rate of decay of the observed lines, four exposures were made with the exposure times so adjusted that the density due to electrons of 65-hour half-life would be nearly the same in each exposure. By covering successive halves of the film, two exposures were made on each of two films. Relative intensities measured may not be correct even in order of magnitude, but can only indicate a trend. Prints (Fig. 2c) and traces (Fig. 4) are shown. Table III lists densities measured from the exposures. It is clear that lines numbered 8 and 9 show a simple 65-hour half-life; the lines of lower energy appear to experience growth and decay, with the possible exception of the line of lowest energy.

ACKNOWLEDGMENTS

The construction of the permanent magnet used in these experiments was made possible by a grant-in-aid-of-research to Professor G. P. Harnwell from the Penrose Fund of the American Philosophical Society. Radioactive cobalt, zinc, and gold were supplied by Drs. J. J. Livingood and B. R. Curtis. Dr. A. S. Jensen prepared a cobalt source from material supplied by Professor L. W. Alvarez. Dr. Floyd Banks prepared the source of radioactive zinc. Dr. Livingood kindly furnished information on the assignment of cobalt activities in advance of publication. I am indebted to Professors L. N. Ridenour and G. P. Harnwell for stimulus and advice throughout.

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Short Range Alpha-Particles from Fluorine Bombarded with Protons

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The ranges of the alpha-particles proceeding from the 334-, 867-, 927-, 1220-, and 1363-kev resonances in the bombardment of fluorine with protons were measured. The Q's of those particles obtained at 334, 867, 927, and 1363 kev were found to be identical, and have the value 1.81 ± 0.04 Mev. The Q of the low energy alpha-particles obtained at the 1220-kev resonance was found to be 1.93 ± 0.07 Mev. The two values thus yield an energy separation of 0.12 ± 0.08 Mev for the two corresponding states of O^{16}. In addition it was shown that at least one of the two resonances which are in the neighborhood of 900 kev must yield short range alpha-particles whose angular distribution is not spherically symmetric.

I. INTRODUCTION

THE history and theory of the fluorine plus proton reactions have been discussed rather completely in a recent paper.[1] Consequently only a brief outline will be presented here.

The bombardment of fluorine by high energy protons has been found to give rise to several reactions, the particular mode depending on the angular momenta and energies of the impinging particles. Gamma-radiation in these reactions has, for the most part, been shown to consist of but a single strong line near 6 Mev, exhibiting well-defined resonances. The most accurate measurement of this energy was that made by Lauritsen, Lauritsen, and Fowler.[2] These authors quoted it as 6.2 ± 0.1 Mev. Dee, Curran, and Strothers,[3] and Lauritsen, Fowler, and Lauritsen[4] have shown this energy to be independent of bombarding voltage, demonstrating that but a single state is involved in the emission of this radiation. The reaction now accepted as the origin of this gamma-ray is:

$$F^{19}+H^1\rightarrow{}^{\gamma}Ne^{20}\rightarrow{}^{\gamma}O^{16}+He^4+Q_1 \qquad (1)$$
$$^{\gamma}O^{16}\rightarrow O^{16}+\gamma,$$

in which the superscript γ refers in the case of the Ne^{20} nucleus to a particular set of excited

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[1] J. F. Streib, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **59**, 253 (1941).

[2] T. Lauritsen, C. C. Lauritsen, and W. A. Fowler, Phys. Rev. **59**, 241 (1941).

[3] P. I. Dee, S. C. Curran, and J. E. Strothers, Nature **143**, 759 (1939).

[4] T. Lauritsen, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **56**, 858A (1939).

states, and in the case of O^{16} to a single excited level. The associated short range alpha-particles were found by McLean, Becker, Fowler, and Lauritsen,[5] and by Burcham and Smith.[6] The value of Q_1 was shown to be approximately 1.75 Mev. Burcham and Devons,[7] employing a magnetic resolution method, found the value of Q_1 to be unchanged at each of the three gamma-ray resonances, 0.33, 0.66, and 0.87 Mev, thus further demonstrating Eqs. (1) to be the correct mechanism.

An alternative mode of the reaction is the emission of long range alpha-particles:

$$F^{19}+H^1\rightarrow {}^{\alpha}Ne^{20}\rightarrow O^{16}+He^4+Q_0, \qquad (2)$$

in which the compound nucleus splits up to form O^{16} in its ground state. In this case the superscript α refers to that set of states of the Ne^{20} nucleus involved in the production of long range alpha-particles. These particles were found by Burcham and Devons to show distinct resonances, superposed on a rising background. Burcham and Smith[8] found the value of Q_0 to be 7.95 Mev. This is in agreement with the sum of Q_1 and the energy of the gamma-ray.

Still another mode of reaction has been pointed out by the work of Halpern and Crane,[9] and of Fowler and Lauritsen.[10] Upon bombarding a CaF_2 target with high energy protons, pairs of electrons were found to emanate directly from the target. Their energies were found by the latter workers to be approximately 5.9 Mev. Fowler and Lauritsen found definite resonances associated with this pair emission. They offered tentatively the following reaction to explain the presence of the pairs:

$$\begin{gathered} F^{19}+H^1\rightarrow {}^{\pi}Ne^{20}\rightarrow {}^{\pi}O^{16}+He^4+Q_2 \\ {}^{\pi}O^{16}\rightarrow O^{16}+e^{+}+e^{-}. \end{gathered} \qquad (3)$$

The superscript π pertains, in the case of the Ne^{20} nucleus, to a particular group of excited states. Applied to O^{16} it designates a single excited state a distance above the ground level just equal to the total energy of a pair.

