The Short-Range Alpha Particles from the Disintegration of Fluorine by Protons

By

Robert A. Becker

Submitted in Partial Fulfillment
of the Requirements for the
Degree of Doctor of Philosophy

California Institute of Technology

1941

Abstract--The ranges of the alpha-particle groups 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 $\pm$ 0.04 Mev. The Q of the low-energy alpha particles obtained at the 1220 kev resonance was found to be 1.93 $\pm$ 0.07 Mev. The two values thus yield an energy separation of 0.12 $\pm$ 0.1 Mev for the corresponding two 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 disintegration of fluorine by protons was first announced by Cockroft and Walton[1] in 1932. These observers, using the scintillation method, and employing bombarding energies from 200 to 450 kev, reported a group of alpha particles of about 3 cm mean range, and suggested as origin the reaction:

$$F^{19} + H^{1} \rightarrow O^{16} + He^{4} \tag{1}$$

These particles were apparently detected later by Oliphant and Rutherford[2], and by Lawrence and Livingston[3]. The latter workers observed, in addition, a group at 5.6 cm, and one at 6.8 cm mean range.

However, more careful work by Tuve, Hafstad and Dahl[4], and by Henderson, Livingston and Lawrence[5] showed that only that group of alpha particles having a mean range near 7 cm resulted from the fluorine, and that the previously reported shorter range groups of particles probably were caused by boron contamination. In the experiment of Henderson and co-workers it was found that throughout the voltage range from 675 to 1630 kev the energy of the alpha particles increased with increasing bombarding energy by just 3/4 of the latter, showing that all of these particles resulted from transitions involving the same final state. Henderson and collaborators found a rather poorly defined threshold for transmutation, and that the excitation function was smooth and in approximate agreement with Oppenheimer's theoretical forfula:

$$N = kVe^{-S}\left(1 + V^{1/2}/6 + V/24 + V^{3/2}/72 + \cdots\right) \tag{2}$$

where numerically $S = \left\{ \frac{8.92}{V^{1/2}} + \frac{28.3}{(8.2+V)^{1/2}} \right\}$

with V in units of Mev, and k an arbitrary constant. However, this work of Henderson and collaborators has since been shown to be in error.

The most accurate determination, to date, of the energy of these alpha particles has been that of Burcham and Smith[6] in 1938 who, at 850 kev bombarding voltage, found an energy release of 7.95 Mev. Assuming that these alpha particles leave the O^{16} nucleus in the ground state they calculated the mass of F^{19} to be 19.0043, a result in very good agreement with Aston's value of 19.0045.

Gamma radiation arising from the proton bombardment of fluorine was first found by MacMillan[7] in 1934 using a Lauritsen electroscope to measure the absorption coefficients of the gamma rays in Pb, Sn, Cu and Al. The radiation was found to be homogeneous and of about 5.5 Mev quantum energy. In good agreement with this was the work of Crane, Delsasso, Fowler and Lauritsen[8] using the absorption method, and in addition observing the curvature in a magnetic field of the secondaries ejected from a thin lead lamina in a cloud chamber.

The above measurements employing the absorption method were criticized from the standpoint that the absorption coefficient which was measured was not that of the primary radiation, but was that of the composite radiation passing through the absorbing material. This radiation consisted in part of the primary quanta, and in part of secondary quanta of lower energy which were more penetrating that the former. It was clear then, that the absorption coefficients observed in the above work were necessarily less than the value due to the monochromatic primary radiation. It was clear too, that the measured value would decrease still further as the absorber thickness was increased, and would approach the value represented by the minimum[9] in the absorption curve.

To circumvent this objection a new method was proposed which was employed first by Delsasso, Fowler and Lauritsen[10], and afterwards by Halpern and Crane[11]. In this method the numbers of secondaries of energy above a certain value, ejected from a thin scatterer in a cloud chamber, were observed both before and after the primary radiation had passed through a known thickness of absorber. In that way the true attenuation coefficient of the primary radiation from the fluorine was determined. The value quoted by Lauritsen's group was $\mu_{Pb} = 0.4 \pm 0.1$ cm^{-1}. This corresponds to a quantum energy of about 6 Mev.

Still another measurement of the energy of this radiation was obtained by Dee, Curran and Strothers[12] in 1939. Employing a magnetic spectrograph these observers reported the quantum energy to be 6.5 Mev.

However, the most accurate determination of this energy was made by Lauritsen, Lauritsen and Fowler[13]. In this experiment the curvatures, in a magnetic field, of secondaries ejected by a thin lead lamina in a cloud chamber were very carefully measured. The magnetic field in this case was held constant to within 0.5 per cent. The absolute value of the field was checked against an accurate standard solenoid by means of a search coil and a Grassot fluxmeter repeatedly during the course of the experiment, and was estimated to be accurate to better than 1 per cent. The value for the quantum energy thus obtained by these workers was 6.2 ± 0.1 Mev.

The excitation function of the fluorine plus proton gamma rays was first studied in 1935 by Hafstad and Tuve[14] who found well-defined resonances in the yield to occur at about 320, 600 and 700 kev. The existence of these sharp excitation thresholds in proton disintegrations not only emphasized the importance of energy levels in these reactions but clearly demonstrated the need for voltage control considerably more refined than that given by any apparatus then in existence. The investigation of such resonance phenomena demands accurate reproducibility of specified voltages to within a very few kilovolts. Accordingly, in an effort to establish an accurate absolute voltage scale for interlaboratory comparison, Hafstad, Heydenburg and Tuve[15] in 1936 made careful measurements of some of the sharper resonances of fluorine. In this work a thick CaF_2 target was used, and the bombarding voltage was measured by means of a calibrated, corona-free, 10,000 megohm voltmeter-resistor. Resonances were observed at 328 kev, half-width 4 kev; 892 kev, half-width 12 kev; and at 942 kev, half-width 15 kev. At the same time the existence of a weak multiplet structure in the region between 500 and 700 kev was indicated, together with a broad but fairly prominent resonance at 650 to 700 kev.

Subsequent work by Herb, Kerst and McKibben[16], and very careful work by Bernet, Herb and Parkinson[17] confirmed the resonance character in the yield of this gamma radiation. Employing a very thin target [thickness about 4 kev at an energy of 1 Mev] these authors found seven well-defined resonances, at bombarding energies of 334, 479, 660, 862, 927, 1335 and 1363 kev.

Recent work by Heydenburg, Hafstad and Tuve[18] in the voltage range near 860 kev, however, indicates the resonance voltage at this point to be 867 kev. The importance and bearing of this result on the present experiment will be brought forth later.

In order to explain the fluorine plus proton radiations several reactions have been proposed. It seemed fairly conclusive from the beginning that the 5.9 cm alpha particles, as was mentioned above, originate in a transition directly to the ground state of O^{16}. Burcham and Devons[19] measured the excitation function of these particles for proton energies of 0.55 to 1.0 Mev, and found two resonance maxima superposed on a rising background. The most marked of these was at 830 kev, and the less distinct one at about 720 kev. Streib, Fowler and Lauritsen[20] have since extended these observations, finding maxima at 720, 840, a very broad maximum between 900 and 1200 kev, and a rather sharp resonance at 1350 kev. It was observed, moreover, that none of the long-range alpha-particle maxima coincide with gamma-ray resonances. Accordingly it was assumed that there exists discrete states of Ne^{20} which are permitted by selection rules to break up into a helium nucleus and an O^{16} nucleus in its ground state, but which apparently cannot yield gamma radiation. Accordingly then, in view of the fact that a distinct set of excited states of Ne^{20} is specifically involved in the long-range alpha-particle emission we may rewrite equation (1) as:

$$F^{19} + H^{1} \rightarrow {}^{\alpha}Ne^{20} \rightarrow O^{16} + He^{4} + Q_{0} \qquad (3)$$

where the measured value of Q_0 is 7.95 Mev. The superscript α designates that particular type of state of Ne^{20} involved in this process.

On the other hand it was evident that there exists also a set of discrete levels of Ne^{20} which give rise to gamma radiation. Due to the non-coincidence of gamma-ray and long-range alpha-particle resonances it was furthermore evident that this latter set is forbidden to disintegrate into O^{16} in the ground state, plus an alpha particle. Several reactions have been proposed to explain the gamma-ray emission. These are:

$$F^{19} + H^{1} \rightarrow {}^{*}Ne^{20} \rightarrow Ne^{20} + \gamma_1 \qquad (4)$$

$$F^{19} + H^{1} \rightarrow {}^{*}Ne^{20} \rightarrow {}^{**}Ne^{20} + \gamma_2 \qquad (5)$$
$$\hookrightarrow Ne^{20} + \gamma_3$$

$$F^{19} + H^{1} \rightarrow {}^{*}Ne^{20} \rightarrow {}^{**}Ne^{20} + \gamma_2 \qquad (6)$$
$$\hookrightarrow O^{16} + He^{4} + Q_1$$

$$F^{19} + H^1 \longrightarrow {}^{\gamma}Ne^{20} \longrightarrow {}^{\gamma}O^{16} + He^4 + Q_1 \quad \hookrightarrow O^{16} + \gamma \tag{7}$$

where the superscript γ refers to a particular set of excited states of Ne^{20}, and also to a set of levels of O^{16}.

In the case of reaction (4) the energy available from the mass difference between Ne^{20} and $F^{19} + H^1$ is about 13 Mev. Inasmuch as gamma radiation of this quantum energy has not been observed it seems fairly certain that a direct transition to the ground state of Ne^{20} is highly improbable.

Alternative modes of decay are those offered by reaction (5) in which two gamma rays of total energy 13 Mev are emitted, reaction (6) in which the gamma ray is first emitted leading to a lower state of Ne^{20} which then breaks up into a short-range alpha particle plus O^{16} in its ground state, and finally reaction (7) in which a low-energy alpha particle is first emitted, with the formation of O^{16} in an excited state, which state then decays with the emission of a gamma ray.

