PHYSICAL REVIEW VOLUME 79, NUMBER 1 JULY 1, 1950

Low Energy Alpha-Particles from Fluorine Bombarded by Protons

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(Received March 6, 1950)

The low energy alpha-groups from the reaction $F^{19}(p, \alpha)O^{16*}$ have been studied at various resonances between proton energies of 340 kev and 1381 kev. Four groups have been identified. For the reaction energy of the α_π group, preceding the pair emission, we find $Q_\pi = 2.061 \pm 0.010$ Mev and for the three other groups preceding gamma-ray emission we find $Q_1 = 1.977 \pm 0.008$, $Q_2 = 1.204 \pm 0.008$ and $Q_3 = 1.002 \pm 0.008$ Mev. Each of the Q-values when added to the corresponding pair-energy or gamma-ray energy found by Rasmussen, Hornyak, Lauritsen, and Lauritsen gives a value for the total reaction energy of $F^{19}(p, \alpha)O^{16}$ which is the same for all the groups, namely 8.113 ± 0.030 Mev. The relative intensities of the α_1, α_2, and α_3 groups are found to vary from one resonance to another and the sum of their absolute yields per proton per 4π-steradians at 138° is found to be very close to the absolute yield of the gamma-rays per proton per 4π-steradians at 90° at all the resonances investigated, the gamma-ray yield being measured simultaneously with the alpha-particle yields. The absolute yield of the α_π-group agrees in order of magnitude with the pair yield determined in this laboratory and elsewhere. The small discrepancies can probably be attributed to angular distribution factors. The excitation functions of the α_1- and α_2-groups have been compared carefully with that of the gamma-rays over certain regions of the proton energy. Over each resonance, the excitation functions of the alpha-groups and the gamma-rays can be represented by the same curve by suitable normalizations. Our excitation curve of the α_π-group is found to run parallel with the excitation curve of the pairs found by Bennett *et al.*

I. INTRODUCTION

THE bombardment of fluorine by protons results in the production of high energy alpha-particles and several low energy groups. The high energy alpha-particles leave the residual nucleus, O^{16}, in the ground state and the low energy groups leave the O^{16} in one level which decays by the emission of a positive and negative electron-pair and several levels which decay by gamma-ray emission. The excitation function and absolute yield of the high energy alpha-particles, of the gamma-rays, and of the pairs were measured simultaneously by Streib, Fowler, and Lauritsen.[1] A review of the literature on the subject prior to 1941 will be found in their paper. The excitation function and yield of the gamma-radiation and of the pairs have also been measured by Kojima[2] and by Bonner and his collaborators.[3] The latter group used monoenergetic proton beams and thin targets and were able to ascertain the natural widths of the sharp resonance levels in the excitation curves with considerable precision.

The energy and intensity of the gamma-ray components have been measured by Walker and McDaniel[4] and recently by Rasmussen, Hornyak, Lauritsen, and Lauritsen,[5] who have also measured the energy and intensity of the pairs. The low energy alpha-particles have been studied by Freeman and Baxter[6] and by Burcham and Freeman.[7] The latter authors found that the observed low energy groups can be explained by assuming the existence of three gamma-ray emitting levels of O^{16} at 6.13, 6.94, and 7.15 Mev in addition to the pair emitting level at about 6.00 Mev. For convenience we shall call the alpha-group corresponding to the pair excitation the α_π-group, and those corresponding to the three gamma-ray levels the α_1-, α_2-, and α_3-groups in the order of decreasing alpha-energy.

We have recently measured the energy and intensity of the four low energy alpha-groups at most of the resonances between 340 kev and 1381 kev bombarding energy and have also determined the excitation functions for α_1, α_2, and α_π over two energy regions of particular interest. The Q-value we obtain for each group when added to the corresponding gamma-ray energy or pair energy found by Rasmussen, Hornyak, Lauritsen, and Lauritsen, gives a value for the total reaction energy of $F^{19}(p, \alpha)O^{16}$, which is constant over all the groups, namely 8.113 ± 0.030 Mev. The relative intensities of the α_1-, α_2-, and α_3-groups also agree very well with their relative gamma-ray intensities and the absolute yields of the alpha-groups agree with previous measurements of the absolute gamma-ray yields.[1] The absolute yield of the α_π-group agrees in order of magnitude with pair yields determined in this laboratory[1] and elsewhere.[3] The discrepancies can probably be attributed to angular distribution factors. The intensity ratios of α_1, α_2, and α_3 are found to vary in a complicated way from one resonance to another. For low bombarding energies and hence relatively low alpha-energies, the barrier effect apparently decreases the probability for the emission of α_2 and α_3 to the point where α_1 is by far the strongest component. Even at the higher energy resonances α_1 remains the strongest of the three, but in some cases α_2 and α_3 reach comparable intensities.

II. EXPERIMENTAL PROCEDURE

The protons were accelerated in an electrostatic generator and their energy was held constant within

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[1] Streib, Fowler, and Lauritsen, Phys. Rev. **59**, 253 (1941).

[2] S. Kojima, Proc. Imp. Acad. Toyko **19**, 282 (1943).

[3] Bennett, Bonner, Mandeville, and Watt, Phys. Rev. **70**, 882 (1946); T. W. Bonner and J. E. Evans, Phys. Rev. **73**, 666 (1948).

[4] R. L. Walker and B. D. McDaniel, Phys. Rev. **74**, 315 (1948).

[5] Rasmussen, Hornyak, Lauritsen, and Lauritsen, Phys. Rev. **77**, 617 (1950).

[6] J. M. Freeman and A. S. Baxter, Nature **162**, 696 (1948).

[7] W. E. Burcham and J. M. Freeman, Phys. Rev. **75**, 1756 (1949).