Streib, Fowler, and Lauritsen[1] have since shown that pair resonances definitely coincide in at least one case, that at 1350 kev, with a long range alpha-particle resonance, and perhaps in one other at 850 kev. These experimenters found other resonances for pair emission, definitely non-coincident with long range alpha-particle resonances, at 1140 and 1220 kev, with some indication of pairs in the region from 600 to 800 kev. Accepting Eqs. (3) as the explanation of the non-coincident pairs they suggested, in order to explain those pairs coinciding with long range alpha-particles, the reaction:

$$\begin{gathered} F^{19}+H^1\rightarrow {}^{\alpha\pi}Ne^{20} \begin{cases} \nearrow O^{16}+He^4+Q_0 \\ \searrow {}^{\pi}O^{16}+He^4+Q_2 \end{cases} \\ {}^{\pi}O^{16}\rightarrow O^{16}+e^{+}+e^{-}, \end{gathered} \qquad (4)$$

in which the particular group of excited states of Ne^{20} here involved is permitted by selection rules to decay and form O^{16} in its ground level with the emission of a long range alpha-particle, or alternatively to emit but a low energy alpha-particle. In the latter case the π state of O^{16} is reached, and subsequently decays accompanied by the emission of an electron pair.

In Fig. 1 are presented the excitation functions of the long range alpha-particles, the gamma-radiation, and the electron pairs detected in the fluorine reaction. The curves are from the data of Streib, Fowler, and Lauritsen.[1]

It was the purpose of the present experiment to make a more precise measurement of Q_1, the energy of the short range alpha-particles preceding the emission of gamma-radiation. It was proposed, too, to carry the investigation of these particles to some of the higher resonances. In addition it was hoped to detect the short range alpha-particles associated with the pair resonances, and to measure their energies. Evidence for the existence of these particles is reported, and verifies the suggestion that the pairs emanate from the O^{16} nucleus.

II. EXPERIMENTAL PROCEDURE

The source of high potential employed in these experiments was the electrostatic generator pre-

[5] W. B. McLean, R. A. Becker, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **55**, 796 (1939).
[6] W. E. Burcham and C. L. Smith, Nature **143**, 795 (1939).
[7] W. E. Burcham and S. Devons, Proc. Roy. Soc. **173**, 555 (1939).
[8] W. E. Burcham and C. L. Smith, Proc. Roy. Soc. **168**, 176 (1938).
[9] J. Halpern and H. R. Crane, Phys. Rev. **55**, 260 (1939).
[10] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **56**, 840 (1939).

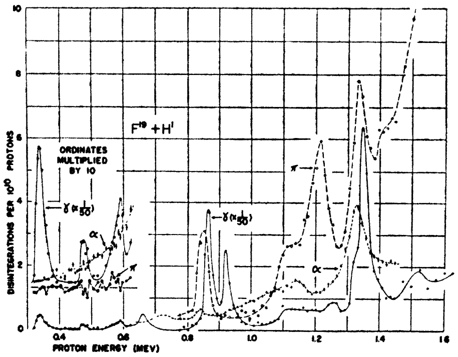

FIG. 1. Excitation curves for the long range alpha-particles, gamma-rays and pairs, from the reaction $F^{19}+H^1$. The ordinates for the gamma-ray curve are reduced to 1/50 of their actual values (after Streib, Fowler, and Lauritsen).

viously described by Lauritsen, Lauritsen, and Fowler.[2] This apparatus, of vertical construction, is capable of operation at a maximum voltage of about 1.7 Mev, with a fluctuation of less than 20 kev. With this generator it is possible to obtain magnetically resolved proton currents of as high as two microamperes at tube pressures of the order of 5×10^{-5} mm Hg.

Throughout the major part of the present work a rotary voltmeter was used. The voltage was read by means of a galvanometer whose deflection was proportional to the current passing between the stator and ground. The constant of proportionality was determined by taking repeated excitation curves of the fluorine gamma-ray resonances near 900 kev, and using the value 867 kev quoted for the lower of the two resonances by Hafstad, Heydenburg, and Tuve,[11] and 927 kev for the upper resonance, given by Bernet, Herb, and Parkinson.[12] It was felt that of the two resonances the most accurately determined value was that for the lower, at 867 kev. Upwards of a dozen such curves were taken, and voltmeter variations of the order of from one to three percent were occasionally observed.

At the time of the concluding series of experiments in the present investigation, some trouble was encountered with the commutator of the rotary voltmeter. Accordingly an oscilloscope was incorporated into the voltmeter circuit so as to permit continuous observation of the shape of the voltage pulse from the stator, thus offering a constant and accurate check of the constancy of the contact resistance between brush and commutator.

In the case of reactions (1), (3), and (4) the expected short range alpha-particle energy is of the order of 2.0 Mev. This corresponds to a range of a little over 1 cm. Consequently the ranges at 90-degree emission of the scattered protons become, at about 700-kev bombarding energy, comparable to those of the ejected short range alpha-particles.

It is evident that for bombarding energies exceeding 600 or 700 kev the scattered protons would mask the alpha-particles, so that in order to observe the latter at high voltages a deflection method would be necessary. For two particles having the same ratio of e^2/m traversing a magnetic field, the radii of curvature will simply be proportional to the square roots of the two energies. Since e^2/m is the same for a proton as for an alpha-particle the restriction is that in order for two such particles to be resolved by means of a magnetic deflection method their energies must differ. One finds that in the case of the fluorine plus proton reaction the energy of an alpha-particle ejected at an angle of 90 degrees to the bombarding beam is given as:

$$E=\tfrac{4}{5}Q+\tfrac{3}{4}E_1, \qquad (5)$$

where E_1 is the bombarding proton energy. If CaF_2 be used then the maximum energy protons are those scattered from the calcium nuclei. Accordingly one finds that the energy of the protons scattered at 90 degrees from Ca^{40} is just 39/41 of the bombarding energy.

