, Phys. Rev. 89, 908(A) (1953).
[7] Peterson, Barnes, Fowler, and Lauritsen, Phys. Rev. 94, 1075 (1954).

these levels carried out concurrently in this laboratory.[8–10]

APPARATUS AND EXPERIMENTAL PROCEDURE

The 2-Mv electrostatic generator of this laboratory was used to accelerate the protons, which were then passed through an 80-degree electrostatic analyzer of 1-meter radius which made them homogeneous in energy to ± 0.05 percent. The outgoing reaction products were analyzed by a 180-degree variable angle double-focusing magnetic spectrometer of $10\frac{1}{2}$-in. radius. A regulator on the magnet held the current constant to ± 0.02 percent. The detection was done either with a thick emulsion photographic plate or with a scintillation counter consisting of a zinc sulfide screen followed by a 931-A photomultiplier tube.

In the high resolution study of the alpha-particle groups to the 2^+ and 1^- O^{16} levels (usually designated α_2 and α_3) thin, uniform targets of sodium fluoride were evaporated in vacuum onto a thin aluminum foil (0.2 mg/cm^2) which was supported on an aluminum frame. Target thicknesses were determined by measuring the gamma-ray intensity and excitation curve at resonances of known width and cross section, and by using methods of analysis which have been previously described.[11]

The detection in this part of the experiment was done with photographic plates in order to obtain higher resolution than is possible with the scintillation counter arrangement for the same amount of target bombardment. Ilford C_2 plates (1 in.$\times$3 in.) were used, with a 100-micron emulsion thickness. A camera was built which placed the long axis of the plate in the exit focal plane of the spectrometer; the short axis made an angle of 30 degrees with the incident alpha particles. The plate could be withdrawn from this position and exit slits moved into the focal plane without loss of vacuum. Just to the rear of the focal plane was the zinc sulfide screen, followed by the photomultiplier tube.

Momentum spectra of moderate resolution were taken, with the scintillation counter as detector, on the alpha-particle groups under study before and after each run with a photographic plate. This procedure served to locate the groups and to check on the over-all stability of the target, analyzer, and spectrometer. Continuous monitoring of the gamma-ray yield was also carried out. There was no evidence of a shift in the peak positions of the alpha-particle groups indicating that surface contamination was not building up on the targets. A liquid nitrogen cold trap between the target and oil diffusion pump was employed to trap out oil vapors.

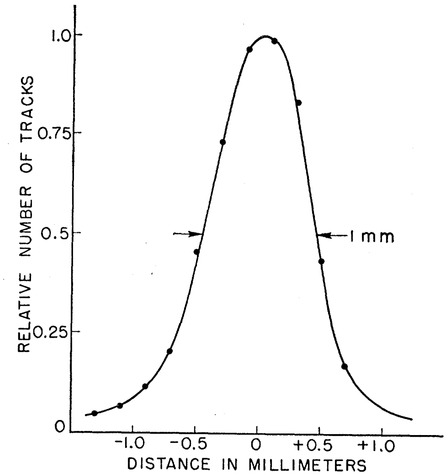

FIG. 1. Distribution in number of particles in the focal plane of the spectrometer normal to the direction of deflection.

After exposure and development of the plates, the alpha-particle tracks were counted employing a microscope which was fitted with a mechanical stage driven by two micrometer screws at right angles, capab e of reproducing any setting to ± 3 microns. A 25$\times$ objective and 8$\times$ eyepiece with counting reticle were used. At this magnification the reticle covered an area approximately $\frac{1}{2}$ mm $\times \frac{1}{3}$ mm on the plate. The position of the tracks measured parallel to the long axis of the plate was a measure of the momentum and thus of the energy of the particles. All tracks in a band $\frac{1}{3}$ mm wide and length 6 mm parallel to the short edge of the plate were counted as due to particles with the same energy. The 6 mm corresponds to a distance of 3 mm in the focal plane normal to the direction of deflection. The distribution of tracks in the focal plane normal to the deflection is shown in Fig. 1. It will be noted that the line image has a half width of only one millimeter. The change in energy per unit length along the photographic plate can be calculated from the expression[12]

$$\delta P/P = \delta E/2E = \delta r/3.6r_0,$$

where P and E are the momentum and energy of a particle in the equilibrium orbit, r_0 is the radius of the equilibrium orbit (10.5 in.), and δr is the distance in the focal plane through which a particle of energy $E+\delta E$ is displaced from one of energy E. For the spectrometer used, $\delta E = E\delta r/480$, for δr in millimeters. For $\delta r = \frac{1}{3}$ mm, $\delta E/E = 1/1440$. Although a magnetic spectrometer essentially measures momentum spectra, it is sometimes convenient in the analysis to convert these to energy spectra and in what follows we will refer to the one most appropriate to the discussion.

In measuring the angular distributions of the alpha particles, uniform targets of the order of 5-kev stopping power for the proton energy used were made as described

[8] Thirion, Barnes, and Lauritsen, Phys. Rev. **94**, 1076 (1954).
[9] Sherr, Li, and Christy, Phys. Rev. **94**, 1076 (1954).
[10] R. F. Christy, Phys. Rev. **94**, 1077 (1954).
[11] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948).
[12] Snyder, Rubin, Fowler, and Lauritsen, Rev. Sci. Instr. **21**, 852 (1950).

above, but the target material was principally zinc fluoride. The gamma-ray intensity and excitation curve was used to measure the target thickness, after which the bombarding energy was set to give the maximum gamma-ray yield. Periodically during runs the gamma-ray excitation curve was run to see whether the resonance peak had shifted, to check against the buildup of surface contaminations on the target. Instead of using the current integrator to determine the amount of bombardment, a fixed number of gamma-ray counts were counted at each point measured. Difficulties in measuring the beam current at the forward angles of observation were thus avoided. This method also is insensitive to variations in target thickness.