In view of the fact that the level spacing of Ne^{20} at excitation energies below 10 Mev is much larger than that above 13 Mev[21], a necessary condition for the validity of any of equations (4), (5) or (6), is that the quantum energy of the gamma radiation vary with bombarding voltage. In the case of (5) the number of transitions must increase, or the quantum energy of either or both γ_2 and γ_3 must increase with increasing voltage. For reaction (6) a similar restriction holds. That this behavior is not the case has been demonstrated by Dee, Curran and Strothers[12], and by Lauritsen, Fowler and Lauritsen[22], who have shown that the gamma radiation emitted in the bombarding range 300 kev to 1400 kev consists for the most part of 6 Mev radiation. A further consideration which appears to preclude reaction (5) was the non-existence of coincidences for 6 Mev radiation observed by Dee, et al.

It must be mentioned that Lauritsen's group did find a small amount of 10.5 Mev radiation at bombarding voltages above 950 kev. However, the relative intensity of this radiation was less than 5 per cent of the main line at 6 Mev, and could well have been due to contaminants.

The remaining alternative mode of decay represented by reaction (7) satisfied the condition of constancy of gamma-ray energy provided a short-range group of alpha particles exist whose energy increases with bombarding energy by 3/4 of the latter. Allowing 6.2 Mev for the quantum energy of the gamma ray this leaves 7.95-6.2, or 1.75 Mev for the value of Q_1 in this reaction. The existence of these particles at the 334 kev resonance was demonstrated in this laboratory by McLean, Becker, Fowler and Lauritsen[23], and simultaneously by Burcham and Smith[24]. The former group found the Q of the reaction to be about 1.75 Mev.

The short-range alpha particles were investigated again by Burcham and Devons[19] who measured their ranges at voltages of 334, 660 and 870 kev, and found the alpha-particle energies to increase with increasing proton energy by the correct amount if the Q value is the same at all three energies. In addition they showed that the low-energy alpha particles showed resonances coinciding with those of the gamma rays at these voltages. It now seems certain that reaction (7) offers the correct explanation of the origin of the gamma radiation and the associated group of short-range alpha particles.

Of special interest are the results of Gaerttner and Crane[25], and of Halpern and Crane[26]. The former workers, employing a thin Al window between target and cloud chamber, found a group of electron pairs which they at first attributed to a second gamma ray of quantum energy about 4 Mev. The latter authors showed these pairs to emanate directly from the CaF_2 target, and concluded that they represent merely an abnormally high pair-internal-conversion coefficient of the 6 Mev gamma rays.

Fowler and Lauritsen[27] have pushed the investigation of these apparent internal conversion pairs further and have shown that the total energy, kinetic plus that due to the masses, represented by the pairs is about 5.9 Mev, as compared to the 6.2 Mev for the gamma ray. These authors further demonstrated that the pairs show definite resonances, and that these resonances do not coincide with those of the gamma rays.

Streib, Fowler and Lauritsen[20] have shown, in addition, that the 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.

In order to explain the origins of the pairs which are non-coincident with the long-range alpha particles, and of the coincident pairs, respectively, they offered tentatively the reactions:

$$F^{19} + H^1 \longrightarrow {}^{\pi}Ne^{20} \longrightarrow {}^{\pi}O^{16} + He^4 + Q_2 \qquad (8)$$
$$\hookrightarrow O^{16} + \varepsilon^+ + \varepsilon^-$$

$$F^{19} + H^1 \longrightarrow {}^{\alpha\pi}Ne^{20} \begin{cases} \longrightarrow O^{16} + He^4 + Q_0 \\ \longrightarrow {}^{\pi}O^{16} + He^4 + Q_2 \\ \quad \hookrightarrow O^{16} + \varepsilon^+ + \varepsilon^- \end{cases} \qquad (9)$$

In these reactions the superscripts π and $\alpha\pi$ denote two distinct sets of levels in the Ne^{20} nucleus. The superscript π is also used to designate a family of states of O^{16}. ~~as well~~.

In Figure 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[20].

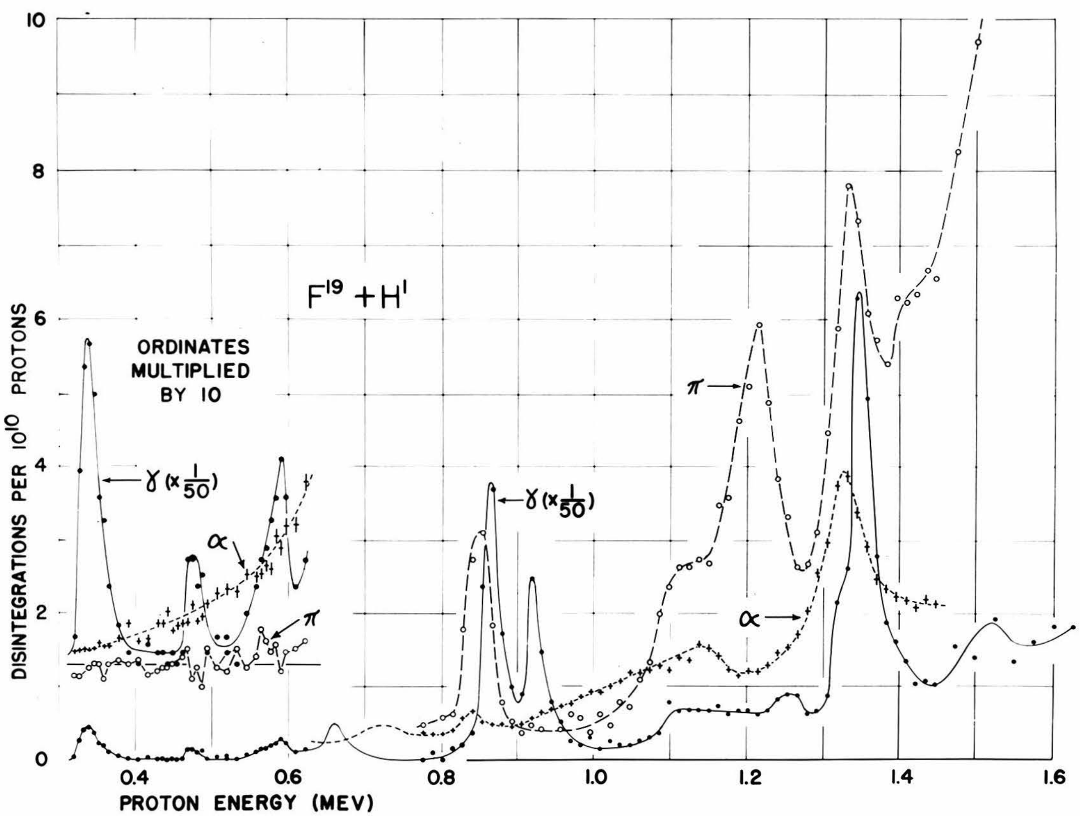

Figure 1. Excitation curves for the long-range alpha particles, gamma rays, and pairs, from the reaction $F^{19} + H^1$. The ordinates for the gamma-ray curve are reduced to 1/50 of their actual values. [after Streib, Fowler and Lauritsen]

In Figure 2 is shown the energy-level scheme[20] devised in order to explain the fluorine reactions. Two emitting levels of O^{16} are shown, together with four sets of levels of the Ne^{20} nucleus. The separation ΔE of the two excited states of O^{16}, as indicated by the measurements of Fowler and Lauritsen[27], is about 0.3 Mev.

In all of these experiments the possibility was clearly recognized that some or all of these emitted pairs might originate in the excited Ne^{20} nucleus rather than in a transition of O^{16}.

In view of some of the difficulties mentioned above it was proposed that these various groups of alpha particles be studied with a cloud chamber. In this way it was hoped to establish with more certainty whether such pair-emitting reactions exist, and if so, to measure more accurately the energy separation of the levels near 6 Mev in O^{16}. At the same time it was intended to carry the investigation of the alpha particles preceding the gamma-ray emission, to higher voltage resonances than had hitherto been attempted.

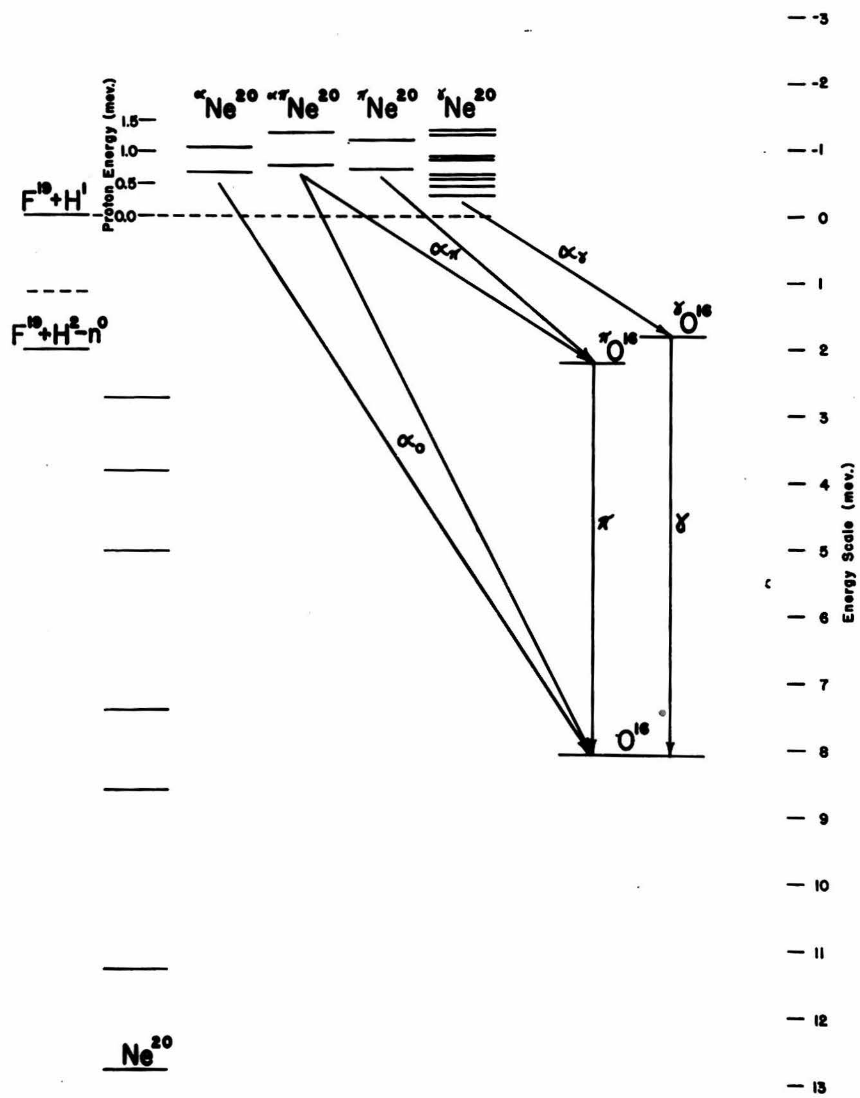

Figure 2. Proposed energy-level diagram. [after Streib, Fowler and Lauritsen]