0.03 percent by an electrostatic analyzer which was calibrated by measurement on the strong gamma-ray resonance in the reaction $F^{19}(p, \alpha\gamma)$ at the proton energy of 873.5 kev.[8] The target consisted of a thin evaporated layer of ZnF_2 deposited on a copper surface. New targets were deposited on clean copper surfaces from time to time throughout the experiment. In general the targets had a stopping power of about 5 kev for 1-Mev protons. The alpha-particles emerging from the target in the angular interval 134.5° to 141.1° with respect to the incident beam were analyzed by a double focusing magnetic spectrograph[9] and detected with a scintillation counter.[10] The resolving power of the spectrograph in momentum was $R = P/\delta P = 128$ and the solid angle of acceptance was 0.0061 steradian $\approx 1/2000$ of the whole sphere. The analyzer was calibrated by observations on protons scattered from copper surfaces into the spectrograph with known energy. The energy of the protons before scattering was determined by the electrostatic analyzer and the energy after scattering at the mean angle of 137.8° was calculated using the usual conservation laws of energy and momentum.

The gamma-ray intensity was measured by a Geiger-Müller counter set at a distance of 6.35 cm from the target in a direction perpendicular to the proton beam. At strong resonances, the counter was set at a distance of 12.7 cm in order to avoid too high a counting rate. The counter was surrounded by an aluminum cylinder of 0.1 inch wall thickness which was enclosed in a lead cylinder of 1 inch wall thickness. A window was cut in the front of the lead cylinder between counter and target and was covered with $\frac{1}{8}$ inch of lead during most of the experiments. In measuring the number of alpha-particles or the gamma-ray intensity, the proton beam was made to charge a condenser to a given voltage. The number of alpha-particles or of gamma-quanta then corresponds to a given number of microcoulombs of protons impinging on the target.

Two types of measurement were made for the low energy alpha-particles: (a) the momentum distribution of the alpha-particles near the exact resonances of the reaction and (b) the excitation functions for the different alpha-groups. For (a), the position of a resonance peak was first located by measuring the gamma-ray intensity or the pair intensity as a function of the proton energy. With the proton energy fixed at the setting corresponding to maximum yield,[10a] the number of alpha-particles which passed through the spectrograph was measured and plotted as a function of the fluxmeter reading, the latter being inversely proportional to the magnetic field of the spectrograph. The area under the profile of each group then gives a measure of the yield of the target for that group. For (b) the spectrograph field was always adjusted to give the maximum number of alpha-particles for the group investigated at any proton energy. This maximum number of alpha-particles was measured as a function of the proton energy and hence gives data from which the excitation curve for the particular group can be derived. The detailed methods of calculation are discussed below.

The maximum energy of the alpha-particles which could be deflected by the spectrograph was about

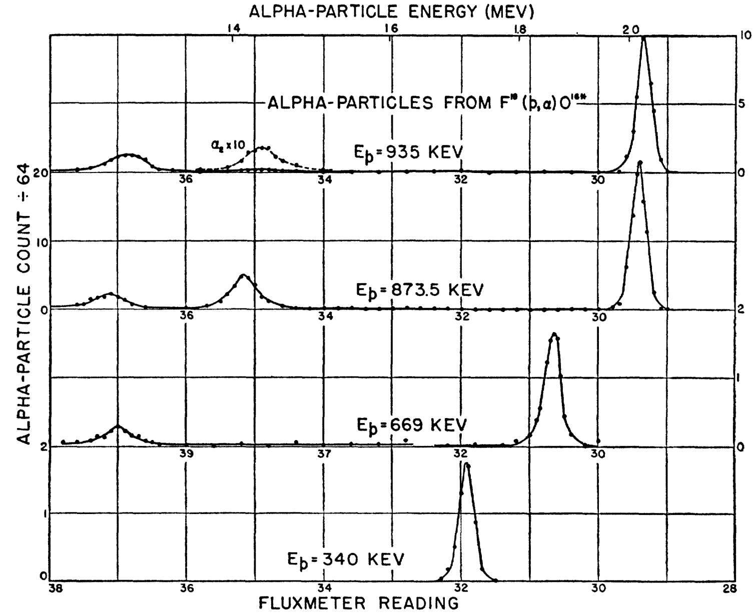

FIG. 1. Spectral distribution of low energy alpha-particles from fluorine bombarded by protons of energies 340, 669, 874, and 935 kev, at 138°.

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[8] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).

[9] Snyder, Fowler, Lauritsen, and Rubin, Phys. Rev. **74**, 1564A (1948).

[10] Tollestrup, Lauritsen and Fowler, Phys. Rev. **76**, 428 (1949).

[10a] This corresponds to the resonance energy plus one-half of the target thickness in energy units. This last value was always less than 5 kev.

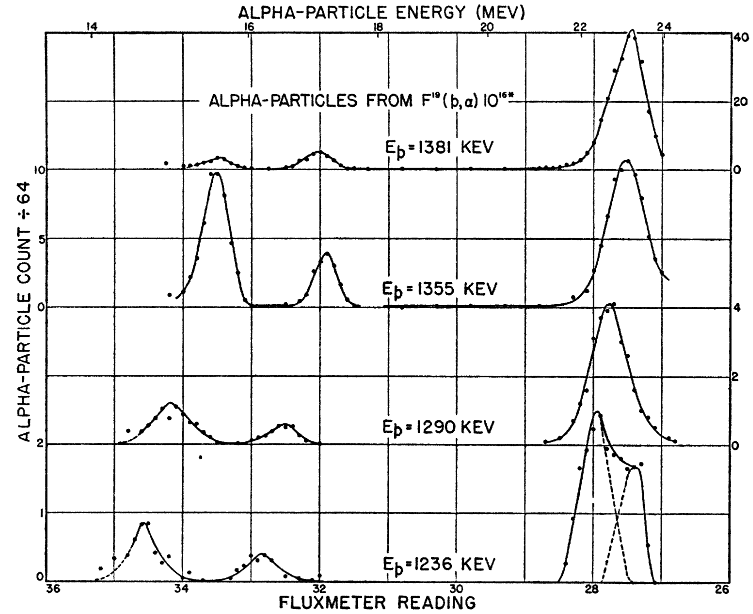

FIG. 2. Spectral distribution of low energy alpha-particles from fluorine bombarded by protons of of energies 1236, 1290, 1355, and 1381 kev at 138°.