In measuring the angular distributions the target was held fixed at either of the two angles +135 degrees or −135 degrees with the incident beam. The angle given is that between the direction of the incident protons and the normal drawn outwardly from the fluorided side of the target. The angle is considered positive when the normal points toward the spectrometer entrance. The target was set at +135 degrees for angles of observation greater than 90 degrees and at −135 degrees for angles less than 90 degrees. In this way, the target thickness was the same for all angles of observation. This method also had the advantage, since the upper energy limit of the spectrometer was 2 Mev for alpha particles, that those particles emitted in forward directions passed through the target backing foil before entering the spectrometer. In addition to this foil, up to two additional foils were inserted in the path of the alpha particles just after leaving the target at the higher energy resonances and at forward angles. The loss in energy of the alpha particles in these aluminum

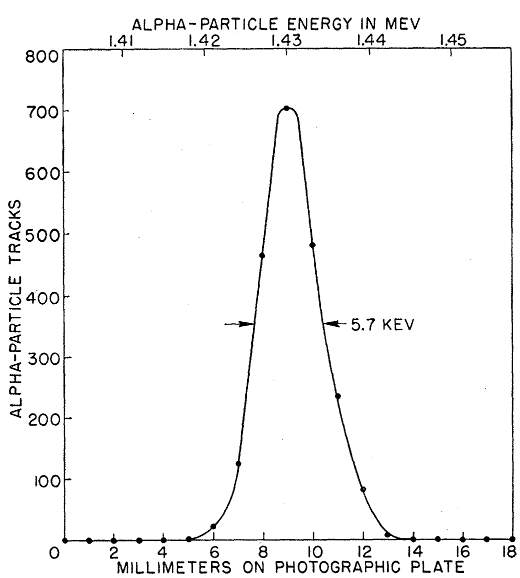

FIG. 2. Energy spectrum of the α_2 group from the $F^{19}(p,\alpha)O^{16*}$ reaction at $\theta_{lab}=137.8°$ and a bombarding energy of 873 kev. In the figure, 5.7 kev should read 8.1 kev.

foils (0.2 mg/cm^2) was 200 kev. A correction factor for loss of alpha particles due to scattering and large energy loss in the foils was determined experimentally by comparing yields which could be obtained with and without foils.

The angles of observation were chosen in order to divide the interval of $\cos^2\theta_{c.m.}$ from zero to one into eight equal parts. All distributions were plotted *vs* $\cos^2\theta_{c.m.}$ for ease in comparison with the theoretical distributions. When plotted in this way, all distributions obtained were fitted reasonably well with either straight lines or parabolas.

The method of obtaining an angular distribution was to determine the momentum-spectrum of the desired alpha-particle group at each angle. The total number of counts at each angle was then obtained by integrating graphically the area under each curve- After dividing this quantity by the momentum corre. sponding to the peak reading,[12] and transforming the resulting quantity to the center-of-mass system, small corrections were made for the losses due to singly charged alpha particles and to the foils, and the data were then normalized to unity at 90 degrees. It was plotted *vs* $\cos^2\theta_{cm}$, forward and back angle points being plotted separately to display fore and aft symmetry if observed.

In studying the inelastic proton groups to the first two known excited levels of F^{19}, the target materials used were principally aluminum fluoride (Al_2F_6) and lithium fluoride (LiF). Here, different target backing materials were also used. Since the Q-values for these reactions (equal to the negatives of the excitation energies of the levels) are so small in magnitude, the inelastic groups fell quite close in energy to the elastically scattered group from F^{19}, and even closer to the elastically scattered groups from O^{16} and C^{12}, which are always present in very thin layers (~10 atoms deep with good trapping) on the target surfaces. In addition to these groups, there were always protons elastically scattered from the target backing material as well as from the other element which made up the fluorine compound used, and from the carbon and oxygen on the rear side of the target support, if this was thin. These groups had lower energy than the groups from O^{16} and C^{12} on the front surface because they traversed the target supporting foil before reaching the spectrometer (see Fig. 7 of reference 12). Because the recoil energy of the scattering nucleus varies with its mass, the various elastically scattered proton groups differ somewhat in energy, the effect being largest at backward angles of observation. Thus very high resolution must be employed to isolate the protons inelastically scattered by F^{19} from the various elastically scattered groups. Two different target backings were used for this purpose. One backing used was a thick layer of lithium deposited in vacuum on copper, the target material in turn being evaporated onto the lithium surface from a second furnace. The protons scattered

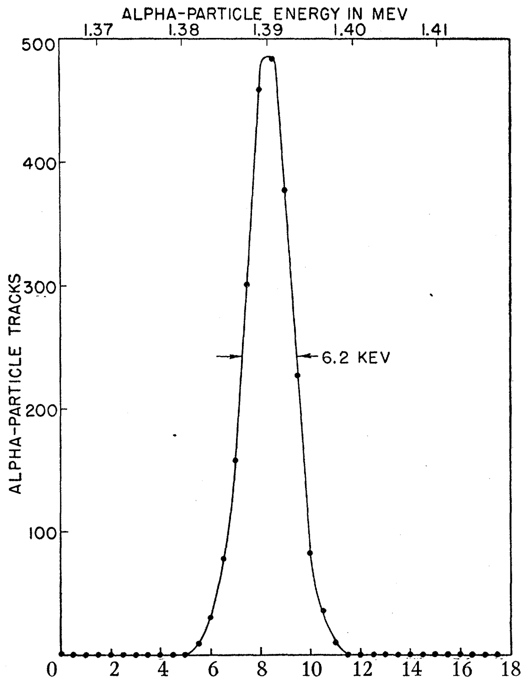

FIG. 3. Energy spectrum of the α_2 group from the $F^{19}(p,\alpha)O^{16*}$ reaction at $\theta_{\text{lab}}=157.7°$ and a bombarding energy of 873 kev.