In this case, then, the energy of the scattered proton increases more rapidly with primary energy than does that of the ejected alpha-particle. However, if one assumes, as an approximation, that $Q=2.0$ Mev, one finds that for bombarding energies substantially below about 8 Mev the energy of the alpha-particles is greater than that of the scattered protons, and hence the radius of curvature of the alpha-particles is considerably greater than that for the protons. For this reaction, therefore, the magnetic deflection method may be successfully employed. Above 8 Mev complications arise because of the wide dispersion

[11] L. R.Hafstad, N. P. Heydenburg, and M. A. Tuve, Phys. Rev. **56**, 1078 (1939).
[12] E. J. Bernet, R. G. Herb, and D. B. Parkinson, Phys. Rev. **54**, 398 (1938).

of proton energies which is due to varied target penetration.

Figure 2 shows the target arrangement for the present experiment. The bombarding beam is perpendicular to the plane of the paper. The target was enclosed in a short section of lucite tubing so as to permit observation of the beam striking the target. The beam was collimated by a $\frac{1}{4}$-inch hole in a quartz disk just above the target, the illuminated spot on the target being thus $\frac{1}{4}$ inch in diameter. The target was in most cases a slab of fluorite crystal of area just larger than the illuminated spot, cemented to the end of a carbon rod with a drop of shellac, and was less than $\frac{1}{16}$ inch thick. In some cases, however, CaF_2 powder was moistened with ethyl alcohol and allowed to dry on a carbon block. In both instances the target was inclined 45 degrees to the impinging beam, due correction being made for deviations from this angle.

The disintegration products were allowed to pass through a collimating tube immersed in a magnetic field, and into a cloud chamber C of about 15-cm diameter and 3-cm depth. In Fig. 2 the field is perpendicular to the plane of the paper. There are $\frac{1}{8}$-inch slits at points A and B. The average radius of curvature of the tube is 20.5 cm. The tube was inserted between the pole pieces of an electromagnet the field of which had a saturation value of about 12,000 gauss.

The particles were permitted to enter the cloud chamber C through a window W of low air equivalence. It is clear that there would be a certain amount of spreading of the various groups of particles in the chamber, e.g., at 1 Mev the scattered protons would, for a given field strength, be observable as the edge of a brush FG representing the maximum energy of those scattered, while a corresponding resonance group of short range alpha-particles would be represented by a small fan, the edge of which is designated in the figure as HJ.

Possible fine structure in the alpha-particle groups was made evident by using as the gas in the expansion chamber, helium at a pressure equivalent to half an atmosphere, together with water vapor. The stopping power of the mixture was of the order of one-tenth that of air under standard conditions. In this way not only was the apparent magnitude of the range R ($\sim$1 cm under standard conditions) extended but also since for two groups of similar particles of energy difference ΔE the range difference ΔR is related to the stopping power σ as:

$$a\sigma\Delta R = \Delta E \qquad (6)$$

it is apparent that the resolving power, in energy, increases as the stopping power decreases. In Eq. (6) a is a constant such that $a\sigma$ is the energy loss per cm, in a given substance, of a particle having an energy E. In this paper the term "stopping power" referred to a substance will be the rate of energy loss of a particle in that material, divided by the rate in air.

The thin window W through which the disintegration products passed into the chamber, consisted of a "Newskin" or lacquer foil of about 2-mm air equivalence supported by a small perforated grid. The hole space of this grid comprised about 60 percent of the total area. It was found that during the whole period of six months of operation the films made of Newskin did not deteriorate.

III. RESULTS

The stopping power of the chamber and air equivalence of the foil were deduced from the ranges observed at 600 kev for the reaction:

$$Li^6 + H^1 \rightarrow He^3 + He^4 + Q, \qquad (7)$$

in which the Q given by Perlow[13] as 3.945 ± 0.06 Mev was used. In the calibration a thick metallic lithium target was bombarded with 600-kev protons. The target arrangement was the same as that employed in the fluorine case. Before being inserted into the target holder, the lithium was

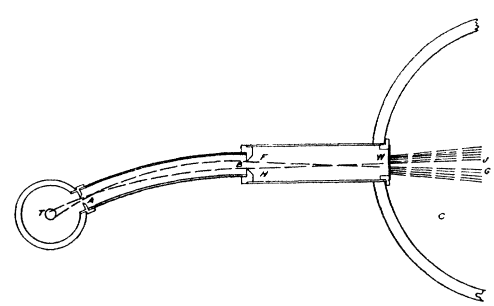

FIG. 2. Target arrangement showing the separation of the alpha-particle group HJ from the scattered protons FG.

[13] Gilbert J. Perlow, Phys. Rev. 58, 218 (1940).

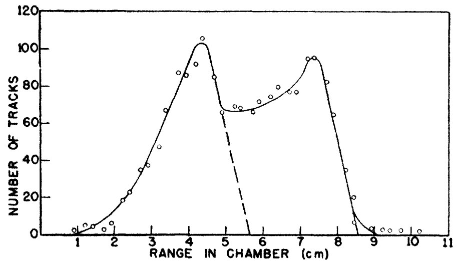

FIG. 3. Alpha-particle groups resulting from the bombardment of a thick lithium target with 600-kev protons.

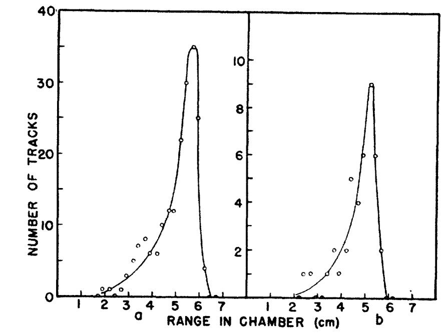

FIG. 4. Alpha-particles observed when bombarding a thick fluorine target with (a) 364-kev protons, and (b) 390-kev protons. In both cases σ had the value 0.105.