2 Mev. When the energy of the alpha-particles exceeded this limit, aluminum foils, each of thickness about 0.2 mg/cm^2 were inserted before the spectrograph so as to reduce the energy of the alpha-particles to a value within the range of the spectrograph.

III. EXPERIMENTAL RESULTS ON Q-VALUES

The spectral distribution of the low energy alpha-particles was investigated at 9 proton energies corresponding to the more prominant resonances for the gamma-ray excitation between 340 kev and 1381 kev, and also at 843 kev and 1236 kev corresponding to two pair resonances. Figures 1 and 2 give the observed number of alpha-particles as functions of the fluxmeter reading for 8 of these resonances. The ordinate gives in each case the actual number of alpha-particles observed divided by 64 when the target received 26.85 microcoulombs of protons. The spectral distribution of the α_1- and α_π-groups in the neighborhood of the pair resonance at 843 kev was investigated for three different proton energies (Fig. 3) with the main purpose of resolving these two groups so that the intensity and energy of each group could be determined.

The excitation function of the α_1-group was investigated between the proton energies 870 kev and 970 kev, that of the α_2-group in the same range and also between 1240 kev and 1420 kev, and finally that of the α_π-group between 1050 kev and 1360 kev. These functions are shown in Fig. 4, together with the simultaneously measured gamma-ray excitation functions. In the same figure, we also show the excitation function for pairs measured by Bennett *et al.*[3]

As was mentioned above, in determining the spectral distribution of the alpha-particles at each resonance, the resonance peak was first located by taking the excitation curve of the gamma-rays. From the observed half-value width Γ' and the true half-value width Γ as given by Bonner and Evans,[3] we can calculate the target thickness ξ from the relation

$$\xi = (\Gamma'^2 - \Gamma^2)^{\frac{1}{2}}. \tag{1}$$

All quantities in (1) must be expressed in energy units. The proton beam was then adjusted to the peak intensity of the gamma-ray excitation and the alpha-particle spectrum determined. It is clear that the energy of the protons was at exact resonance at the middle layer of the target and that the energy of the alpha-particles produced in this layer represents the average energy of the group. This average energy is given by the peak of the symmetrical spectral distributions. The energy of these alpha-particles was reduced, however, by a certain amount in emerging from the target. This amount can be estimated from the target thickness ξ for the proton beam, the relative stopping power of the target for protons and alpha-particles of the appropriate energies, and the angles between the alpha-beam and proton beam and the normal to the target. In calculating the energy of each alpha-group we apply this correction[10b] throughout, which is about 3 percent in the most unfavorable case. For the sake of uniformity we take the resonance energies of Bonner and Evans and apply a correction factor such that the standard gamma-ray resonance is at 873.5 kev. From the measured alpha-particle and proton energies the energy released in the reaction, Q, can be computed by customary methods. Relativistic corrections to the alpha-particle and proton energy determinations have been made but they are less than 0.1 percent in relative magnitude.

[10b] The correction for the energy of the alpha-particles in emerging from the target is about 20 kev for the α_π- and α_1-groups, 26 kev for the α_2-group, and 28 kev for the α_3-group. The corrections in Q are about 25 percent greater.

For the evaluation of the Q-values, we use only those data which were obtained with fresh targets. The results are given in Table I, where Q_1, Q_2, Q_3, and Q_π are the Q's corresponding to the ejection of the α_1-, α_2-, α_3-, and α_π-groups, respectively. It is to be noted that most of the Q-values given in Table I were obtained at $E_p = 874$ kev.

In our experiments, the α_π-group was completely resolved from the α_1-group only near 840 kev and it was analyzed by the magnetic spectrograph after passing through an Al foil of 0.2 mg/cm^2. The results for three bombarding energies, 842 kev and 851 kev both close to the pair resonance, and 874 kev the gamma-ray resonance, are shown in Fig. 3. The target used at 842 kev and 874 kev had an equivalent thickness of 5.2 kev and that used at 851 kev had an equivalent thickness of 2.7 kev. Note that at 874 kev the yield has been multiplied by a factor of 1/64. Note also the increase in energy of α_1 and α_π with increasing proton energy. The absolute energy of the α_π-group obtained using the Al foil is not as accurate as the energies of the other groups. However, the α_1-group energy was also measured after passage through the foil, as well as directly. From the data obtained using the foil we obtain $(Q_\pi - Q_1)$ with good accuracy. This value, when combined with the value of Q_1 determined directly, gives the value of Q_π.

The statistical probable errors of the Q-values given in Table I evaluated from the mean square deviation from the mean values vary from 0.1 percent in the case of Q_1 (± 2 kev) to 0.5 percent in the case of Q_3 (± 5 kev). We have attempted to estimate possible systematic errors in our experiments. We estimate these systematic errors to be 0.2 percent in the bombarding energy, 0.3 percent in the measured energy of the alpha-particles and 0.3° in the angle of observation. These various sources of error and the statistical error have been combined in the usual manner to give the results included in Table I. In general our Q-values are slightly higher than previously published results[7,11] although the recent values of Burcham and Freeman[7] agree with our values within their probable error (± 0.08 Mev). Our value for Q_1 also agrees with the value $Q_1 = 1.969$ Mev given recently by Strait *et al.*[12]