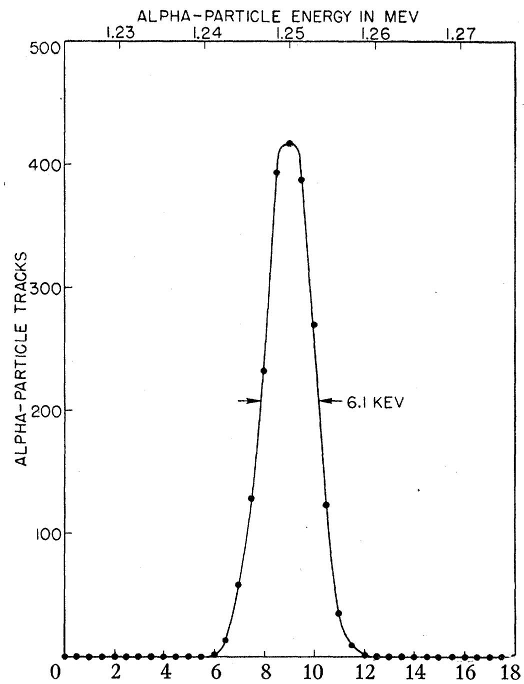

FIG. 4. Energy spectrum of the α_3 group from the reaction $F^{19}(p,\alpha)O^{16*}$ at $\theta_{\text{lab}}=157.7°$ and a bombarding energy of 873 kev.

elastically from the lithium had much less energy than the inelastic groups at angles of observation greater than 90 degrees, and the lithium deposit was thick enough to prevent the incident protons from striking the copper and its surface contaminations. A second target backing was thin aluminum leaf (0.2 mg/cm^2). Protons scattered elastically from the aluminum were at higher energies than the two inelastic groups. However, due to the finite foil thickness and straggling, protons scattered from the rear surface fell too close in energy to the first inelastic group at some angles of observation; in addition, there were always four elastic groups from the carbon and oxygen on the two surfaces of the aluminum leaf. All of these undesired elastic groups made it impossible to observe the inelastic groups separately at all angles in determining angular distributions and the data suffer from incompleteness in this regard. (See Fig. 1 of reference 7.)

DISCUSSION OF RESULTS

(a) $F^{19}(p,\alpha)O^{16*}$

Good energy spectra were obtained with the photographic plates at a bombarding energy of 873 kev for the α_2 group from $F^{19}(p,\alpha)O^{16*}$ at $\theta_{\text{lab}}=90$, 137.8, and 157.7 degrees, and for the α_3 group at $\theta_{\text{lab}}=157.7$ degrees (Figs. 2–4). There is no evidence of doublet structure in any of the curves, and all of the curves are quite symmetrical. In addition, in the best case for each group, the width at half maximum of the peak is about 6 kev. This leads to the conclusion that if a 2^- level exists, its separation from either the 1^- or 2^+ levels is less than 3 kev or more than 100 kev, the energy range covered by the photographic plate. We assume that groups separated by half their width will be clearly resolved.

In searching for a 2^- level separated by more than 100 kev from the known levels, the region of excitation energy higher than the 1^- level at 7.12 Mev was examined, the region of lower energy having been investigated by Chao *et al.*[2] The proton energy was set at 873 kev and a search made for lower energy alpha particles than the α_3-group. The excitation range in O^{16} from 7.12 to 8.7 Mev was covered in this way without finding any new alpha-particle groups. Since there is no simple selection rule which will prevent an alpha-particle transition from the 2^- level in Ne^{20} at 873-kev bombarding energy to a 2^- level in O^{16}, and since the penetration factor is most favorable for *s*-wave alpha particles which can make the transition, we conclude that a 2^- level does not exist in O^{16} in this region. We cannot completely rule out the existence of levels of other spin and parity values.

In order to determine if there was a 2^- level closer than 3 kev to the 2^+ or 1^- levels, the angular distributions of the alpha particles to these levels were studied in detail. Seed and French[1] had already measured the angular distributions for the α_1, α_2, and α_3 groups at the 873-kev resonance for the three angles 90, 120, and 135 degrees, and found agreement with their assign-

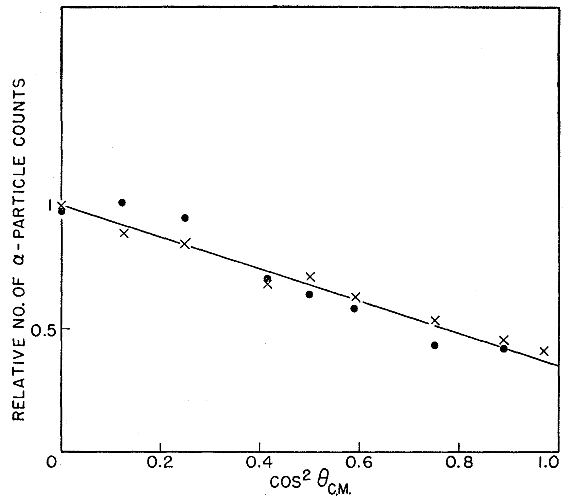

FIG. 5. Angular distribution of the α_2 group from the $F^{19}(p,\alpha)O^{16*}$ reaction at a bombarding energy of 873 kev; the crosses are points taken at angles forward of 90° and the circles are back angle points; the solid curve is $W(\theta)=1-0.65\cos^2\theta$.