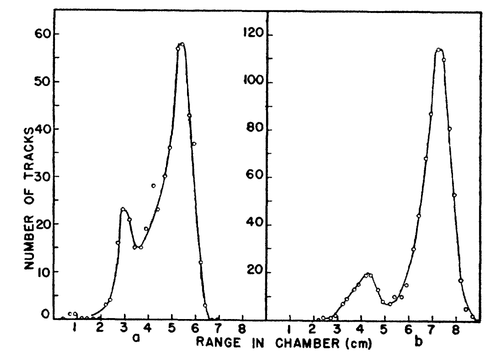

FIG. 5. Alpha-particles found when bombarding a thick fluorine target with 910-kev protons. (a) $\sigma=0.145$, (b) $\sigma=0.105$.

carefully scraped so that a fresh surface might be exposed to the beam. In all interpretations of alpha-particle range data obtained in the present work the range-energy curve of Holloway and Livingston[14] was used. Similarly all computations involving the range-energy relation for protons were made on the basis of the Cornell Curve Revised, drawn from the data of Parkinson, Herb, Bellamy, and Hudson.[15]

In obtaining the lithium data the scattered protons were separated from the alpha-particles by a field of about 10,000 gauss. The results are plotted in Fig. 3 as numbers of tracks *versus* apparent range in the cloud chamber. The curve represents the data selected from about 1200 stereoscopic pictures. The gas in the chamber was 50 cm of the mixture, helium plus water vapor. In the figure the extrapolated range of the He^3 particles may be taken as 8.55 cm, while that of the He^4 group is 5.63 cm. These values remain to be corrected for foil thickness and reduced stopping power of the chamber.

In computing the mean ranges of the He^3 and He^4 particles, the range exponent n is useful. This was obtained as a function of energy from the data of Holloway and Livingston. The value of n for a helium nucleus of mass 3 is identical with that for a He^4 nucleus having $\frac{4}{3}$ the energy of the former. In the present arrangement only those particles emitted at angles of from 89 to 91 degrees to the bombarding beam were observed. Bethe's[16] condition for "good geometry" was well satisfied for the lithium case.

Employing the methods of Bethe and determining the mean ranges by successive approximations from the extrapolated ranges, one finds the air equivalence of the foil for 2-Mev alpha-particles to be 2.5 mm air, and the stopping power of the chamber to be 0.145 when a 50-cm mixture of helium and water vapor was employed. The stopping power of the chamber when filled with a mixture (35 cm) of helium and water vapor was found by comparing the apparent mean ranges in the chamber of the alpha-particles at 1237 kev, with chamber pressures of 35 cm and 50 cm of the helium-water vapor mixture. The observed mean ranges in the two cases were 9.0 cm and 6.5 cm, respectively. If 0.145 is accepted as the stopping power in the latter case this yields 0.105 as the stopping power of the chamber gas at the more reduced pressure.

In order to have an accurate means of computing the Q's for the fluorine alpha-particles account must be taken of target penetration, and for this the stopping power of CaF_2 must be

[14] M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 18 (1938).
[15] D. B. Parkinson, R. G. Herb, J. C. Bellamy, and C. M. Hudson, Phys. Rev. **52**, 75 (1937).
[16] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 277 (1937).

known. Since this has never been measured a close approximation to it was estimated by a consideration of Mano's[17] measurements. The atomic stopping powers are there given as functions of particle velocity for A ($Z=18$), O ($Z=8$), Ne ($Z=10$) and Al ($Z=13$). Since the stopping power σ is linearly proportional to the atomic number one may assume:

$$\sigma(\mathrm{CaF_2})=\sigma(\tfrac{1}{2}\mathrm{O_2})+\sigma(\mathrm{Ne})+\tfrac{7}{5}\sigma(\mathrm{A})-\tfrac{2}{5}\sigma(\mathrm{Al}). \quad (8)$$

Figures 4a and b show the alpha-particle groups obtained by bombarding at energies of 364 and 390 kev, respectively. Presumably these alpha-particles were due to the 334-kev resonance for the gamma-rays. The apparent mean ranges were taken to be 5.7 and 5.2 cm, in the chamber. In each case a mixture of helium and water vapor was used at a pressure of 35 cm Hg. Figure 4a comprises 141 tracks, while the curve of part b of this figure is deduced from 20 tracks.

Figure 5a depicts the structure observed at 910-kev bombardment. The peak represents the alpha-particles emitted at the 867-kev gamma-resonance. The small peak will be considered later, in the theoretical discussion. The pressure in the expanded chamber was in this case 50 cm Hg. The data represent 219 tracks, obtained from about a thousand pictures. Figure 5b shows the data obtained at the same bombarding energy, but with only 35-cm pressure in the chamber. This was taken at a later date than that for the data shown in part (a) of the figure. It comprises 387 tracks, obtained from some 500 photographs.

The result of bombardment at 987 kev is represented in Fig. 6. The alpha-particles emanating from both the 867- and 927-kev levels are clearly resolved. A great deal of work was done at this voltage, 594 tracks being measured from a total of about 2300 pictures. As a result, statistical variations are considerably suppressed.

Figures 7a and b depict the alpha-particles obtained under bombardment by 1389- and 1414-kev protons, respectively. The particles emitted were from the 1363-kev resonance. The curve in part (a) of the figure represents a total of 107

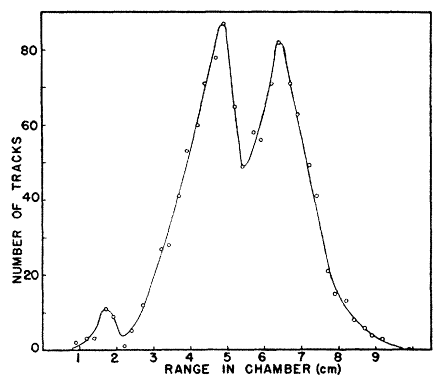

FIG. 6. Two groups of alpha-particles observed as a result of the bombardment of a thick fluorine target with 987-kev protons.