II--Experimental Procedure--The source of high potential employed in these experiments was the electrostatic generator previously described by Lauritsen, Lauritsen and Fowler[13]. 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 2 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 making repeated excitation curves of the fluorine gamma-ray resonances near 900 kev, using the value 867 kev quoted for the lower of the two resonances by Hafstad, Heydenburg and Tuve[18], and 927 kev for the upper resonance, given by Bernet, Herb and Parkinson[17]. A typical excitation curve using a CaF_2 target and employing a Lauritsen electroscope is depicted in Figure 3. Since it was felt that of the two resonances the most accurately determined value was that for the lower, at 867 kev, the value of the proportionality factor deduced was 51.4, if the galvanometer deflection is expressed in cm. Upwards of a dozen such curves were taken, and voltmeter variations of the order of from 1 to 3 per cent were occasionally observed.

At the time of the concluding series of experiments in the present work, some trouble was encountered with the commutator of the rotary voltmeter. Accordingly an oscilloscope was incorporated into the voltmeter curcuit 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 contact resistance of the commutator. At the same time the circuit was

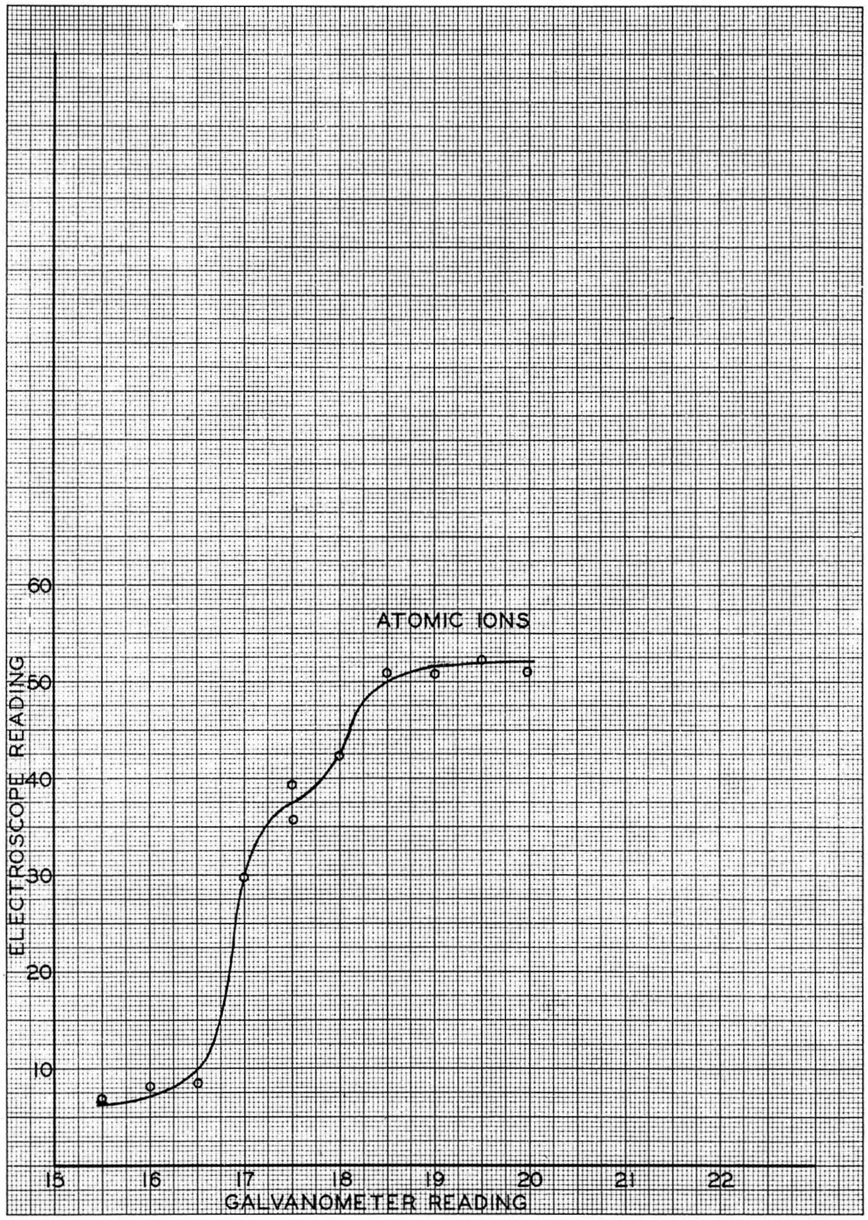

Figure 3. Voltage calibration: thick target $CaF_2 + H_1$ excitation curve showing the 867 and 927 kev resonances.

slightly altered so as to give a null method of measuring this pulse. The new arrangement is presented in Figure 4. Figure 5 shows a typical excitation curve for this set-up, from which the proportionality factor was chosen to be 613.

In the case of either reaction (6) or (7) 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. In Figure 6 is presented approximately the expected variation of range with bombarding proton energy, of the alpha particles ejected at right angles to the proton beam, from a fluorine target. Two different hypothetical Q values are presented, together with the range variation with energy of the protons scattered at 90 degrees from Ca^{40}.

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 a particle of charge e, mass m, and energy E, passing through a field of magnetic induction B, one has the relation:

$$B\rho = \sqrt{\frac{2Em}{e^2}} \qquad (10)$$

where ρ is the radius of curvature of the resulting path. Clearly, for two particles having the same ratio of e^2/m traversing such a 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 has for the energy of a particle ejected in a nuclear reaction, the relation[28]:

$$E_2^0 = \frac{M_3}{M_2 + M_3} Q + \frac{M_3 - M_1}{M_2 + M_3} E_1 \qquad (11)$$

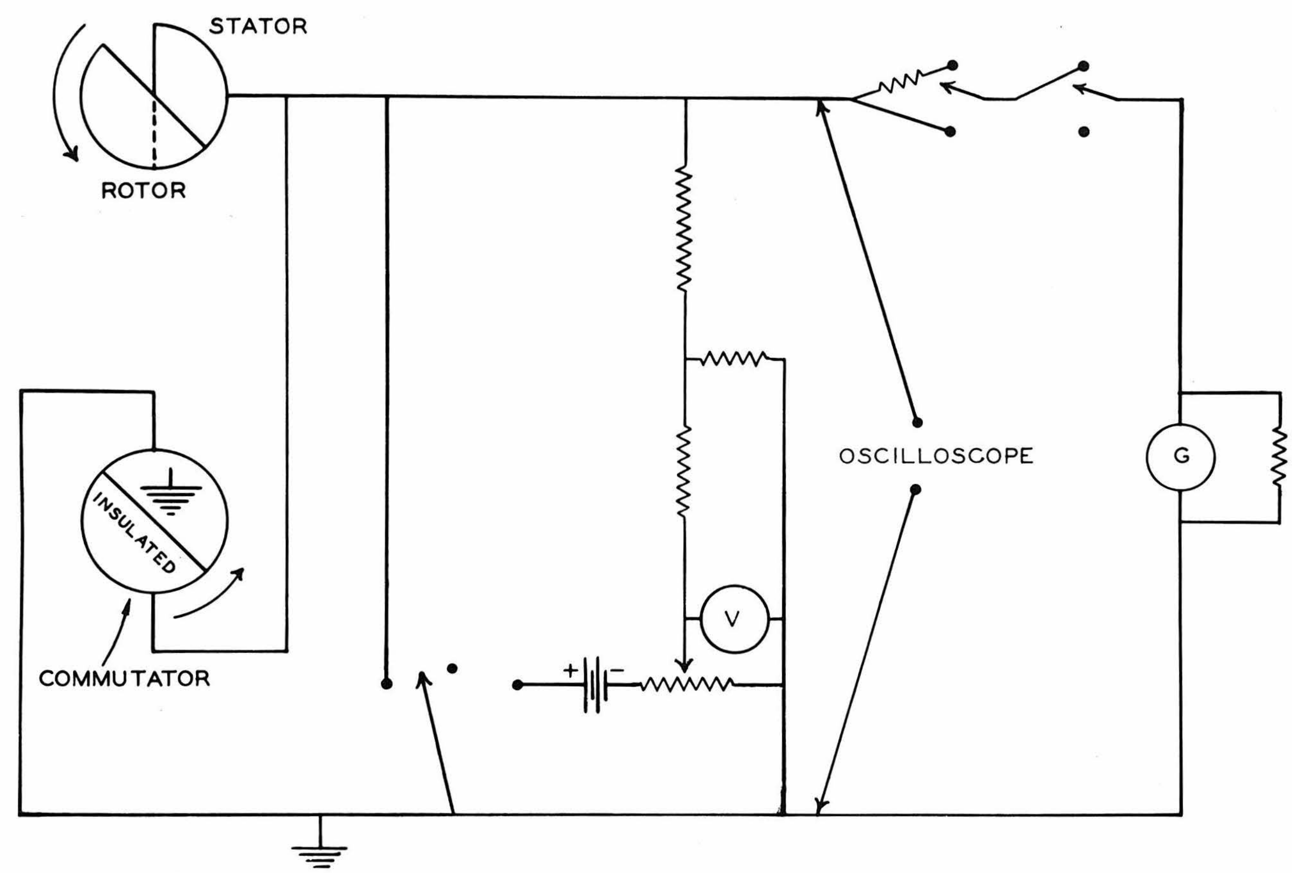

Figure 4. Circuit used in measurement of voltage. The shape of the pulse is observed on the oscilloscope screen.