ments made on the basis of the α-γ angular correlation measurements without the presence of a 2^- level. With the bombarding energy at 873 kev, the α_2 group was observed at forward and back angles, and an angular distribution described by $1-0.65\cos\theta^2$ obtained with fore and aft symmetry (Fig. 5). As noted previously, the 873-kev resonance level in Ne^{20} is a 2^- level.[1] The theoretical angular distribution for the transition $Ne^{20}(2^-)\rightarrow O^{16}(2^+)$, considering only the lowest values for the orbital momenta of the reacting particles ($l_p=1$, $l_\alpha=1$), is $1-7/9\cos^2\theta=1-0.78\cos^2\theta$. The observed coefficient of $\cos^2\theta$ is lower in magnitude than the predicted one by some 17 percent. If there were a 2^- level, almost or completely degenerate with the 2^+ level, s-wave ($l_\alpha=0$) alpha particles would be permitted, and their angular distribution would be isotropic. This would tend to reduce the coefficient of the $\cos^2\theta$ term as was observed. However, the barrier penetration factor would greatly favor the s-wave alpha particles to the 2^- level, and one would expect an even greater lowering of this coefficient. This is not a conclusive argument since the barrier penetration factor is not the only factor determining transition rates. However, the reduced value of the coefficient may be accounted for without resorting to a new level, simply by taking into account the other two orbital momentum values possible in this transition; $l_p=3$, $l_\alpha=3$. The distributions which consider these next higher values have been calculated by Seed and French.[1] If the relative amplitude of protons with orbital momentum $l+2$ to those with orbital momentum l is A, and their phase difference is α, and if B and β are the same quantities for the alpha particles, then the observed distribution may be fitted with $A=0.06$, $\cos\alpha=0.439$, $B=0.29$, and $\cos\beta=-0.244$. These values of A and B are in agreement with those obtained by Seed and French[1] from the α-γ angular correlation measurements: $A=0.1\pm0.1$, $B=0.35$. The values of α and β may be calculated[13] up to a factor of π, and the signs of $\cos\alpha$ and $\cos\beta$ chosen to give the best fit. We use the same values as calculated by Seed and French.

The angular distribution of the α_3 group (Fig. 6) at the 873-kev resonance was also satisfactorily fitted with the use of the known 1^- level in O^{16} at 7.12 Mev only. Here the same value of A was used (0.06), but only $l_\alpha=2$ is possible.

Finally the α_1 group to the $6.13(3^-)$ level in O^{16} was measured at the 873-kev resonance. Since these particles are too high in energy to be deflected by the spectrometer, their distribution was only measured at back angles, and aluminum foils employed to reduce them to an energy measurable by the spectrometer. The straggling in energy was less than 10 percent. The measured distribution was consistent with the 2^- assignment to the Ne^{20} level and the 3^- assignment to the O^{16} level, with the effects of the higher l-values taken into account. Here B was determined to be 0.37.

These results show that at least in this reaction there is no evidence of a 2^- level in the region one would expect from the alpha-particle model of the O^{16} nucleus. This model predicts the positions of the four known levels only with rather anomalous values of the parameters involved,[4] and from the present results seems to fail in an important respect unless the inversion frequency of the tetrahedral structure is much larger than can be reasonably expected. The implications of these results were anticipated independently by Inglis who has discussed the matter in considerable detail in reference 4, page 433. Our results would seem to

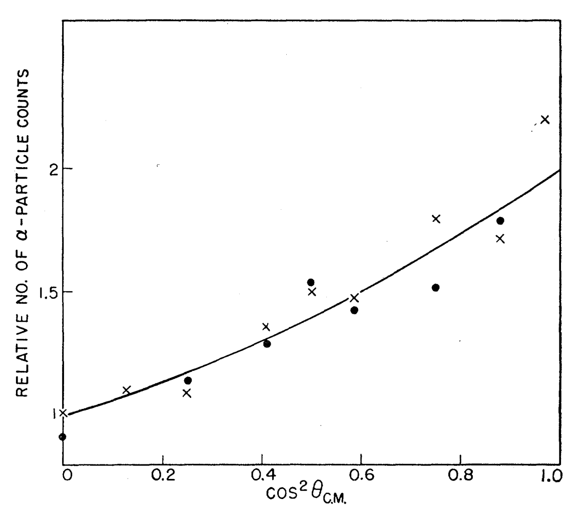

FIG. 6. Angular distribution of the α_3 group from the $F^{19}(p,\alpha)O^{16*}$ reaction at a bombarding energy of 873 kev; the crosses are points taken at angles forward of 90° and the circles are back angle points; the solid curve is $W(\theta)=1+0.61\cos^2\theta+0.39\cos^4\theta$.

[13] Bloch, Hull, Broyles, Bouricius, Freeman, and Breit, Revs. Modern Phys. 23, 147 (1951).

indicate two or four particle excitation for the 2^+ state and probably also for the 0^+ state in O^{16}.