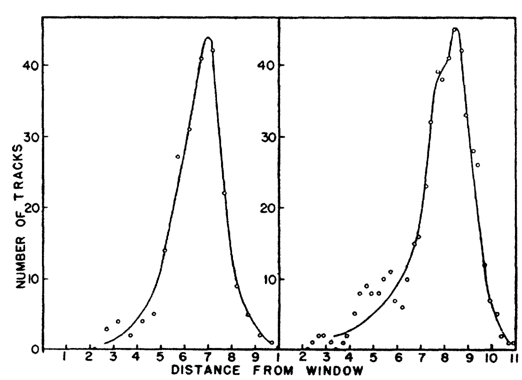

FIG. 7. Alpha-particles found when bombarding a thick fluorine target with (a) 1389-kev protons, and (b) 1414-kev protons. Here $\sigma=0.145$ and 0.105, respectively.

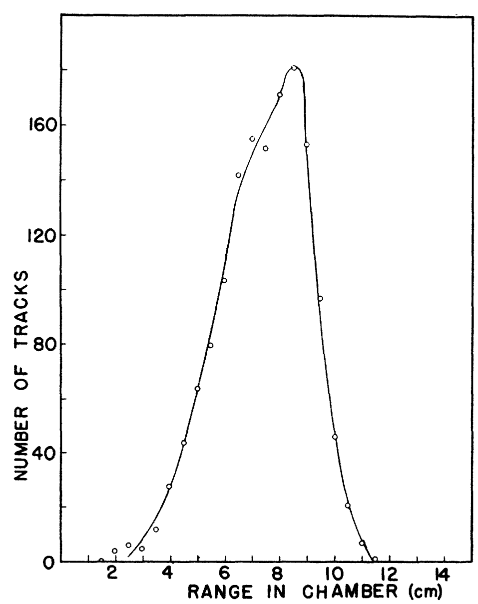

FIG. 8. Alpha-particles observed as a result of the bombardment of a thick fluorine target with 1274-kev protons.

[17] G. Mano, J. de phys. et rad. 5, 628 (1934).

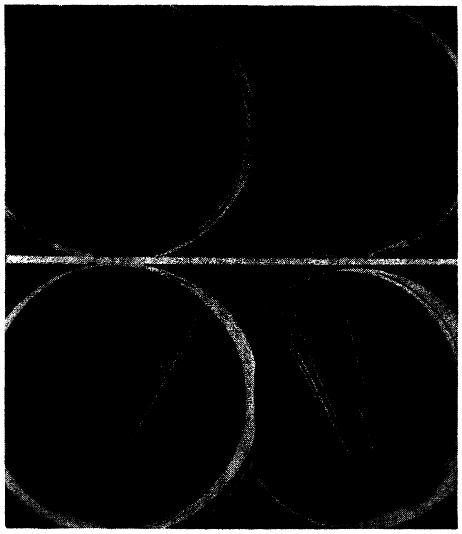

FIG. 9. (Above.) Stereoscopic views of two short range alpha-particles observed at 987-kev bombarding voltage. The longer range particle has suffered a 90-degree collision with a helium nucleus in the chamber.

FIG. 10. (Below.) Stereoscopic views of a long and a short range alpha-particle observed at 1414-kev bombarding voltage.

tracks, and was deduced from about 250 photographs. The curve in part (b) comprises 251 tracks obtained from some 500 pictures.

In Fig. 8 is given the curve obtained at a bombarding energy of 1274 kev, just above the prominent resonance for pair emission at 1220 kev. A great deal of work was done at this bombarding energy, some 3000 photographs having been taken, yielding 737 acceptable tracks.

Figure 9 is a photograph taken at 987 kev. The two alpha-particle tracks are seen to be well separated from the edge of the proton brush. The shorter of the two emanates from a lower point in the target, and presumably arises at the 867-kev resonance. The longer track, originating at the 927-kev resonance, has a right-angled fork near the end of the range, at which point the alpha-particle suffered a collision with a helium nucleus in the chamber. The 90-degree character of the encounter confirms the hypothesis that the disintegration particles are helium nuclei. The only alternative is that the recoil nucleus is a proton, and the initial track a proton scattered by the grid. The heaviness of the track, however, seems to preclude this.

Since the end of the range was greatly magnified in the chamber due to the low stopping power there, much detail for this portion of the tracks was observed. The majority of the alpha-particle tracks observed possessed the spurious curvature exhibited by the short track in Fig. 10. The theory for this type of behavior in a cloud chamber has been developed by E. J. Williams.[18] The track was obtained during 1414-kev bombardment, and was emitted at the 1363-kev gamma-ray threshold of fluorine. In the same photograph is found a long range alpha-particle, which was emitted in a transition to the ground state of O^{16}. As is evident from Fig. 1 there is a resonance maximum for the higher energy particles in this region. It is noticeable, in the pic-

[18] E. J. Williams, Phys. Rev. **58**, 292 (1940).

TABLE I. Summary of data.