IV. DISCUSSION OF THE ENERGY MEASUREMENTS

By means of an electron spectrometer, Rasmussen, Hornyak, Lauritsen, and Lauritsen have recently made a careful study of the energies and intensities of the gamma-ray components and of the pairs of the reaction $F^{19}(p, \alpha)O^{16*}$. Each of our Q-values given in Table I when added to the corresponding pair-energy or gamma-ray energy will give the total Q of the reaction $F^{19}(p, \alpha)O^{16}$. Their experiment gives a unique answer for the energy of the pair and of the γ_1-component corresponding to the α_1-group. But their resolution was not high enough to resolve γ_2 and γ_3. They observed, however, in the intensity curve a shift of the common peak arising from these two components as the energy of the proton beam was changed from one resonance to another. This is because the relative intensities of the two components are not the same for all resonances. In other words, they have measured an average value of the gamma-ray energy weighted according to the relative intensities of the two gamma-rays. As will be discussed in more detail in a later section we have measured the alpha-particle intensities as well as the Q-values. We are thus able to calculate an appropriately averaged value for Q_2 and Q_3 which combined with the measured gamma-ray energy should give the total energy release in the reaction. Of course our intensity measurements on the alpha-particles were made at a specific angle of observation (138°) while the gamma-rays were observed in the forward direction. Thus our result may contain a small error if the angular distribution of the alpha-particles or gamma-rays is markedly anisotropic. The results are given in Table II. In determining the final mean value $Q_0 = 8.113 \pm 0.030$ for the $F^{19}(p, \alpha)O^{16}$ reaction we give one-half weight to each of the two measurements based on the average results for the lower energy alpha-groups and the corresponding gamma-rays. The internal consistency of the results is excellent.

It is of some interest to compute the energy values of the excited states of O^{16} using the average value for Q_0

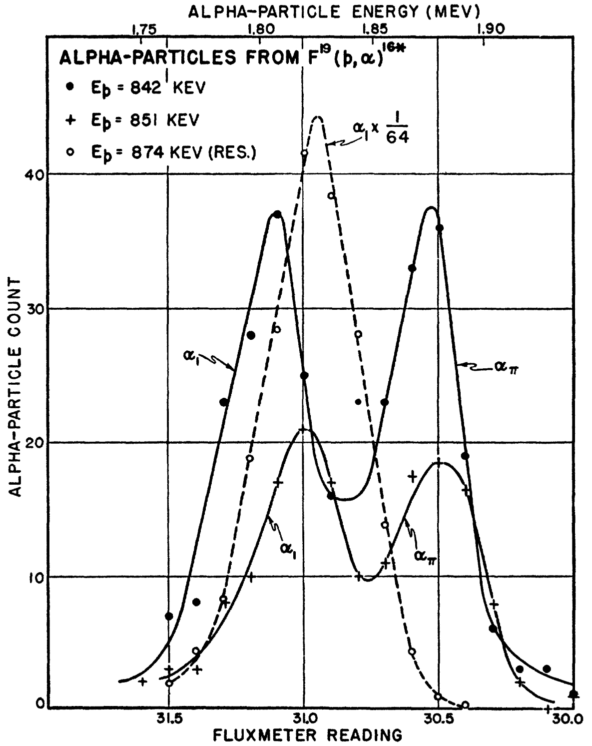

FIG. 3. Spectral distribution of α_1 and α_π groups in the neighborhood of the pair resonance at 843 kev. ($\theta = 138°$.)

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[11] Becker, Fowler, and Lauritsen, Phys. Rev. **62**, 186 (1942).

[12] Strait, Van Patter, and Buechner, Phys. Rev. **78**, 337A (1950).

calculated above and the measured values for Q_π, Q_1, Q_2, and Q_3. The results are given in the bottom line of Table I. The absolute probable errors are about 30 kev but the difference in any pair of values has an error of only 10 kev or less.

V. THE YIELD OF THE LOW ENERGY ALPHA-PARTICLES

Let $N_\alpha(I)$ be the number of alpha-particles observed at given fluxmeter[13] reading, I, of the spectrograph when q microcoulombs of protons are received by the target. Because of the loss of energy of the incident protons and of the emergent alpha-particles in the target material, the alpha-particles will be distributed over a finite interval in energy and momentum. Even with the thin targets used in these experiments this interval was larger than that accepted by the spectrograph. It was thus necessary to integrate the alpha-particle counts over all readings corresponding to one group to obtain the total yield for each group. Let $R=P/\delta P=|I/\delta I|$ be the momentum resolution of the spectrograph as determined by its entrance and exit slits and let Ω_c be the solid angle in the center-of-mass system within which alpha-particles can traverse the spectrograph from target to counter. Then the number of alpha-particles per proton per 4π-steradians per unit interval on the fluxmeter scale is

$$y(\alpha)=(4\pi R/q\Omega_c)(N_\alpha(I)/I)\times 1.602\times 10^{-13}. \qquad (2)$$

Integrating over the total area under the peak corresponding to a given group we obtain

$$Y(\alpha)=\int y(\alpha)dI=(4\pi R/q\Omega_c)\int (N_\alpha(I)/I)dI \times 1.602\times 10^{-13}, \qquad (3)$$

which is the yield in alphas per proton per 4π-steradians appropriate to the target thickness and angle of observation, 137.8°, used in the measurement of $N_\alpha(I)$. The integrals in (3) were evaluated graphically from plots of $N_\alpha(I)$ *vs.* I such as are shown in Figs. 1 and 2.

The quantity Ω_c can be calculated from the solid angle in the laboratory system, Ω, by the following formula

$$\Omega_c=\frac{(1+2\alpha\cos\theta_c+\alpha^2)^{\frac{3}{2}}}{1+\alpha\cos\theta_c}\Omega$$

$$\approx(1+2\alpha\cos\theta_c)\Omega \quad \text{(for small values of } \alpha\text{)},$$

where

$$\alpha=\left[\frac{M_1M_2E_1}{(M_1+M_0)M_3Q+M_0M_3E_1}\right]^{\frac{1}{2}}$$

and where the angle of ejection in the center of mass system, θ_c, is related to that in the laboratory system, θ, by the equation

$$\cot\theta_c+\alpha\csc\theta_c=\cot\theta. \qquad (5)$$

For small values of α useful forms of this last expression are

$$\cot\theta_c=\cot\theta-\alpha\csc\theta+\cdots,$$

and

$$\theta_c=\theta+\alpha\sin\theta-\alpha^2\sin^2\theta+\cdots.$$

In the expression for α, given above, M_0, M_1, M_2, and M_3 are the masses of the target nucleus, incident particle, ejected particle and residual nucleus while Q is the energy release, $(M_0+M_1-M_2-M_3)c^2$, in the reaction.