The angular distribution of the α_3 group was measured at the 935-kev resonance as a check on the experimental techniques used, and on the previous assignment[1,2] of spin and parity for this level in Ne^{20}. The 935-kev resonance corresponds to a 1^+ level in Ne^{20} and may be formed by *s*-wave protons. The expected distribution should be mainly isotropic, with *d*-wave protons modifying the distribution slightly. The measured distribution was quite isotropic and served as a satisfactory check. No attempt was made to measure the angular distribution of the α_2 group at this resonance as the yield is very small.

The next distributions measured were those at the 1355-kev resonance. Chao,[2] analyzing the data of Day *et al.*[14] on the de-excitation gamma rays found that satisfactory agreement could be had by assuming the level in Ne^{20} to be either 2^- or 3^+. The alpha-particle distributions, measured for the α_2 and α_3 groups, and shown in Figs. 7 and 8, lead to a 2^- assignment for the Ne^{20} level. The assumption of *p*- and *f*-wave protons leading to a 2^- Ne^{20} level, which decays by *p*- and *f*-wave alpha particles to the O^{16} 2^+ level, and by *d*-wave alpha particles to the O^{16} 1^- level gave a very satisfactory fit to the data. The analysis gave values of $A=0.14$; $B=0.43$ for the α_2 group.

The yields of the α_2 and α_3 groups at the 1290-kev resonance were quite small, and made accurate analysis impossible without more extensive data. The background yield is roughly of the same order of magnitude as the alpha-particle intensity from the resonance itself. The distributions obtained are not inconsistent with the assignment of 3^+ made to the level by Chao.[2]

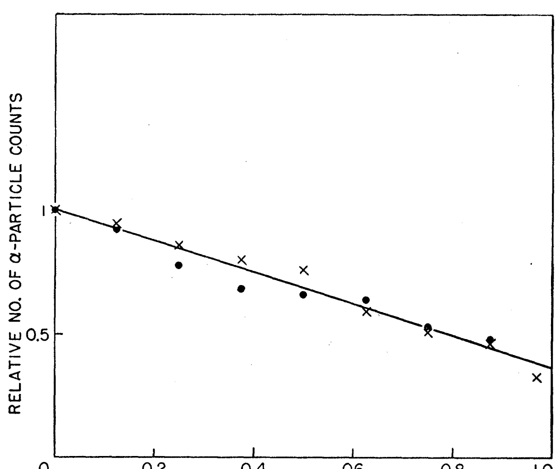

FIG. 7. Angular distribution of the α_2 group from the $F^{19}(p,\alpha)O^{16*}$ reaction at a bombarding energy of 1355 kev; the crosses are points taken at angles forward of 90° and the circles are back angle points; the solid curve is $W(\theta)=1-0.63\cos^2\theta$.

[14] Day, Chao, Fowler, and Perry, Phys. Rev. **80**, 131(A) (1950).

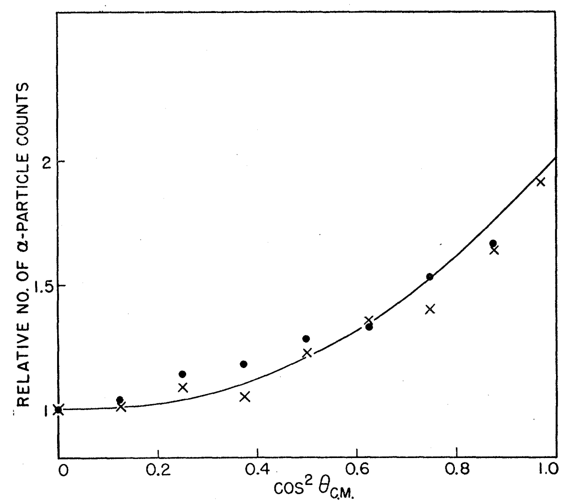

FIG. 8. Angular distribution of the α_3 group from the reaction $F^{19}(p,\alpha)O^{16*}$ at a bombarding energy of 1355 kev; the crosses are points taken at angles forward of 90° and the circles are back angle points; the solid curve is $W(\theta)=1-0.19\cos^2\theta+1.19\cos^4\theta$.

The 1381-kev resonance was previously studied by Day *et al.*[14] The gamma rays were observed with Geiger-Müller counters and no attempt was made to resolve the three high-energy gamma rays which follow the emission of the α_1, α_2, and α_3 groups. All distributions were fitted with curves of the form $1+a\cos^2\theta$. However, as the bombarding energy was varied across the resonance, the coefficient a was found to vary linearly from -0.2 to 0.1, with the value -0.073 at the resonance. This behavior suggests the possiblity of interference, although it could result merely from the change in the relative intensities of the gamma rays as the bombarding energy was changed. On the basis of the smallness of the coefficient at resonance, and of the ratio of gamma-ray intensity at 90 degrees to alpha-particle intensity at 138°, Chao[2] made the assignment of 1^+ to this Ne^{20} resonance level.

Sanders[15] separated the 6.14-Mev gamma ray from the 6.91- and 7.12-Mev gamma rays, using a deuterium-filled ionization chamber. Measurements of the angular distributions of the 6.14-Mev gamma ray and the combination of the 6.91- and 7.12-Mev gamma rays led to a 2^- assignment for the Ne^{20} level. This assignment is in agreement with a preliminary analysis of the data from the elastic scattering of protons studied in this laboratory[16] at this resonance.