Stopping power of chamber	Resonance energy kev	Bombarding energy kev	Apparent mean range cm	ΔR_H cm of air	ΔR_α cm of air	True mean range cm of air	Energy of alpha-particles Mev	Q Mev	No. of tracks
0.105	334	390	5.2	0.10	0.093	0.889	1.69	1.79	20
0.105	334	364	5.7	0.055	0.051	0.899	1.71	1.82	141
0.105	334	368	5.7	0.06	0.056	0.904	1.72	1.83	54
0.145	867	910	5.25	0.15	0.132	1.138	2.12	1.83	219
0.105	867	910	7.2	0.15	0.132	1.138	2.12	1.83	387
0.145	867	936	4.65	0.24	0.211	1.131	2.11	1.81	305
0.105	867	987	4.7	0.435	0.381	1.125	2.10	1.80	594 (both rows)
0.105	927	987	6.6	0.22	0.192	1.135	2.12	1.77	
0.145	1363	1389	6.95	0.12	0.104	1.355	2.475	1.81	107
0.105	1363	1414	8.45	0.235	0.204	1.341	2.455	1.78	251
0.105	1220	1274	8.5	0.23	0.201	1.343	2.46	1.93	737

ture, that the deflection is less for the longer range particle.

The computed Q values for the reaction at various bombarding energies are presented in Table I. Corrections were necessary, and are mentioned below in the sample calculation.

In the table the column headed ΔR_H is the equivalent depth of the target, in cm of air, which the protons must have penetrated before their energies had decreased to the value of the resonance energy. Similarly, the column headed ΔR_α is the equivalent thickness of target material, in cm of air, which the alpha-particles must have traversed in getting out of the target, from the point at which the reaction took place.

As a sample calculation of Q one may take the example of Fig. 4a. The apparent mean range was taken to be 5.7 cm. In this case the bombarding energy was 364 kev, corresponding to a proton range in air at 15°C and 760 mm Hg of 0.415 cm. When the proton energy has decreased to 334 kev the midpoint of the resonance is reached. Since the range of 334-kev protons is 0.36 cm one finds a penetration ΔR_H of the target equivalent to 0.055 cm of air at the above-mentioned conditions of temperature and pressure.

Now the average velocity of the proton in traversing this thickness of target material is 0.8×10^9 cm/sec. The energy of the emitted particle is about 1.7 Mev, and it has a velocity of 0.87×10^9 cm/sec. From Eq. (8) the stopping powers of CaF_2 for particles of these velocities are 3.875 and 3.935, respectively. There is an additional correction, to the extent that the angle of the target was 48.5 degrees. The alpha-particles were compelled to traverse but 0.92 of the geometrical distance through which the protons must have passed in order to reach the given depth in the target. Therefore the increment of range ΔR_α of the alpha-particles, in the target, was $(0.92\times 3.935\times \Delta R_H)/3.875$, or 0.051 cm. Furthermore, since the air equivalence of the window was taken to be 0.25 cm we have the true mean range R to be $5.7\times 0.105+0.25+0.051=0.899$ cm, whence the energy of the emitted particle was 1.71 Mev. Using the methods of Bethe one finds Q to be 1.80 Mev. A slight correction due to the fact that the alpha-particles were observed at 88 degrees to the original beam rather than at 90 degrees subtracts about 10 kev from the Q value. The corrected Q, then, is 1.79 Mev.

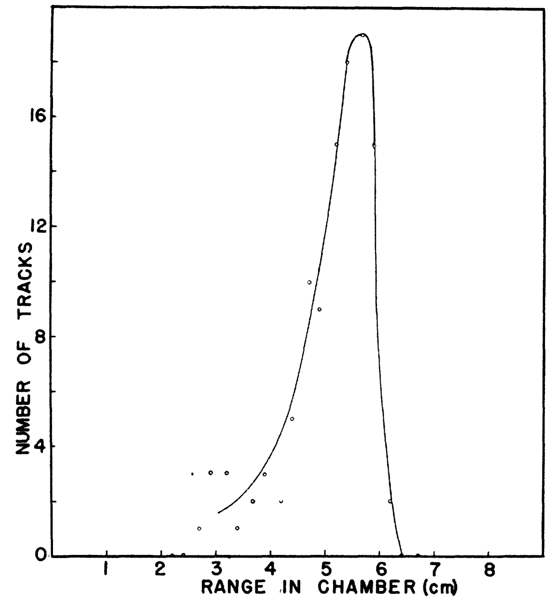

Fig. 11. Alpha-particles found as a result of the bombardment of a thick fluorine target with 368-kev protons.

It is to be emphasized here that the absolute values for Q obtained are dependent only on the slope of the stopping power curve for CaF_2, and are independent of the absolute values of the ordinates. A similar statement can be made for the use, in the computations, of the range-energy relations for both alpha-particles and protons, since the contribution due to proton penetration is just proportional to the difference between two ranges, and in the case of the alpha-particles the curve is standardized by comparing with alpha-particles of known energy which is of the same order as that of the particles measured.

In order to have an additional check on the correctness of the above values for Q a run just above the 334-kev resonance was made after a lapse of about three months. The observations are summarized graphically in Fig. 11, which represents the distribution of 54 tracks. At this later time the null reading voltmeter was employed. The bombarding energy in this case was 368 kev. The apparent mean range was taken as 5.7 cm, yielding a value of 1.83 Mev for Q, in very good agreement with the preceding measurements.

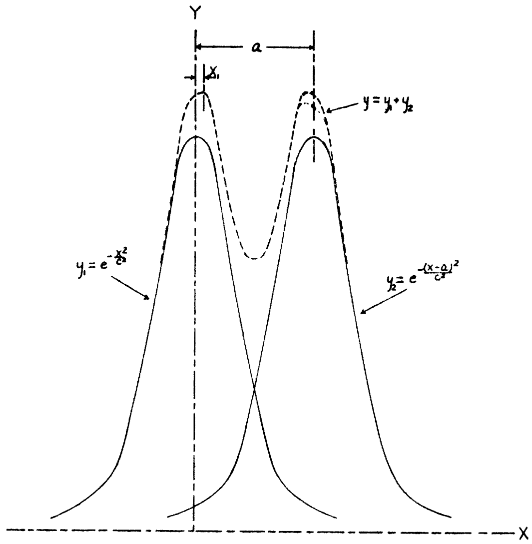

FIG. 12. Sketch showing the shift of two Gaussian peaks due to their proximity to each other.