The quantity $4\pi R/\Omega$ was obtained by measuring the number of protons scattered by a copper target into the spectrograph and by calculating the number ex-

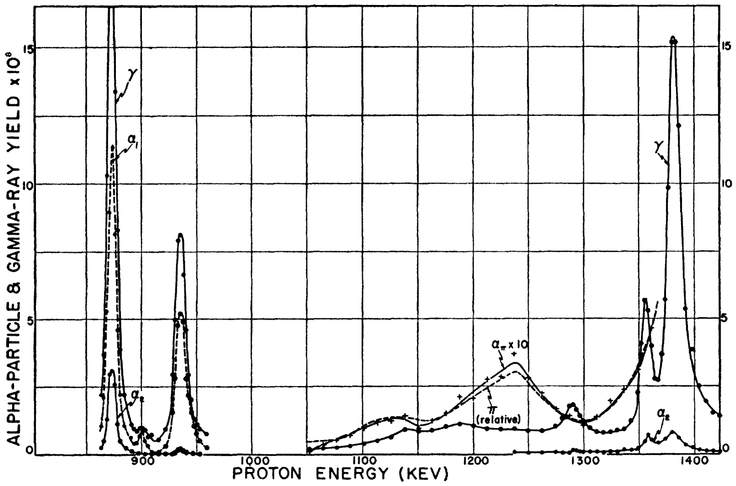

FIG. 4. Excitation functions of α_1-, α_2- and α_π-groups and of gamma-rays. ($\theta=138°$, target thickness = 8 kev at 874 kev proton energy.)

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[13] C. C. Lauritsen and T. Lauritsen, Rev. Sci. Inst. **19**, 916 (1948). The fluxmeter reading is inversely proportional to the spectrograph field and thus inversely proportional to the momentum/charge of the particles traversing the spectrograph.

TABLE I. Q-values for $F^{19}(p, \alpha)O^{16*}$ (all in Mev).

E_p	Q_1	Q_2	Q_3	$Q_\pi - Q_1$	Q_π
0.340	1.982				
0.842				0.087	
0.851				0.080	
0.874	1.972				
0.874	1.974	1.212	1.010		
0.874	1.980	1.198	1.005		
1.353		1.203	0.990		
Mean	1.977 ±0.008	1.204 ±0.008	1.002 ±0.008	0.084 ±0.006	2.061 ±0.010
$h\nu$	6.136	6.909	7.111		6.052

$h\nu$ is calculated using $Q_0 = 8.113$ Mev.

TABLE II. Calculated energy for the $F^{19}(p, \alpha)O^{16}$ reaction (Mev).

Resonance	Alpha-group	Q_α†	$h\nu$	Q_0
1236	α_π	2.061±0.010	6.04±0.03	8.101±0.03
874, 935	α_1	1.977±0.008	6.14±0.04	8.117±0.04
874	α_2 and α_3	1.140±0.012	6.99±0.06	8.130±0.06
935	α_2 and α_3	1.024±0.012	7.09±0.06	8.114±0.06
		Weighted mean		8.113±0.030

† In the last two cases Q_α is averaged for α_2 and α_3 according to their relative intensities.

TABLE III. Relative yield of alpha-particles, gamma-rays, and pairs from $F^{19}(p, \alpha)O^{16*}$. Angles of observation: alphas, 138°; gammas, 90°; pairs, 13°. All yields are total yields at the resonance peaks and particularly in the case of α_π and π include some non-resonant background.

Level (kev)	$Y(\gamma)\cdot 10^8$	$Y(\alpha_1)\cdot 10^8$	$Y(\alpha_2)\cdot 10^8$	$Y(\alpha_3)\cdot 10^8$	$\Sigma Y(\alpha)\cdot 10^8$	$\Sigma Y(\alpha)/Y(\gamma)$
γ340	0.24	0.21	—	—	0.21+	0.88+
γ598	0.071	0.064	—	—	0.064+	0.90+
γ669	0.31	0.24	<0.02	0.06	0.30	0.97
γ874	18.4	10.80 (65%)	3.93 (24%)	1.78 (11%)	16.5	0.90
γ900	0.98	0.82	<0.04	—	0.82+	0.84+
γ935	8.5	5.73 (76.5%)	0.19 (2.5%)	1.58 (21%)	7.5	0.88
γ1290	1.74	1.28 (74.5%)	0.13 (7.5%)	0.31 (18%)	1.72	0.99
γ1355	6.6	3.42 (53.5%)	0.74 (11.5%)	2.25 (35%)	6.4	0.97
γ1381	15.1	11.58 (87%)	1.03 (8%)	0.71 (5%)	13.3	0.88
Level	$y(\pi)\cdot 10^{10}$	$Y(\alpha_\pi)\cdot 10^8$			$y(\alpha_\pi)\cdot 10^{10}$	$y(\alpha_\pi)/y(\pi)$
π843	1.1	0.12			2.5	~2
π1236	3.7	0.37			6.6	~2

pected per 4π-steradians using the Rutherford scattering law. The result was

$$(4\pi R)/\Omega = 2.63 \times 10^5. \tag{6}$$

From the width of the slit at the detector, R is calculated to be 128 in agreement with observations on line shape. This yields $\Omega = 0.0061$ steradian which is in agreement with estimates of the solid angle based on the geometry of the spectrograph.

The measurements were in general restricted to counting the number of doubly ionized alpha-particles emerging from the target surface and entering the spectrograph. Small corrections were made to obtain the total number of particles, doubly ionized, singly ionized and neutral, in a manner similar to that previously described.[14]

As the low energy alpha-groups are followed by gamma-radiation and pair emission from the residual excited O^{16} nuclei, we have been interested in comparing the yields of the gamma-rays and pairs with the yields of the appropriate alpha-groups. Quantitative considerations aside, it is important to ascertain that the relative excitation curves for the alpha-groups and gamma-rays are identical functions of the proton energy. We have studied this question with greatest care for the α_1-group and the gamma-rays at the 874 and 935 kev resonances. The results are shown in Fig. 5 with the alpha-particle readings normalized at the peak values of the two resonances respectively. The detailed agreement in shape of the two excitation curves is satisfactory. Additional evidence for the correlation of the other alpha-groups with the appropriate gammas or pairs will be discussed below.