The alpha-particle angular distributions obtained at resonance (Figs. 9 and 10) are difficult to fit with either a 1^+ or 2^- assignment, even with the higher *l*-values taken into account. Considering the number of levels in this region, it seems likely that interference effects are modifying the distributions one would expect from a 2^- level. Besides the level in question,

[15] J. E. Sanders, Phil. Mag. **44**, 1302 (1953).
[16] Webb, Hagedorn, Fowler, and Lauritsen, Phys. Rev. **96**, 851 (1954).

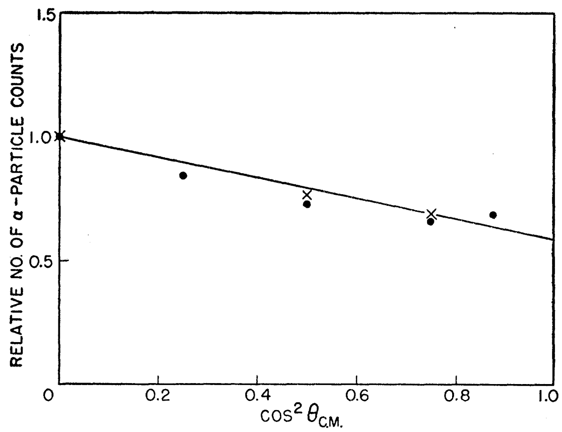

FIG. 9. Angular distribution of the α_2 group from the $F^{19}(p,\alpha)O^{16*}$ reaction at a bombarding energy of 1381 kev; crosses are points taken forward of 90° and circles are back angle points; the solid curve is $W(\theta)=1-0.43\cos^2\theta$.

there is the 2^- gamma-ray resonance at 1355 kev, the 2^+ pair and long-range alpha-particle resonance[17] at 1365 kev, the 1^+ inelastic scattering resonance[16] at 1431 kev, and a nonresonant background.

In order to determine whether interference effects were modifying the alpha-particle angular distributions, the bombarding energy was set at the energies where the gamma-ray yield was equal to one-half its value at the maximum, since the distributions should be quite sensitive to bombarding energy if they are the result of the interference of two or more levels. There was very little change in the α_3 distribution at either bombarding energy, and in the α_2 distribution at the lower bombarding energy. However, at the higher bombarding energy the α_2 distribution was almost isotropic.

A preliminary analysis of the data to determine if any of the above distributions could result from the interference of a 2^- level with one of the other known levels was unsuccessful. Interference with an even parity level seems unlikely since the observed distributions at resonance had fore and aft symmetry at the points measured. The assignment to the level appears to be known with certainty from the elastic scattering[16] and gamma-ray measurements;[15] more extensive data is necessary for complete analysis of the alpha-particle results. The results of the angular distribution measurements of this section are summarized in Table I.

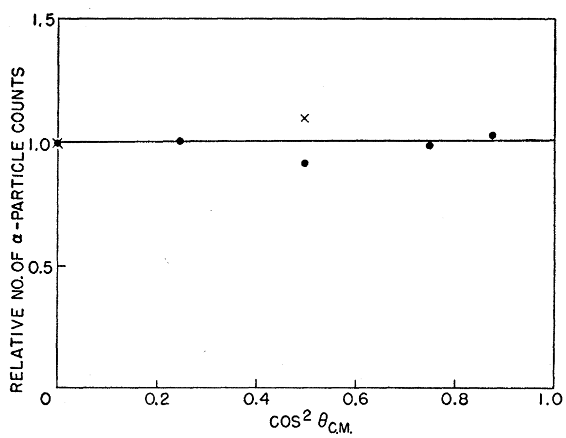

FIG. 10. Angular distribution of the α_3 group from the $F^{19}(p,\alpha)O^{16*}$ reaction at a bombarding energy of 1381 kev; the crosses are points taken at angles forward of 90° and the circles are back angle points; the solid curve is $W(\theta)=1$.

(b) $F^{19}(p,p')F^{19*}$

After finding the two inelastic proton groups corresponding to the two lowest excited levels of F^{19} at a proton energy of 1381 kev, a brief excitation curve was run from just below 1355 kev to about 1500 kev. Both groups were observed to follow the well-known resonances at 1355 and 1381 kev, and in addition there was a much stronger resonance for the first group at 1431 kev, a proton capture resonance reported by Sinclair.[18]

TABLE I. Measured angular distributions of the $F^{19}(p,\alpha)O^{16*}$ reaction.

Resonance energy (kev)	Excitation in Ne^{20} (Mev)	Alpha-particle group[a]	Ne^{20}-level assignment	Measured distribution
873	13.70	α_1	2^-	$1-0.49\cos^2\theta$
		α_2		$1-0.65\cos^2\theta$
		α_3		$1+0.61\cos^2\theta+0.39\cos^4\theta$
935	13.76	α_3	1^+	1
1290	14.10	α_2	$3^+(?)$	1
		α_3		$1+\cos^2\theta$
1355	14.16	α_2	2^-	$1-0.63\cos^2\theta$
		α_3		$1-0.19\cos^2\theta+1.19\cos^4\theta$
1381	14.18	α_2	2^-	$1-0.43\cos^2\theta$
		α_3		1

[a] The α_1 group leads to the 6.13-Mev (3^-) level in O^{16}; the α_2 group to the 6.91-Mev (2^+) level; and the α_3 group to the 7.12-Mev (1^-) level.

The group corresponding to the first excited level was about twenty times as intense as that due to the second excited level. Further excitation curves for the protons were not investigated, since the gamma rays from the de-excitation of the levels were being observed concurrently,[7] and it was a simpler task to observe the resonances for inelastic scattering from the gamma-ray yields.