In computing the results for the bombardment at 987 kev, allowance was made for the shift of the two maxima due to their proximity to one another. Figure 12 shows a sketch idealizing the conditions of the problem at this voltage. Two Gaussian peaks, each of half-width b, are depicted with a true separation a. Because of the proximity of the two peaks the observed separation will be some quantity $a-2x_1$, where $x_1 \ll a$. Let

$$y_1 = \exp(-x^2/c^2) \quad \text{and} \quad y_2 = \exp(-(x-a)^2/c^2).$$

The positions of the two maxima will be determined by setting

$$dy/dx = 0 \quad \text{where} \quad y = y_1 + y_2.$$

Assuming a good approximation to the observed curve to be when $a=b$ one finds an apparent shift of 20 percent in the separation. When this is taken into consideration it is clear from Table I that within a possible error of 30 kev the two resonances exhibited in Fig. 6 possess identical values for Q.

That the two resonance groups in this case are resolved is due to the fact that alpha-particles originating at the lower resonance must come out from a deeper layer in the target. This is indicated in Fig. 13 which shows a proton beam of 987-kev energy incident on a thick target of CaF_2. At a certain depth in the target the protons will, on the average, have lost 60 kev, which reduces their average energies to 927 kev. At this point many of them will react with fluorine nuclei, and those alpha-particles from this reaction which are emitted at 88 degrees to the original beam are observed in the chamber. Those protons which do not react at this level will penetrate further into the target until they reach that depth of the target at which they will, on the average, have their energies reduced to 867 kev. At this point many will react, as at the higher level, with the fluorine, save that the alpha-particles from the lower level will, in addition to possessing a smaller contribution from the incident proton energy, have to pass through an increased target thickness in order to be observed in the chamber.

It is worthy of note that because the expected alpha-particle ranges are very close to those used in calibrating the apparatus the error in calculated Q's, arising from errors in σ and the air equivalence of the foil, will be a small quantity of the second order.

IV. THEORETICAL DISCUSSION

The small peak on the low energy sides of Figs. 5 and 6 cannot be attributed to a gamma-resonance since the nearest lower gamma-ray resonance is at 660 kev. Consequently the short range alpha-particles from this resonance could not have emerged from the target for either of these bombarding energies. This group cannot be due, therefore, to a resonance of the 6.2-Mev radiation of $F^{19}+H^1$.

It is of importance to notice the difference in the relative height of the two peaks in Fig. 6 from that in the corresponding part of Fig. 1. Because of the comparatively long lifetime (about 10^{-15} second) of the 6.2-Mev state of oxygen it is to be expected that the coupling between the initial and final states of motion of the particles involved will be completely lost, and that consequently the yield of the gamma-radiation should show spherical symmetry. It has recently been demonstrated experimentally by Van Allen and Smith[19] that the fluorine gamma-radiation at three bombarding voltages—370, 900, and 1000 kev—possesses a spherically symmetric angular

[19] J. A. Van Allen and N. M. Smith, Phys. Rev. 59, 501 (1941).

distribution. This is not necessarily true for the short range alpha-particles preceding this emission, which in general would have an angular distribution deviating from spherical symmetry. Spherical symmetry would be observed if the captured particle possesses zero angular momentum, if the compound nucleus possesses zero angular momentum, or if the emitted particle possesses zero angular momentum, or lastly, for any combination of these three cases.

It is clear that since the relative intensity of the 867- and 927-kev peaks is different for the alpha-particles from that for the gamma-rays, one or both of those two groups of alpha-particles must show an angular distribution different from that of spherical symmetry. This is to be looked for in future distribution measurements of the short range alpha-particles.

Figure 6 furnishes, in addition, an accurate check for the separation of the 867- and 927-kev resonances if one begins by assuming the Q values for the two states to be identical. For example, if one takes for the lower threshold, the value 862 kev, the final Q value for the alpha-particles of this resonance would be 1.84 Mev, or 40 kev greater than the magnitude obtained when using the slightly greater value for the resonance energy. We thus see that the computed Q is very sensitive to the precise value for the resonance voltage. Since the Q for the 927-kev resonance was found to be 1.78 Mev, it might be reasonable to suppose that the separation 927–867 should actually be 4 or 5 kev less than the 60 kev it is at present assumed to be.

The shape of the 1363-kev resonance alpha-particle yield seems to be somewhat different from that of the gamma-radiation shown in Fig. 1. In Fig. 7a and b the back sides of the peaks seem relatively more pronounced than for the gamma-rays. This seems to indicate that the relative intensity at 90-degree emission for the alpha-particles from the 1335- and 1363-kev resonances is somewhat different from the integrated relative intensity which is shown by the gamma-ray peaks.

The Q value for the alpha-particles preceding gamma-ray emission is 1.81 ± 0.04 Mev. The probable error is but 0.01 Mev. However, owing to a possible systematic discrepancy the error is quoted as being 0.04 Mev. In Fig. 1 it is noticed that the ordinates for the pair emission curve should be multiplied by 1/50. This at once rules out the possibility of observing the alpha-particles from the 850-kev resonance for pair emission, since these would be entirely obliterated by the alpha-particles emitted from the 867-kev gamma-ray resonance. The small peak on the low energy side in Figs. 5 and 6 cannot be attributed to this unless the pair alpha-particles possess energies less than those of the particles leading to the 6.2-Mev state of O^{16}. This seems to be very unlikely. Similarly the alpha-particles emitted at the 1350-kev pair resonance would be obliterated by those proceeding from the 1363-kev state.