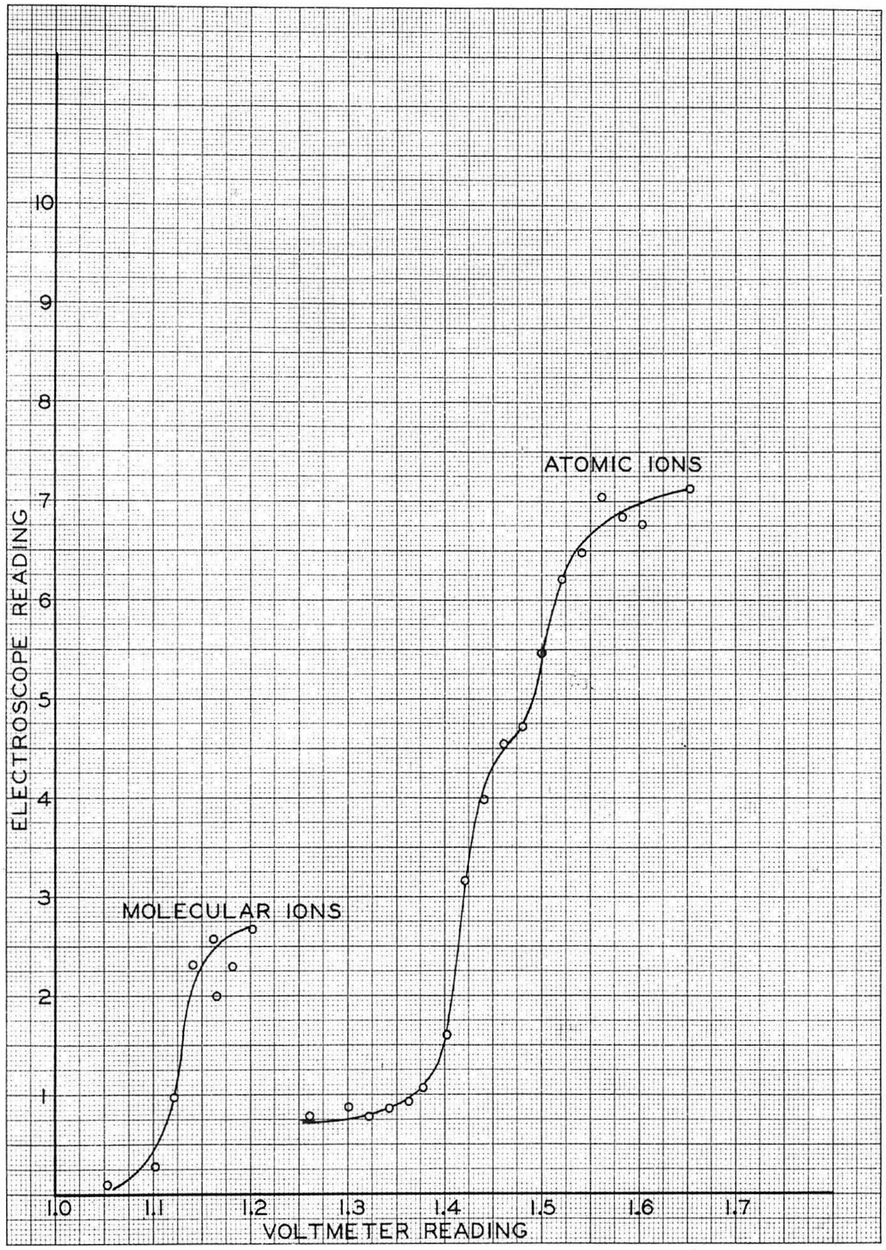

Figure 5. Excitation curve taken with null-reading voltmeter arrangement.

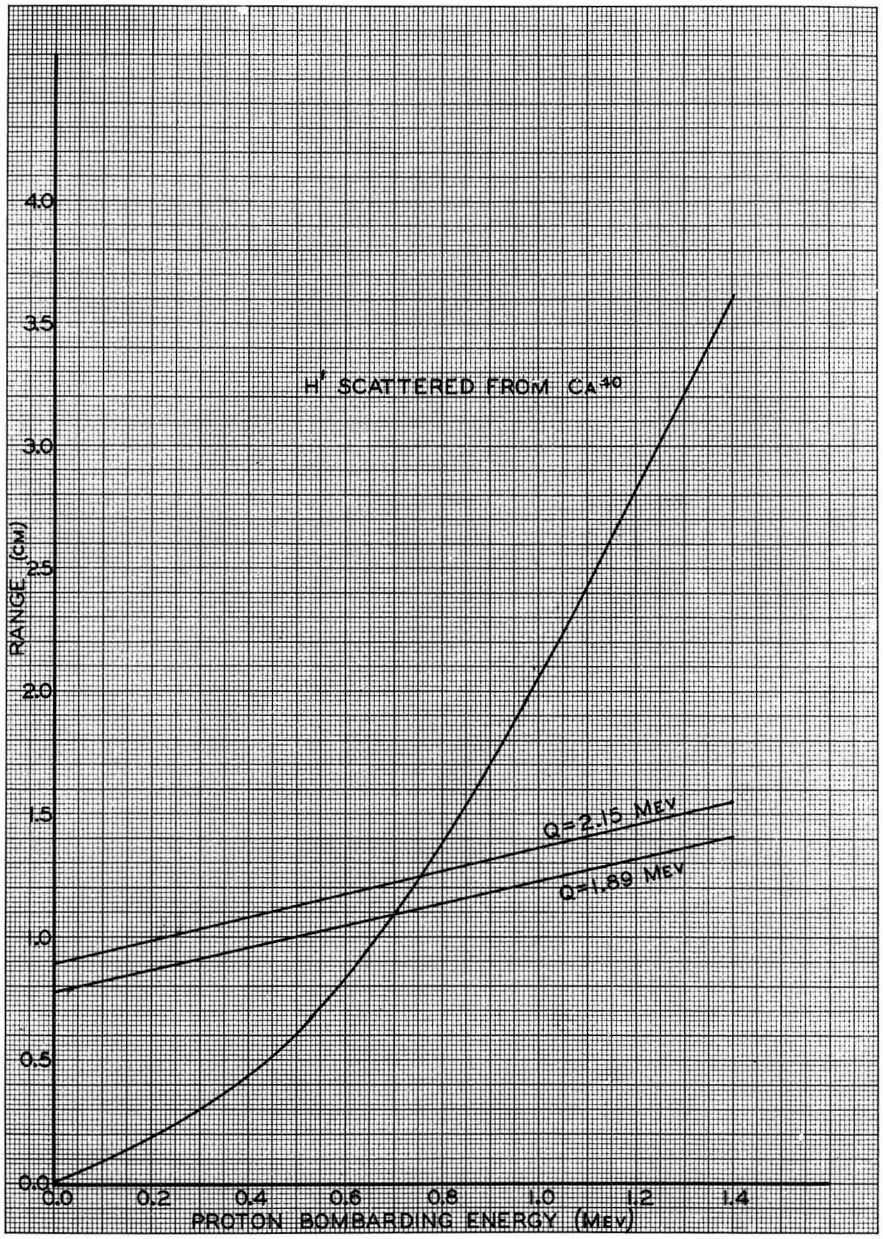

Figure 6. Curves showing the variation of range with bombarding energy, at 90 degree emission, of two hypothetical groups of alpha particles from $F^{19} + H^1$, and of the protons scattered by Ca^{40}.

where M and E denote the mass and energy of the particles involved, and the subscripts 1, 2 and 3 refer to the bombarding particle, produced particle, and residual nucleus, respectively. The superscript o signifies that particle 2 is observed at an angle of 90 degrees with the bombarding beam. In the case of the fluorine plus proton reaction one gets:

$$E_\alpha = \frac{4}{5} Q + \frac{3}{4} E_1 \tag{12}$$

If CaF_2 be used then the maximum energy protons are those scattered from the calcium nuclei. Accordingly, for the energy of the protons scattered from Ca^{40} nuclei one obtains:

$$E_H = \frac{40-1}{41} E_1 = \frac{39}{41} E_1 \tag{13}$$

In this case, then, the energy of the scattered proton increases more rapidly with primary energy than does that of the ejected alpha particle. Solving equations (12) and (13) simultaneously, and assuming Q = 2.0 Mev, one gets that at E_1 = 8.0 Mev the secondary energies are equal, and consequently the radii of curvature of the low-energy alphas and scattered protons are identical. For this reaction, therefore, the magnetic deflection method may be successfully employed at bombarding energies substantially below 8.0 Mev. Above 8.0 Mev complications arise because of the wide dispersion of proton energies which are due to varied target penetration.

In Figure 7 is depicted the variation in $B\rho$ as a function of energy E, for both protons and alpha particles. For the short-range alpha particles from fluorine, the ratio ρ_α / ρ_H at 1 Mev bombarding energy would be about 1.55.