The Q-values of the reaction were measured at several bombarding energies and angles of observation by determining the energies of the inelastic proton groups. This led to the average values for the excitation energies of the first two excited levels of 108.8 ± 0.8 and 196.0 ± 1.4 kev. These values supercede the previously published values.[7] These results are the averages of twenty measurements, whose statistical error was ±0.4 kev; three measurements whose deviation from the mean was greater than 5 times this value were discarded in the averaging. As a check on these values, calculated by standard methods using the calibrated scales of our analyzer and spectrometer,

[17] Paul, Clarke, and Sharp, Phys. Rev. **90**, 381(A) (1953); and private communication.

[18] R. M. Sinclair, Phys. Rev. **93**, 1082 (1954).

a difference method of calculating Q for inelastic scattering was used in those cases where the F^{19} elastic group was observed at the same time as the inelastic groups. The nonrelativistic expression which may be used for Q in these cases is

$$Q=E_1\left[\frac{M_0+M_1}{M_0}k(r-1)-2\cos\theta\frac{M_1}{M_0}k^{\frac{1}{2}}(r^{\frac{1}{2}}-1)\right],$$

where E_1 is the bombarding energy, M_0 the mass of the target nucleus, M_1 the mass of the incident particle, θ the angle of observation in the laboratory system, $k=E_{el}/E_1$ and $r=E_{inel}/E_{el}=I_{el}^2/I_{inel}^2$.

Here I is the observed fluxmeter setting of the magnetic spectrometer and is inversely proportional to the momentum of the particles observed. The quantity k was calculated using the conservation of energy and momentum for the elastic scattering in which $Q=0$. E_1 was taken as the standard resonance energy and θ was measured on the vernier protractor which has been checked as reliable in numerous previous measurements. The primary measurements involved $r-1$ and $r^{\frac{1}{2}}-1$ and these differences could be determined with high precision independent of extensive calibrations of the spectrometer. This method of calculation cancels out many sources of error but neglects target surface layer corrections to second order in that the elastic and inelastic groups have slightly different energies and hence have different energy losses in the layers. This check was satisfactory, the values 109.5 and 196.1 kev being obtained in those cases where the F^{19} elastic group was observed simultaneously with the inelastic groups, and these values agreed very closely with the values calculated for these cases using our standard calibrations and surface layer corrections. The average values of all the measurements which we give in the previous paragraph are considered to be the best results.

TABLE II. Measured coefficient in the angular distribution, $1+a\cos^2\theta$, for the reaction $F^{19}(p,p')F^{19*}$.

Resonance energy (kev)	Excitation in Ne^{20} (Mev)	Ne^{20} level assignment	Value of a: To 109-kev level	To 196-kev level
873	13.70	2^-	···	0 ± 0.1
1355	14.16	2^-	···	0 ± 0.1
1381	14.18	2^-	···	-0.45 ± 0.04
1431	14.23	1^+	0 ± 0.1	···

The cross sections for the inelastic scattering processes were measured at two bombarding energies. The method of calculating these cross sections was to observe the momentum spectrum of the fluorine elastic group along with the two inelastic groups, and to calculate the area under each of these graphically. The cross section for each of these processes is proportional to this number divided by the momentum reading at the peak. The ratios of the inelastic scattering cross sections to the elastic scattering cross section were thus obtained. The absolute cross sections for the inelastic scattering were determined by using the absolute differential cross section for the elastic scattering process which were measured in this laboratory.[16] The values obtained in this manner were in good agreement with those obtained from the gamma-ray yields.[19]

The cross sections for both groups were measured at the 1431-kev resonance. The measurements were made at 159.7 degrees in the laboratory system; the elastic scattering measurements[16] indicated that this resonance level in Ne^{20} had spin and parity 1^+. Since this state may be formed by s-wave protons, angular

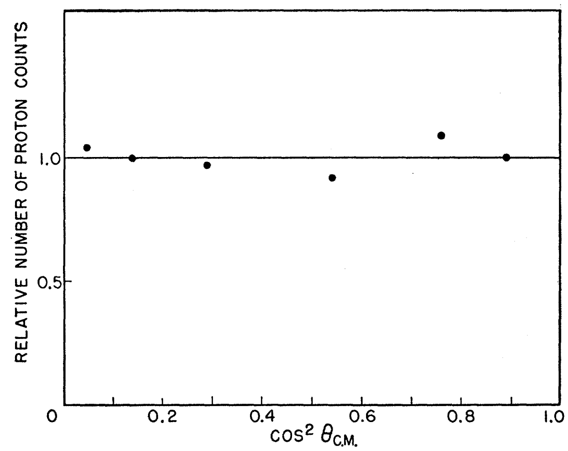

FIG. 11. Angular distribution of the inelastic proton group to the 196-kev excited level of F^{19} at a bombarding energy of 1355 kev; all points were taken at angles greater than 90°; the solid curve is $W(\theta)=1$.

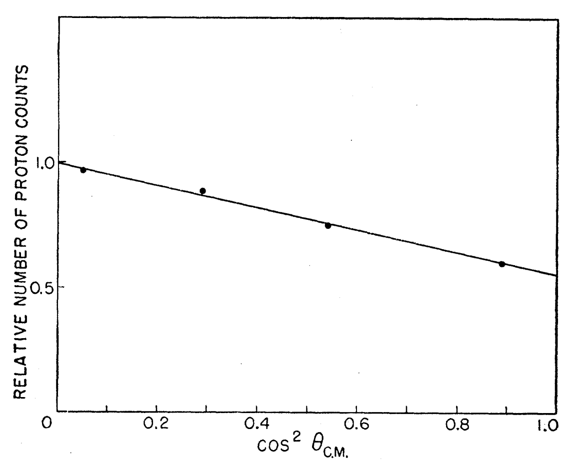

FIG. 12. Angular distribution of the inelastic proton group to the 196-kev excited level of F^{19} at a bombarding energy of 1381 kev; all points were taken at angles greater than 90°; the solid curve is $W(\theta)=1-0.45\cos^2\theta$.