The only remaining possibility seemed to be to bombard just above the very broad pair maximum, the center of which is located at 1220 kev. The peculiar shape of this peak seems to preclude the possibility that it is due to only a single resonance level, but suggests that it is due to a superposition of several closely spaced resonances.

It is to be mentioned further that this shape should be observed at all angles of emission of the pairs since one expects that owing to the long lifetime of the pair state of O^{16} the emitted electrons should show spherical symmetry. If the peak does actually represent a multiplicity of levels this shape is not necessarily to be expected for the alpha-particles, in which the relative yields may vary somewhat as the angle of emission is changed, the amount of variation depending upon the values of angular momentum involved.

It should be noticed by referring again to Fig. 1

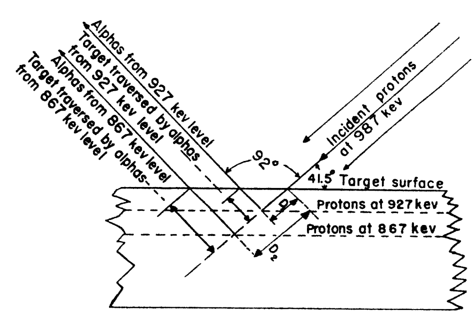

FIG. 13. Resolution of two groups of particles by means of varied target penetration. D_1 is penetration of protons in losing 60 kev; D_2 is penetration of protons in losing 120 kev.

that there seems to be a measurable background of gamma-radiation in the vicinity of 1200-kev bombarding energy. That this did not appear to smear out the emitted short range alpha-particles may indicate that this gamma-radiation is not that emitted by the 6.2-Mev state of O^{16}. It is suggested that this background may be low energy radiation arising from a non-capture excitation of fluorine, similar to that which is known to exist in the Li^7+H^1 reaction at bombarding energies near 800 kev.

Choosing 8.5 cm as the apparent mean range in Fig. 8 for the pair resonant alpha-particles one obtains a Q value of 1.93 ± 0.07 Mev, given in Table I, for the bombarding energy of 1274 kev. The error is somewhat larger in this case, first because the value could be determined at but one voltage, and secondly because the variation in angular distribution, if the peak be complex, might conceivably shift the position of the maximum somewhat. It was thought that a quoted error of 70 kev would be a reasonable one.

It should be mentioned at this point that the existence of a group of alpha-particles at this bombarding voltage, and whose Q value is greater than that of those groups preceding gamma-ray emission, offers the needed evidence that the pairs are given off from O^{16} rather than from Ne^{20}. Until this point had been reached the statement that the electrons were emitted in the decay of a state of O^{16} had been but an assumption. Further evidence is indicated by the somewhat similar structure of the alpha-particle group to that of the pair peak shown in Fig. 1.

The above results indicate a separation for the two states of O^{16} to be about 0.12 ± 0.1 Mev. Although just on the limit of error it is indicated that the pair emitting state is lower than the gamma-ray emitting state. Had the former been higher than the latter, low energy gamma-rays in a transition to the 6.2-Mev gamma-ray state would have been emitted rather than the pairs. Accepting 6.2 ± 0.1 Mev as the energy of the gamma-ray emitting state of O^{16}, one finds the energy of that state giving rise to electron pairs to be 6.1 ± 0.1 Mev. Tomlinson[20] has recently measured the energy of the pairs directly by means of a magnetic spectrograph. The value quoted for the energy was 6.0 ± 0.2 Mev, a result in fair agreement with that quoted in the present work.

An explanation of the small peak in Figs. 5 and 6 could be the existence of a pair peak at about 750 kev. Some evidence for this was obtained in the excitation curves of Streib, Fowler, and Lauritsen. It was not conclusive, however, and was not indicated in Fig. 1.

Other means for measuring the energy of the pair emitting state of O^{16} seem necessary in order to determine more accurately the separation of this from the 6.2-Mev state. Because of the difficulties mentioned above in determining this quantity indirectly by measurement of the associated alpha-particle energy it seems more promising to attempt another determination directly of the pair energy itself. It seems of value, also, to measure the angular distributions of the alpha-particle groups proceeding from the higher energy resonances, and to compare them with the relative intensities here observed at 90-degree emission.

Thanks are due Dr. J. F. Streib for the use of Fig. 1, and also for the preparation of Fig. 2.

[20] E. P. Tomlinson, Phys. Rev. 60, 159A (1942).

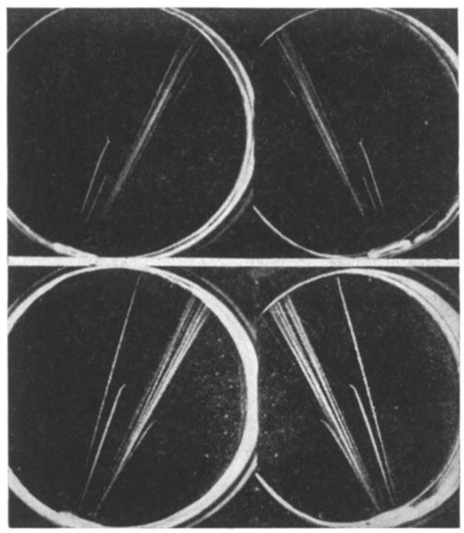

FIG. 9. (Above.) Stereoscopic views of two short range alpha-particles observed at 987-kev bombarding voltage. The longer range particle has suffered a 90-degree collision with a helium nucleus in the chamber.

FIG. 10. (Below.) Stereoscopic views of a long and a short range alpha-particle observed at 1414-kev bombarding voltage.