From the quantitative standpoint the absolute yield comparison is mainly of interest in that it serves as a check on computed efficiencies of Geiger counter detection of gamma-rays.[15] For the yield of gamma-rays per proton per 4π-steradians we have

$$Y(\gamma) = (4\pi/q\Omega_\gamma)(N_s/a\epsilon) \times 1.602 \times 10^{-13}, \tag{7}$$

where N_s is the number of secondaries at a given angle of observation registered by the counter when q microcoulombs of protons impinge on the target, ϵ is the efficiency[15] of secondary production in the converter surrounding the counter, a is an absorption factor arising from material between target and counter, and $4\pi/\Omega_\gamma$ is the geometrical solid angle factor.

For the $F^{19}(p, \alpha\gamma)$ radiation ϵ varies from 0.042 to 0.045 depending on the relative intensities of the three components while $a = 0.90$ from the absorption of the radiation in $\frac{1}{8}$ inch of lead and $\frac{1}{16}$ inch of aluminum. The solid angle factor $4\pi/\Omega_\gamma$ equals 39.6 for a counter of diameter 1.8 cm and length 7.6 cm at a distance 6.35 cm from the target.[15]

For each of the gamma-ray resonances we have measured $Y(\gamma)$ at 90° and $Y(\alpha_1)$, $Y(\alpha_2)$ and $Y(\alpha_3)$ at 137.8° for the target employed at that resonance. $Y(\gamma)$ is the yield of all three components of the gamma-radiation. Fresh targets were employed at the different resonances but the same target was used throughout the measurements at any one resonance. As noted previously, after ascertaining the gamma-ray excitation curve the alpha-particle profile was obtained at the voltage giving the peak of the gamma-ray curve. The gamma-ray counter served as monitor throughout the profile measurements. The gamma-ray yields and the integrated profile yields for alphas are tabulated in Table III. The results for $Y(\gamma)$, $Y(\alpha_1)$, and $Y(\alpha_2)$ are shown graphically and in greater detail in Fig. 4. In

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[14] Thomas, Rubin, Fowler, and Lauritsen, Phys. Rev. **75**, 1612 (1949).

[15] Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. **20**, 236 (1949).

Table IV. Comparison of intensity ratios.

	$\left(\frac{\alpha_1}{\alpha_2}\right)$	$\left(\frac{\alpha_1}{\alpha_3}\right)$	$\left(\frac{\alpha_1}{\alpha_2+\alpha_3}\right)$	$\left(\frac{\alpha_1}{\alpha_2}\right)_{BF}$	$\left(\frac{\alpha_1}{\alpha_3}\right)_{BF}$	$\left(\frac{\gamma_1}{\gamma_2+\gamma_3}\right)_{RL}$
Angle	138°	138°	138°	83°	83°	13°
669	>12	4.0	>3		6.0	
874	2.7	6.1	1.9	3.0		2.5
935	30	3.6	3.2		3.7	3.3
1355	4.6	1.5	1.1			1.0
1381	11.2	16.3	6.7			4.7

this figure $Y(\alpha_1)$ and $Y(\alpha_2)$ are calculated from peak alpha-readings and from estimates of the shape of the group. At the resonances the shape was, of course, measured in detail and the yield normalized to that given by Eq. (3). For these excitation curves the thin ZnF_2 target had an equivalent thickness of 8 kev at 874 kev. In Table III we also tabulate $\sum_1^3 Y(\alpha)$ and its ratio to $Y(\gamma)$. In spite of the fact that the alpha-particle yields have been measured at 137.8° (~140° in the center of mass system) and the gamma-ray yields at 90° the ratio is very close to unity, having an average value of 0.92±0.03. Measurements on the angular distribution of the gamma-radiation have recently been made for the resonances below 900 kev by Devons and Hine.[16] They find isotropic distributions at all resonances except at 598 and 874 kev where the distributions follow $1+A\cos^2\theta$ with $A=0.2$ in the first case and $A=0.1$ in the second. Since our observations have been made at 90°, a correction factor $f=1+\frac{1}{3}A$ must be employed to give the total yield. We have $f=1.067$ at 598 kev and 1.033 at 874 kev; the correction is small. The angular distributions of the low energy alpha-particle groups have not been measured. Only for marked asymmetries will the total yields differ from our measured yields per 4π-steradians. The close agreement in our measurements between $\sum Y(\alpha)$ and $Y(\gamma)$ at all resonances as shown in Table III would seem to preclude the possibility of any *large* asymmetries in alpha- or gamma-distributions except for accidental effects. In any case the value 0.92±0.03 for $\sum Y(\alpha)/Y(\gamma)$ averaged over all resonances coupled with some assurance concerning the accuracy of alpha-particle counting definitely indicates that an error of at most 10 percent is involved in the calculation of counter efficiencies for gamma-rays up to 7 Mev made by Fowler, Lauritsen, and Lauritsen[15] in 1948. The efficiency curve given in this reference can thus be used with some confidence over the low energy region. It is hoped to make similar checks at higher energies in the near future.