Figure 8 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

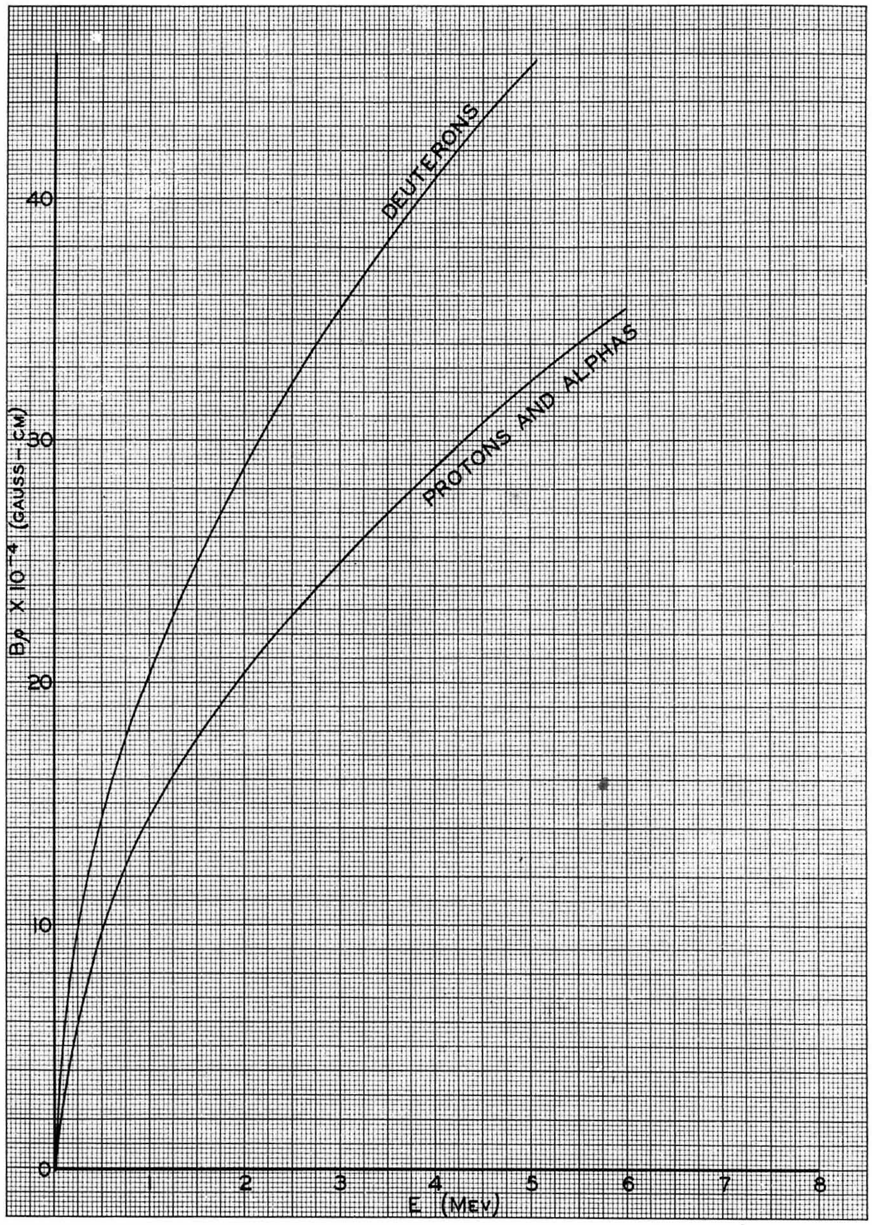

Figure 7. Curve depicting the variation of Bρ with energy, for protons, alpha particles, and deuterons.

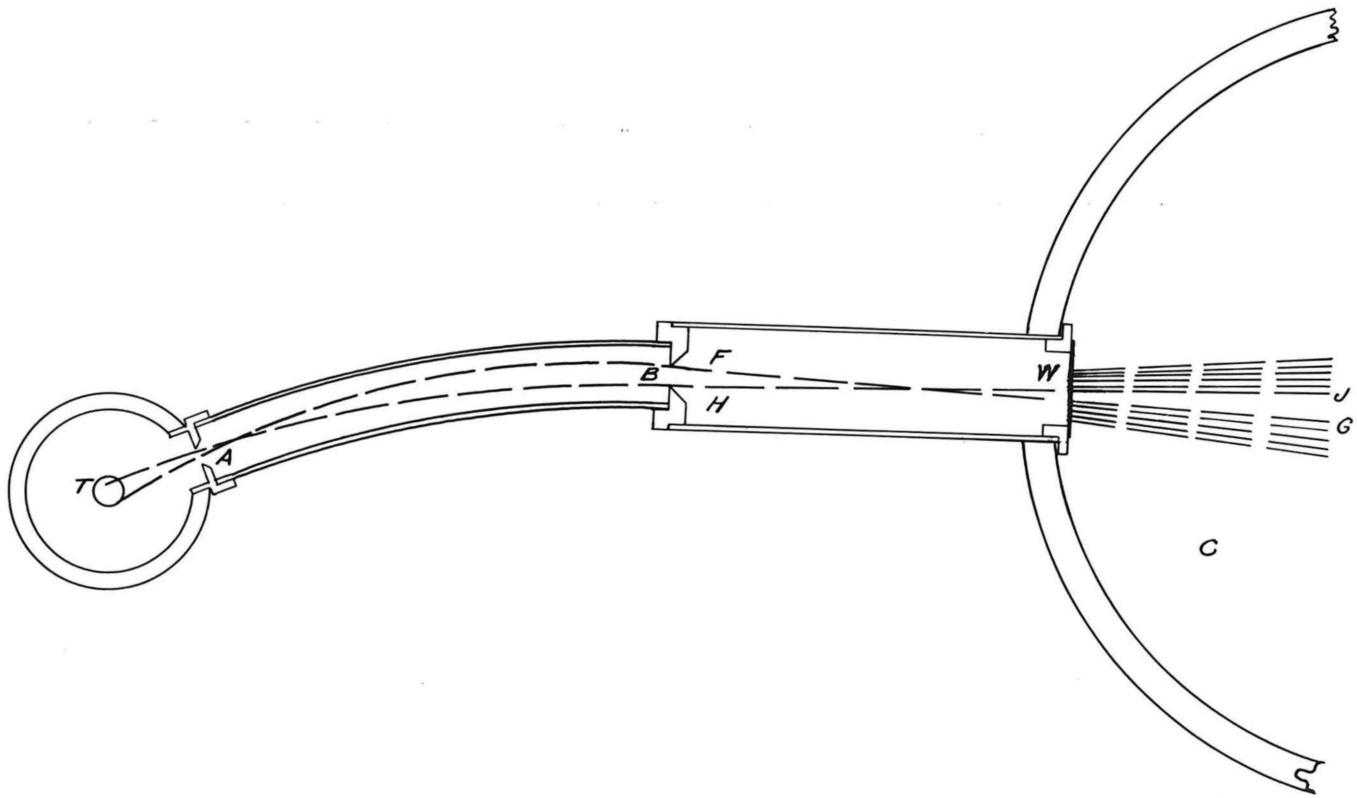

Figure 8. Target arrangement showing the separation of the alpha-particle group HJ from the scattered protons FG.

the beam striking the target. The beam was collimated by a 1/4 inch hole in a quartz disc just above the target, the illuminated spot on the target being thus 1/4 inch in diameter. The target was in most cases a slab of fluorite crystal cemented to the end of a carbon rod with a drop of shellac, and was less than 1/16 inch thick. The entire target had an area just larger than the illuminated spot. In some cases, however, CaF_2 powder was moistened with ethyl alcohol and allowed to dry on a carbon base, forming a fairly durable target. In both instances the target was inclined 45 degrees to the impinging particles, 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 the figure the field is perpendicular to the plane of the paper. There are 1/8 inch slits at points A and B, also perpendicular to the plane of the figure. The average radius of curvature of the tube is 20.5 cm. The tube was inserted between the pole pieces of an electromagnet at which point the field was limited in magnitude by the air gap produced by the presence of the collimating tube. The variation of the magnetic field as a function of magnet current is depicted in Figure 9. The saturation value of the field is evidently of the order of 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 1.0 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

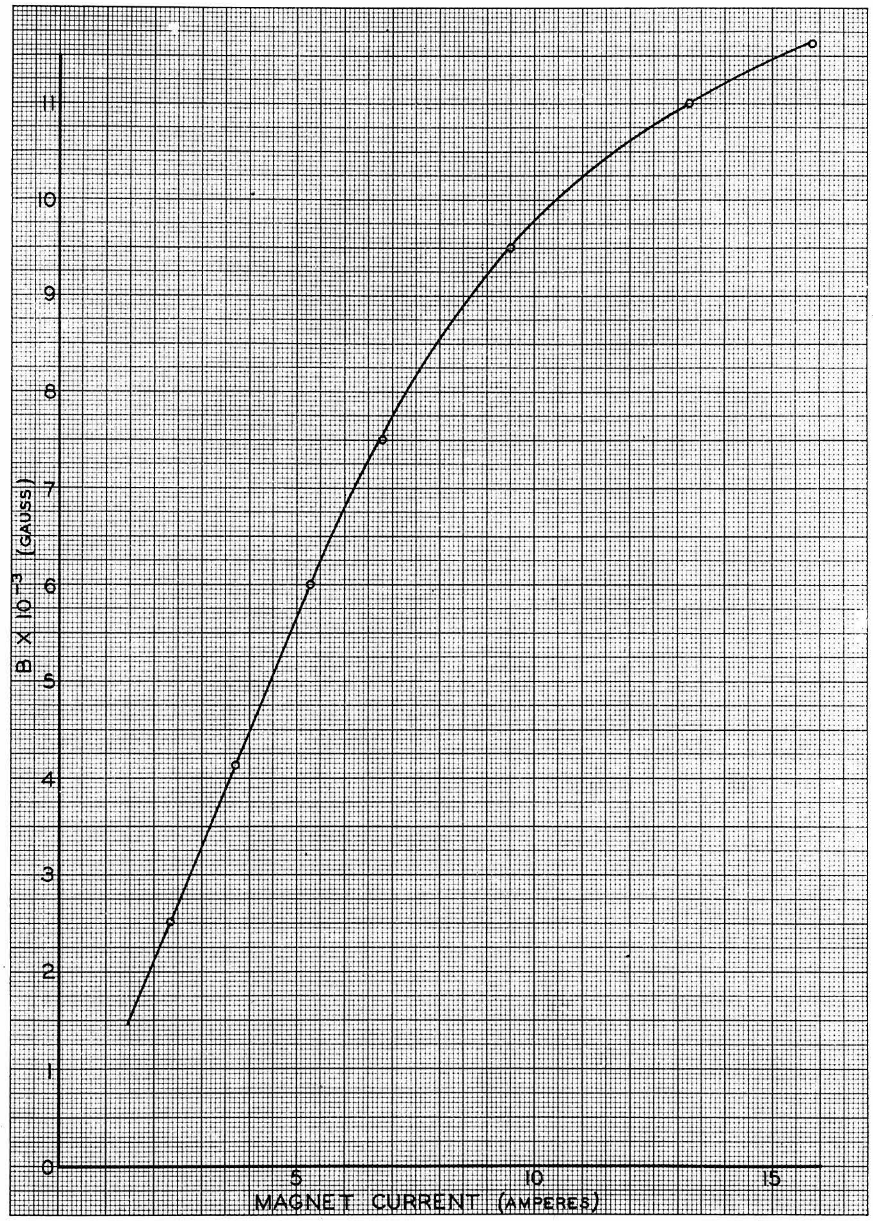

Figure 9. Curve showing the variation with magnet current, of the magnetic induction between the pole-pieces.