[19] Barnes, Fowler, Lauritsen, and Peterson, Phys. Rev. **96**, 851 (1954).

distributions for both of the inelastic groups were expected to be isotropic. This was checked experimentally for the first group. The resulting cross sections were 0.187 ± 0.015 barn for the group to the first excited level, and 0.007 ± 0.002 barn for the second group. At the 1381-kev resonance the yield of the second group was measured at 90 degrees. The measured angular distribution was $1-0.45\cos^2\theta$, and this was used to get the cross section from the differential cross section. The result was 0.0427 ± 0.0040 barn as the cross section for the second group.

The results of the angular distribution measurements are listed in Table II. All distributions were fitted with curves of the form $1+a\cos^2\theta$; the coefficients a are listed. In addition, the angular distributions for protons to the 196-kev level at bombarding energies of 1355 kev and 1381 kev are shown in Figs. 11 and 12. The angular distribution data is meager, due to the difficulties involved in isolating the groups from elastically scattered groups. In addition, the 935- and 1431-kev resonances were not useful in attempting to determine the spins and parities of the two F^{19} excited levels as both are 1^+ levels formed by s-wave protons. The results are made more difficult to analyze due to the presence of the proton spin, making two outgoing channel spins possible in general.

Unique assignments for the excited levels of F^{19} could not be made on the basis of the inelastic proton results alone due to the reasons discussed above. However, measurements on the de-excitation gamma ray and on the $F^{19}(\alpha,\alpha')F^{19*}$ reaction did result in the assignments $\frac{1}{2}^-$ and $\frac{5}{2}^+$ for the first and second excited states respectively. These assignments are discussed in detail in an accompanying publication.[20] Our results are consistent with those assignments.

In conclusion we wish to express our appreciation to C. A. Barnes, R. F. Christy, R. Sherr, and J. Thirion for many discussions of these results.

Note added in proof.—In a recent paper, Dennison [Phys. Rev. **96**, 378 (1954)] has extended his original calculations[3] on the tetrahedral alpha particle model of O^{16} and has made two different identifications of the theoretically predicted energy levels with those observed experimentally. In the first identification the 6.91-Mev level is identified with a 2^+ level of the first excited state of the triply degenerate normal mode of vibration of the alpha particles (ω_3). A 2^- level is not associated with this level. In the second identification, which corresponds to our previous discussion based on the original paper,[3] the 6.91-Mev level is identified with a $2^\pm$ level of the first excited state of the doubly degenerate mode of vibration (ω_2). In the light of these considerations, our results stand as a strong argument in favor of Dennison's first identification unless, as indicated above, the inversion frequency separating the 2^+ and 2^- states in the second identification is much larger than can be reasonably expected.

[20] Sherr, Li, and Christy (following paper).

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Coulomb Excitation of F^{19} by Alpha Particles*

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Gamma rays emitted in the excitation of F^{19} by α particles of 0.6 to 2.8 Mev have been studied. Resonances are found in the reaction $F^{19}(\alpha,p)Ne^{22*}$ at α particle energies greater than 1.3 Mev and in the inelastic excitation of 109-kev and 196-kev levels in F^{19} at energies greater than 2.2 Mev. At bombarding energies below 2 Mev, the cross sections for inelastic excitation of F^{19} decrease much too slowly for compound nucleus formation and are identified as being due to Coulomb excitation. The observed cross sections in the region 0.6 Mev to 2 Mev agree well with the theory for Coulomb excitation. The electromagnetic transition probabilities for decay of these states deduced from the excitation cross sections are in good agreement with those found from direct measurement of the lifetimes by Thirion, Barnes, and Lauritsen. Together with the results of Peterson, Barnes, Fowler, and Lauritsen on the inelastic excitation of fluorine by protons, these experiments lead to spin and parity assignment of $\frac{1}{2}^-$ for the 109 kev state and $5/2^+$ for the 196-kev state of F^{19}. The observed angular distributions of the γ rays from Coulomb excitation by α particles are also in accord with theory.

I. INTRODUCTION

Although extensive investigations of nuclear reactions in light nuclei have been carried out with protons and deuterons, relatively little work has been done with artificially accelerated α particles. In the present paper we wish to summarize our results on several reactions induced in F^{19} by α particles in the energy range 0.6 to 2.8 Mev. We have studied only those reactions yielding γ radiation. These are the $F^{19}(\alpha,p)Ne^{22*}$ reaction leading to the excited state of Ne^{22} at 1.28 Mev ($Q=426$ kev) and the excitation of F^{19} states at 109 kev and 196 kev[1] in the reaction $F^{19}(\alpha,\alpha')F^{19*}$.

The first and second excited states of F^{19} are particularly interesting insofar as they are exceptionally

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[1] The energies of the low states of F^{19} quoted in this paper are somewhat lower than those in references 6–9 and reflect revised estimates based on private communication from R. B. Day, recent measurements by Mills, Hilton, and Barnes (unpublished); and new calculations of data of Peterson, Barnes, Fowler, and Lauritsen.