We have also made a comparison of the excitation functions and yields of the α_π-group and the pairs. In Fig. 4 we show our measured excitation function for the α_π-group in comparison with the excitation curve for the pairs given by Bennett *et al.*[3] This latter curve has been normalized to give the best fit with our data and

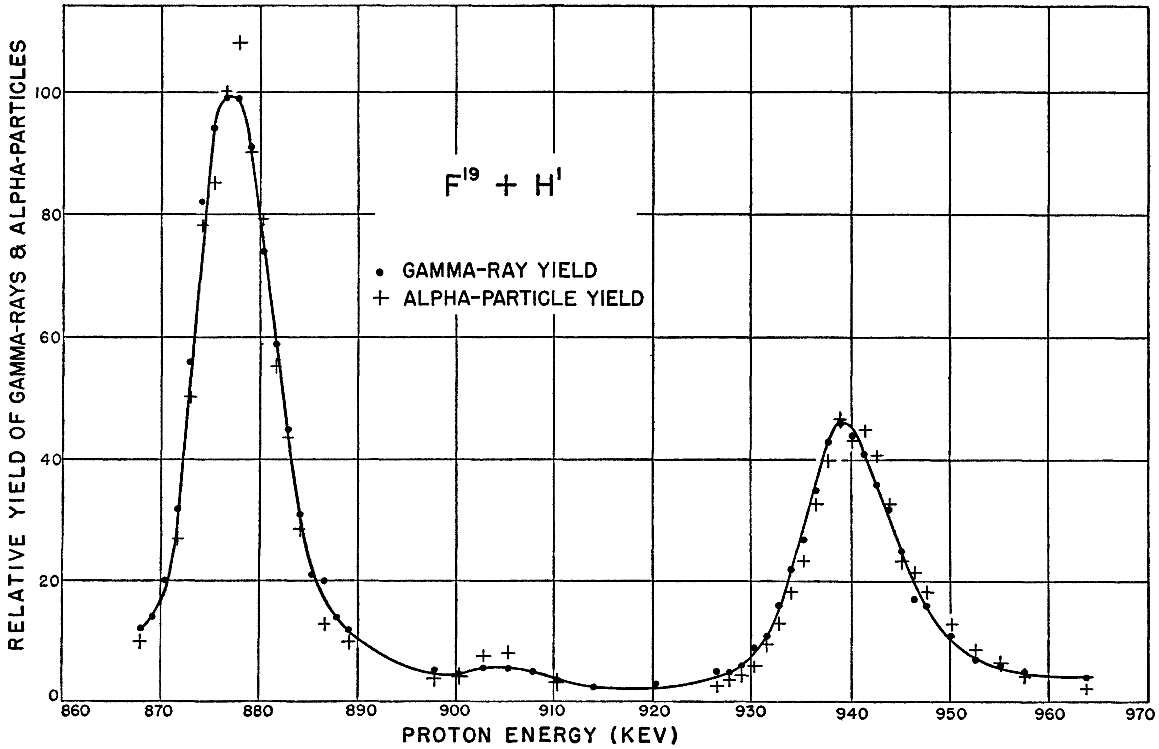

Fig. 5. Relative excitation curves for α_1-group and gamma-rays at the 874 and 935 kev resonances. ($\theta=138°$.)

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[16] S. Devons and M. Hine, Proc. Roy. Soc. **199A**, 56 (1949).

TABLE V. Gamma-radiation from $F^{19}(p, \alpha\gamma)O^{16}$.

Resonance energy (kev)	Relative intensities of the three components 6.14 Mev	6.91 Mev	7.11 Mev	Thick CaF_2 target yield quanta/10^7 protons	Angular distribution A	Width Γ(kev)	Partial width $\omega\gamma$(ev)	Cross section $\sigma_R(10^{-24}\ cm^2)$
222[a]				0.0002		<2[a]	0.03	>0.0002
340.4[b]	0.96	0.04		0.174*	0	1.7[a, b]	32	0.16
486	~0.8	~0.2		0.054*	0	<2[a]	11	>0.032
598				0.27*	0.2	37	55*	0.0071
669	0.75	<0.06	0.19**	0.48*	0	7.5	100	0.057
831				0.2		8.3	45	0.019
873.5[c]	0.65	0.24	0.11	3.7*	0.1	5.2	850*	0.54
900†	>0.95	<0.05		0.15		4.8	35	0.023
935.3†	0.76	0.025	0.21	2.0		8.0	470	0.18
1092				0.024		<1.2	6	>0.013
1137				0.1		4.1	25	0.015
1176				3.9		~130	1010	0.019
1290†	0.74	0.075	0.18	0.92		19.2	250	0.029
1355†	0.53	0.12	0.35	1.37		8.6†	360	0.089
1381†	0.87	0.08	0.05	8.2		15.0	2170	0.30

Resonance energies and widths: Bonner and Evans, Phys. Rev. **73**, 666 (1948). All resonance energies multiplied by 873.5/862. The energy at 873.5 kev was taken as a standard.

† Designates new determinations made in connection with investigations reported in this paper.

Yields: from measurements made in this laboratory.

* Designates total yields. Other yields are for 4π-steradians at 90°.

Angular distribution: Devons and Hine, Proc. Roy. Soc. **199A**, 56 (1949). $I(\theta)=1+A\cos^2\theta$.

Proportion of gamma-ray components: calculated from measurements on alpha-group intensities reported in this paper or from direct measurements of Walker and McDaniel, Phys. Rev. **74**, 315 (1948).

** Also 2 percent radiation near 13 Mev ($\omega\Gamma\gamma \sim 2$ ev, $\sigma_R \sim 10^{-27}$ cm²), Devons and Hine, Nature **164**, 586 (1949).

[a] R. Tangen, Kgl. Norske. Vid. Sels. Skr., NR1 (1946).

[b] A. H. Morrish, Phys. Rev. **76**, 1651 (1949).

[c] Herb, Snowdon and Sala, Phys. Rev. **75**, 246 (1949).

it will be noted that the curves run almost parallel with each other over their full extent. In regard to absolute yields we have made a comparison with the pair yields at 13° with the incident beam reported by Rasmussen *et al.*[5] They report the yields, $y(\pi)$, for CaF_2 targets of one kev equivalent thickness, at 843 and 1236 kev. These values are given in the last two lines of the second column of Table III.[17] For a similar calculation for $Y(\alpha_\pi)$ we need to estimate the thickness of the target used in our pair measurement and this we have done by applying Eq. (1) to measurements with the same target on the gamma-ray breadth at 873.5 kev. Our measurements with very thin targets had confirmed the value $\Gamma=5.2$ kev given in reference 3 for the natural width of this resonance. Our results are given in the next to last column of Table III, and it will be noted that $y(\alpha_\pi)$ at 137.8° is approximately twice $y(\pi)$ at 13° both at 843 and 1236 kev. Since the pair emitting state presumably has angular momentum zero, it can be expected that the angular distribution for the pairs will be isotropic. Thus we have $y(\alpha_\pi, 141°)/\bar{y}(\alpha_\pi)\approx 2$. This would seem to indicate a marked asymmetry, something like a $\cos^2\theta$ distribution, for the angular distribution of the α_π-group.