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 is 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 ρ as:

$$\Delta R = \rho \Delta E \tag{14}$$

it is then apparent that the resolving power increases as the stopping power decreases.

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 per cent of the total area. The foil was produced by gently dropping the "Newskin", by means of an eye-dropper, on to a water surface, and permitting it to spread out over that surface. After drying on the water, the collodian, or lacquer, furnished a very thin but tough skin which was then picked up by means of a wire ring. The edges of the grid were next painted with a thin layer of lacquer. After this had dried for a few moments the dry film was laid on the grid, the edges of the film adhering to the freshly painted spots on the grid. It was found that during the whole period of six months of operation the films made of "Newskin" did not deteriorate. However, films made of various lacquers such as, for example, Egyptian Lacquer would break through after only a few days of withstanding atmospheric pressure. Much trouble was also experienced with the latter substance because of fine particles being suspended in the liquid. This led to weak spots in the dried film. It was further found necessary to use distilled water in the dropping pan in order to eliminate the deposits left by the solutes in ordinary tap water.

III--Calculation of 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:

$$Li^6 + H^1 \rightarrow He^3 + He^4 + Q \tag{15}$$

in which the Q given by Perlow[29] as 3.945 ± 0.06 Mev was used, rather than the value 3.72 ± 0.08 given by Neuert[30]. The former made a very accurate determination of this quantity by comparing the ranges directly with those of the alpha particles from the reaction $Be^9[p\alpha]Li^6$. The energy of the latter reaction is accurately known from electrostatic deflection experiments.

There is good evidence to support the higher Q value for the $Li^6 + H^1$ reaction[29]. If one considers, in addition to (15), the reactions:

$$H^2 + H^2 \rightarrow H^3 + H^1 + 3.98 \pm 0.02 \text{ Mev} \tag{16}$$

$$Li^6 + H^2 \rightarrow He^4 + He^4 + 22.20 \pm 0.04 \text{ Mev} \tag{17}$$

one obtains, on combining these:

$$(H^3 - He^3) = (2H^2 - He^4) - (2H^1 - H^2) - 26.18 + Q \tag{18}$$

The brackets on the left side are well-known mass-spectroscopic quantities. Making use of Bainbridge's values for these, and choosing Q = 3.945, one gets for $[H^3 - He^3]$ the value 0.19 ± 0.09 Mev. Choosing Aston's values one obtains for this quantity the result 0.10 ± 0.1, so that in both cases H^3 is unstable by a small amount against beta decay. Alvarez and Cornog[31] have found these beta particles, and estimated their energy to be about 10 kev. Recently Brown[32] has measured the range of the beta particles emitted from H^3

and has found the maximum to be at about 13 mm, corresponding to an energy of about 9.5 kev. These observations are in very good agreement with the results of reactions (15), (16) and (17) if one assumes Perlow's value for Q to be correct. If, on the other hand, one assumes Neuert's value to be the acceptable one then the H^3 nucleus turns out to be stable against beta disintegration by from 4 to 13 kev, depending upon whether Bainbridge's, or Aston's masses are used.

In addition to the preceding considerations, Perlow's measurement gives greater consistency than Neuert's with the series of reactions:

$$H^2 + H^2 \rightarrow H^1 + H^3 + Q_1 \qquad (19)$$

$$H^2 + H^2 \rightarrow n^1 + He^3 + Q_2 \qquad (20)$$

$$Li^6 + H^1 \rightarrow He^4 + He^3 + Q_3 \qquad (21)$$

$$Li^6 + n^1 \rightarrow He^4 + H^3 + Q_4 \qquad (22)$$

In calibrating the foil and chamber, a thick metallic lithium target was bombarded with 600 kev protons, using the same target arrangement as was actually employed in the fluorine case. Before being inserted into the target holder, the lithium was carefully scraped so that a fresh surface might be exposed to the beam. This will be discussed again later.

Figure 10 depicts the expected ranges of the He^3 and He^4 particles, and shows also the ranges of the protons scattered from the heavier of the two lithium isotopes. For the alpha particles the range-energy curve of Holloway and Livingston[33] was used. For the scattered protons, the Cornell Curve Revised, drawn from the data of Parkinson, Herb, Bellamy and Hudson[34] was accepted as being the correct range-energy relationship.

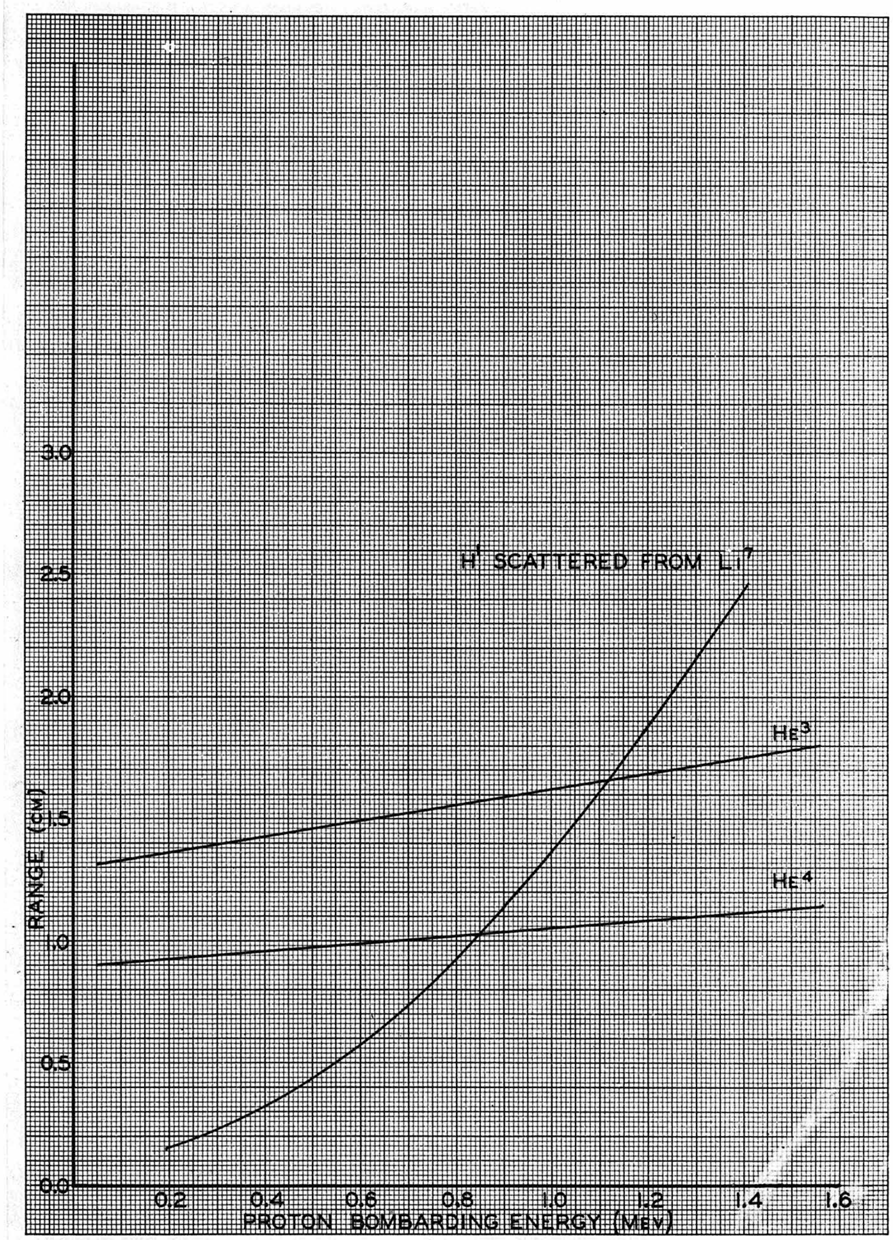

Figure 10. Curves depicting the expected ranges, at 90 degree emission, of the alpha particles from the reaction $Li^6 + H^1$, and of the protons scattered from Li^7.

In obtaining the lithium data the scattered protons were deflected away from the alpha particles by a field of about 10,000 gauss. The results are plotted in Figure 11 as numbers of tracks versus apparent range in the cloud chamber. The curve represents the data selected from about 1200 stereoscopic pictures. It is noticed that the figure in this case is a differential curve. In observing a group of particles the quantity most readily measured is the extrapolated range of the integral curve [experimental curve giving the number of particled detected, as a function of the distance from the source]. When the target used is a thick one [air-equivalent depth of target greater than range of produced particles] this parameter is completely identical with extrapolated range of the differential curve. In the figure the extrapolated range of the He^3 particles is seen to be 8.55 cm, and 5.63 cm for the He^4 particles. In both instances these values represent the apparent ranges observed in the chamber, not having been corrected as yet for the foil thickness and reduced stopping power of the gas in the chamber. Here, the gas used in the chamber was 50 cm pressure of helium plus water vapor.

In computing, from the figure, the mean ranges of the He^3 and He^4 particles, the range exponent n is useful. It is defined by the relation:

$$n = 2\, d(\log R)/d(\log E) \tag{23}$$

and is the logarithmic derivative of the range R, with respect to the energy, E. It is instructive to point out that if n were constant, R would be proportional to v^n. Since the range-energy curves in Bethe's article have been superseded by more recent data, the exponent curves there are also obsolete. Accordingly range-exponent curves were drawn from Holloway and Livingston's[33] data for the alpha particles, and from Parkinson, Herb, Bellamy and Hudson's[34] data for the protons. These are represented in Figures 12 and 13, respectively.

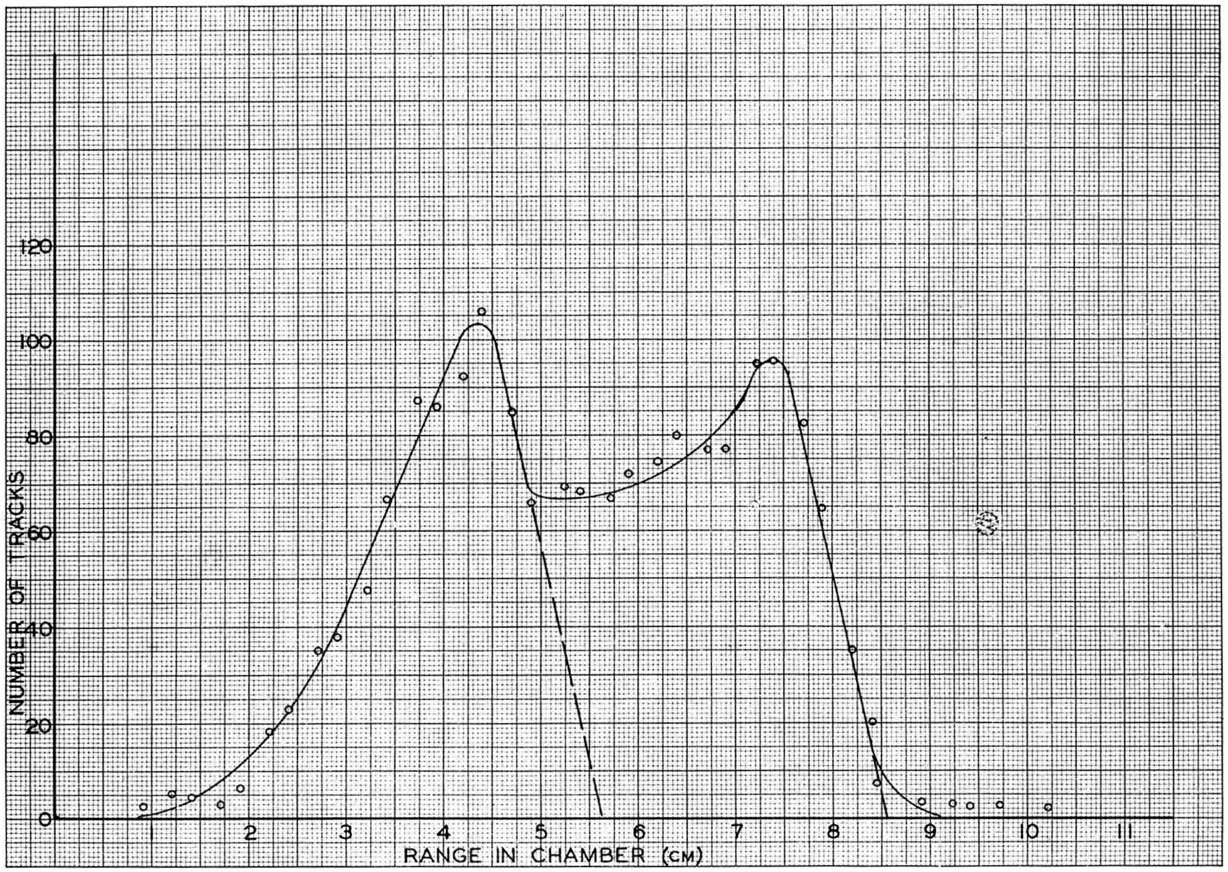

Figure 11. Alpha-particle groups resulting from the bombardment of a thick lithium target with 600 kev protons.

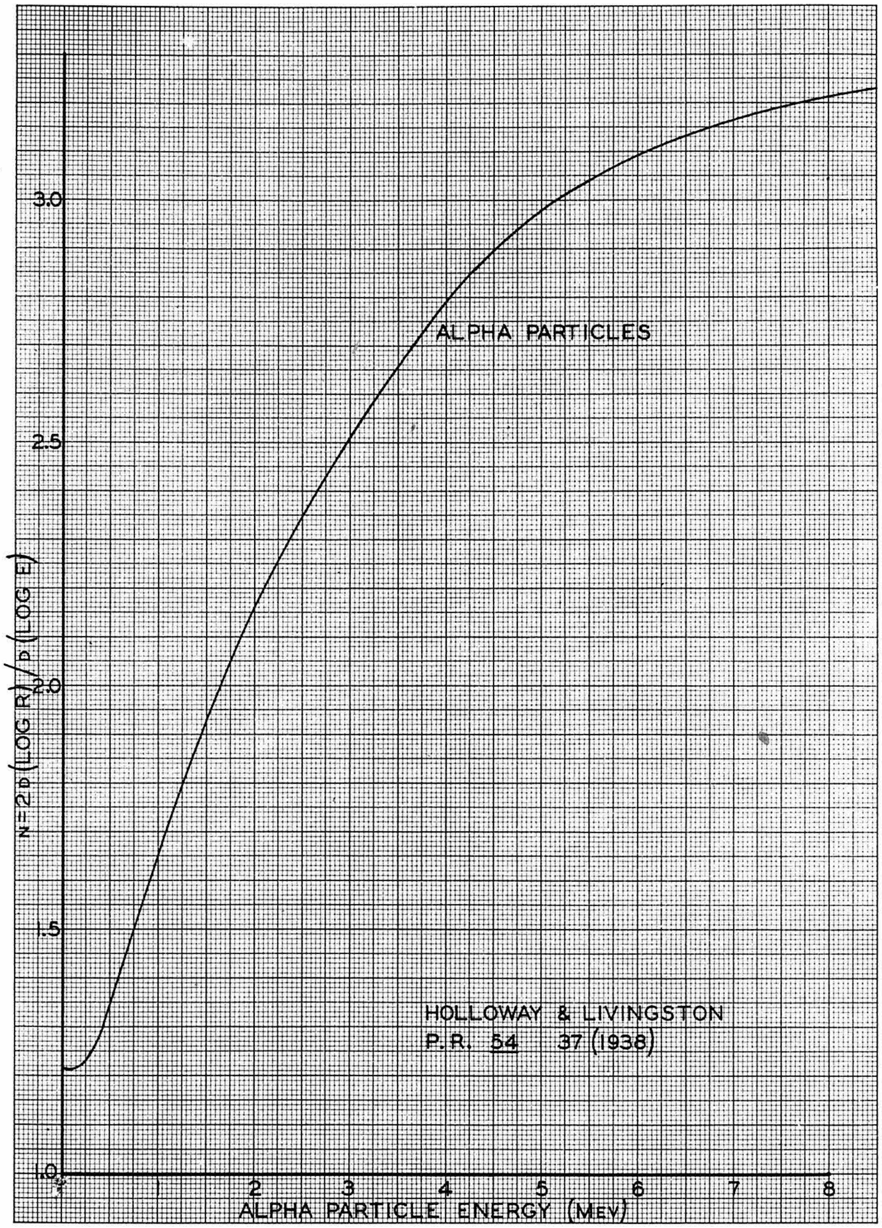

Figure 12. Range exponent curve for alpha particles. [from the data of Holloway and Livingston]