In Table IV, columns two to four, we give also our intensity ratios of the α_1-, α_2-, and α_3-groups for certain resonances. Our ratios are compared on the one hand with the ratios given by Burcham and Freeman[7] (columns five and six) and on the other hand with the ratio $\gamma_1/(\gamma_2+\gamma_3)$ (column seven) given in references 5 as I_6/I_7.

Finally we give in Tables V, VI, and VII a tabulation of what we believe to be the best data on the gamma-radiation, pair radiation, and full energy alpha-particle emission from the bombardment of F^{19} with protons up to 1.4 Mev in energy. The values given have been selected from references 1, 3, 4, 8, and 15 as well as from the present work and from the work of Tangen[18] and of Morrish.[19] In the calculation of pair and full energy alpha-particle yields we have returned to the point of

TABLE VI. Electron-positron pair radiation from $F^{19}(p, \alpha\pi)O^{16}$.

Resonance energy (kev)	Thick CaF_2 target yield, pairs per 10^7 protons	Total width Γ(kev)	Partial width $\omega\gamma$(ev)	Cross section $\sigma_R(10^{-24}\ cm^2)$
843†	0.048	30	12	0.0012
1115	0.089	60	22	0.0010
1236†	0.31	75	82	0.0025
1380	0.39	25	100	0.0085
1400*	0.85	$D\sim 1$ Mev	1600	0.0038*

Resonance energies: Bennett *et al.*, Phys. Rev. **70**, 882 (1946). All resonance energies multiplied by 873.5/862.

† designates new determinations made in connection with investigations reported in this paper.

Resonance yields and widths: taken from curves of Bennett *et al.*, normalized to yield at 1236 kev measured by Rasmussen *et al.*, Phys. Rev. **77**, 617 (1950). The yields and widths have been estimated assuming the resonance yield to be only that portion of the yield above a smooth curve drawn through the minima in the experimental excitation curve. As interference effects are almost certainly important the true widths of the level may be considerably greater than those tabulated.

Angular distribution of pairs: probably isotropic.

* Non-resonant yield: see remarks above. The cross section is that at 1.4 Mev and the partial width is calculated from the sum of this cross section and the corresponding cross section for the full energy alpha-particles assuming, D, the average separation between broad contributing levels to be ~1 Mev.

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[17] Earlier results given in reference 1 were $y(\pi)=1.6\pm0.6\times10^{-10}$ pair/proton at 843 kev and $y(\pi)=3.6\pm0.6\times10^{-10}$ pair/proton at 1236 kev. These agree within their error limit with the results given in Table III.

[18] R. Tangen, Kgl. Norske. Vid. Sels. NR 1 (1946).

[19] A. H. Morrish, Phys. Rev. **76**, 1651 (1949).

TABLE VII. Full energy alpha-particles from $F^{19}(p, \alpha)O^{16}$.

Resonance energy (kev)	Thick CaF_2 target yield, alphas per 10^7 protons	Total width Γ(kev)	Partial width $\omega\gamma$(ev)	Cross section $\sigma_R(10^{-24}\ cm^2)$
730	0.008	$\sim$30	1.6	$\sim$0.0002
850	0.006	$\sim$30	1.4	$\sim$0.0002
$\sim$1100	0.06	$\sim$60	15	$\sim$0.0006
1380	0.14	$\sim$25	36	$\sim$0.0031
1400*	0.5	$D\sim$1 Mev	1600	0.0013

Energies, yields, and widths: Streib *et al.*, Phys. Rev. **59**, 253 (1941).
* See remarks under Table VI concerning resonant and non-resonant yields and widths.
Angular distribution: not included but see Rubin, Phys. Rev. **72**, 1176 (1947).

view adopted in reference 1 where the yield below the minima in the thin target excitation curve was considered to be non-resonant. This non-resonant yield is believed to arise from the capture of *s*-wave protons by F^{19} in states of Ne^{20} having zero angular momentum and even parity from which alpha-particle transitions to the pair producing and ground states of O^{16} are highly probable giving large total widths and no marked resonance structure in the yield. From this point of view the non-resonant yield should follow the barrier penetration factor for *s*-wave protons multiplied by $\lambda\!\!\!^{-2}\sim 1/E$, and this is true experimentally to a fair approximation. The partial width for proton emission can be calculated at any point from the expression for the Breit-Wigner cross section averaged over many resonances,

$$\sigma = 2\pi^2\lambda\!\!\!^{-2}(\omega\Gamma_p\Gamma_\alpha/D\Gamma) = 2\pi^2\lambda\!\!\!^{-2}(\omega\gamma/D),$$

where D is the average separation of contributing levels in the region of interest. We arbitrarily assume $D\sim 1$ Mev and obtain a value for $\omega\Gamma_p \approx \omega\gamma = 1.6$ kev at 1.4 Mev from the sum of the α_0- and α_π-cross sections which is in reasonable agreement with the $\omega\Gamma_p$ for nearby gamma-ray resonances. On this picture the low yield of the long range alpha-particles and pairs relative to the gamma-radiation is not entirely unreasonable. Studies of the scattering of protons by F^{19} which are to be undertaken in this laboratory may yield some clarification of this point.

In conclusion the studies reported in this paper indicate the essential correctness of the general picture of the reactions following the disintegration of F^{19} by protons as worked out by numerous observers over the past decade. The yield and energy measurements on the short range alpha-particle groups correlate excellently with corresponding measurements on the pairs and gamma-rays which follow the emission of these groups. Among the numerous problems yet remaining are those having to do with the angular distributions of the reaction products and with the angular correlations between them as well as with those concerning the elastic scattering just discussed above.

In conclusion we wish to thank Dr. R. F. Christy for many illuminating discussions of this paper. This work was assisted by the joint program of the ONR and AEC.