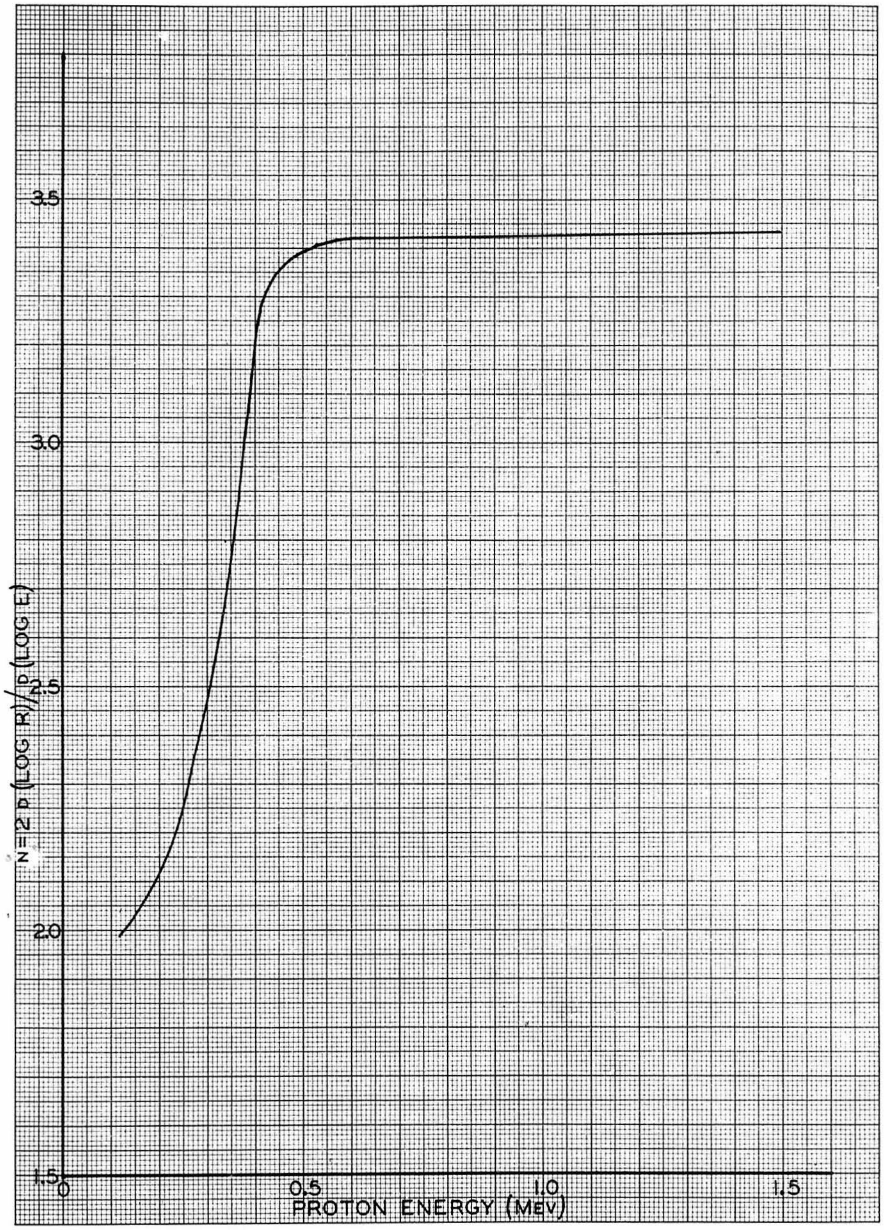

Figure 13. Range exponent curve for protons. [from the data of Parkinson, Herb, Bellamy and Hudson]

The value of the range exponent for a helium nucleus of mass 3 is readily obtained from the curve for alpha particles in the following manner:

The range-energy relations for the ions of the other hydrogen and helium isotopes may be obtained immediately from those of the proton and alpha particle, respectively. Capture and loss of electrons being the same for all hydrogen isotopes [or all helium isotopes] one has:

$$R_{Z,M}(E) = \frac{M}{M_0} R_{Z,M_0}\left(E \frac{M_0}{M}\right) \tag{24}$$

where $R_{Z,M}(E)$ is the range of a particle of charge Z, mass M, and energy E. From this, one finds that the range of a He^3 particle of energy E is 3/4 that of a He^4 particle of energy (4/3) E, i.e.:

$$R_3(E) = \frac{3}{4} R_4 \left(\frac{4}{3} E\right) \tag{25}$$

$$\log R_3 = \log 3/4 + \log \left[R_4 \left(\frac{4}{3} E\right)\right] \tag{26}$$

Differentiating logarithmically:

$$\frac{d(\log R_3)}{d(\log E)} = \frac{d\left[\log\{R_4(\frac{4}{3}E)\}\right]}{d(\log E)} \tag{27}$$

Now $\log \frac{4}{3}E = \log \frac{4}{3} + \log E$ & $d(\log \frac{4}{3}E) = d(\log E)$

$$\therefore \frac{d(\log R_3)}{d(\log E)} = \frac{d\left[\log R(\frac{4}{3}E)\right]}{d\left[\log(\frac{4}{3}E)\right]} = n_{He^3} \tag{28}$$

Thus we see that the range exponent for a helium nucleus of mass 3 is identical to that of a He^4 particle of energy (4/3) E.

In computing the values for ρ, the stopping power of the chamber gas, and k, the air-equivalent of the foil, one takes as a first approximation, the simultaneous equations:

$$\begin{aligned} 7.60\rho + k &= 1.485 \\ 4.20\rho + k &= .985 \end{aligned} \tag{29}$$

whence $\rho = .147$.

In equations (29), 1.485 is the actual expected mean range, in cm of air under standard conditions, of the He^3 particle, taking Q = 3.945 Mev, and with a bombarding energy of 600 kev. That expected for the He^4 particle is .985 cm. The numbers on the left sides of the equations are the corresponding apparent probable ranges of the particles, after allowing for a possible 0.2 cm shift due to the proximity of the peaks. [This shift will be treated quantitatively for the simpler case of two of the fluorine peaks.]

The above values of ρ and k would be the correct ones if the most probable ranges were identical to the mean values of the ranges. In order to find the mean ranges from the most probable ranges, use was made of the methods of Bethe[28].

The conditions of the present case fulfill the criterion of Bethe for "good geometry", i.e., that all particles emitted at an angle less than θ_0 are prevented from reaching the detecting apparatus. θ_0 is defined by the relation:

$$\cos \theta_0 = n \frac{(M_1 M_2)^{1/2}}{M} \left(\frac{E_1}{E_2^0} \right)^{1/2} \qquad (30)$$

where n is the range exponent of the produced particle, M_2 its mass, and $E_2{}^0$ its energy when emitted at 90 degrees to the impinging beam. E_1 and M_1 are the energy and mass, respectively, of the bombarding particle. The value thus calculated for θ_0 is about 71 degrees. However, with the present experimental arrangement only those particles emitted at angles in the range of from 89 to 91 degrees to the bombarding proton beam were observed. Therefore Bethe's condition for "good geometry" was well satisfied for the lithium case.

The mean range R is obtained from the most probable range R_0 by adding a small amount sx_0 to the latter, and from the extrapolated range R_{extr} by subtracting a small amount sx_{extr}. The quantities x_o and x_{extr} are shown on page 286 of Bethe's article as functions of another quantity β. β is defined there as:

$$\beta = \frac{\left[z Z \left(\frac{M_1}{E_1}\right)^{1/2} + 4 \right] \frac{s_2}{R_2}}{\left[\frac{R_1}{R_2} n_1 + \frac{E_1}{E_2} \frac{M_3 - M_1}{M} n_2\right]} \tag{31}$$

in which z, M, E, R, n, refer to the charge, mass, initial energy [energy before target penetration], range, and range exponent of the incident particle. Z, M_2, E_2, R_2, n_2, s_2 refer to the charge, mass, energy, range, range exponent, and straggling coefficient of the emitted particle.

For the He^3 particle one has:

$$\beta = \frac{\left\{1.3 \left(\frac{1}{.6}\right)^{1/2} + 4 \right\} s'/R}{\left\{\frac{.93}{1.485} 3.42 + \frac{.6}{2.512} \frac{4-1}{7} 2.62\right\}} = 3.27 \; s'/R \tag{32}$$

where s'/R is to be determined by successive approximations. Trying s'/R = .06 one has β = .196 whence $x_o + x_{extr}$ = 1.48, giving a range difference of .06[1.48]1.485 = .14 cm. Now the actual difference is $R_{extr} - R_o$ = .14. One may therefore take s'/R = .06 for the He^3 particles.

In a similar manner for the He^4 particles one gets:

$$\beta = 2.3 \frac{s'}{R} \tag{33}$$

The observed difference is $R_{extr} - R_o$ = .166. This agrees with what one calculates when taking s'/R = .12, for:

$$\frac{s'}{R}(x_o + x_{extr}) R = .12 \cdot .140 \cdot .985 = .166 \tag{34}$$

Using the above values of s'/R and taking, in each case, the average of the values of $\bar{R}$ deduced from the extrapolated and from the most probable ranges, one finds that in the case of the He^4 particles $\bar{R} = 5.11$ cm, and for the He^3 particles $\bar{R} = 8.40$ cm, both being measured in the chamber. Using these values for the apparent mean ranges the stopping power ρ is redetermined to be .154.

With $\rho = .154$ one may determine another approximation to the apparent mean range $\bar{R}$. For the He^3 particle one has:

$$\bar{R} = \frac{(8.55 \cdot .154 - .06 \cdot .231 \cdot 1.485) + (7.60 \cdot .154 + .06 \cdot 1.25 \cdot 1.485)}{2 \cdot .154} = 8.38 \text{ cm} \quad (35)$$

in the chamber. Similarly that for the He^4 particles is 5.09 in the chamber.

One may now determine the air-equivalent k from the equations:

$$\begin{aligned} 1.485 &= 8.38\rho + k \\ .985 &= 5.09\rho + k \end{aligned} \quad (36)$$

whence $\rho = .154$, and $k = .2$ cm.

However, it was felt that inasmuch as k was obtained here as the difference between two large numbers, with a consequent large possible error, a check might be obtained by weighing a given amount of the foil material itself. In order to estimate the air equivalence of the foil from the stopping power of the substance of which it was composed, and later also to compute the stopping power of the CaF_2 target material it will be helpful at this point to discuss the nature of ρ, and to show its variation with energy for several simple substances.

Bethe's formula for the rate of energy loss in a substance, of a particle of energy E, charge ze, and velocity v gives:

$$-\frac{dE}{dX} = \frac{4\pi e^4 z^2}{mv^2} N Z \log \frac{2mv^2}{I} \quad (37)$$

where m is the mass of the electron, N the number of atoms per cm^3 of the material, Z the nuclear charge, and I the average excitation potential of the atom.

For the ratio of the rate of energy loss in a substance for an alpha particle of velocity v_α to that for a proton of velocity v_H one has, from (36):

$$u = \frac{(dE/dx)_\alpha}{(dE/dx)_H} = \frac{4V_H^2}{V_\alpha^2} \frac{\log \frac{2mV_H^2}{I}}{\log \frac{2mV_\alpha^2}{I}} \qquad (38)$$

We also see that if $v_\alpha = v_H$, then u = 4.

Further, since the stopping power ρ of a substance is defined as the ratio of the rate of energy loss in the substance to that in air one gets, if $v_\alpha = v_H$:

$$\frac{\rho_H}{\rho_\alpha} = \frac{\frac{(dE/dx)_H}{(dE/dx)_{H,air}}}{\frac{(dE/dx)_\alpha}{(dE/dx)_{\alpha,air}}} = \frac{1}{4} \frac{(dE/dx)_{\alpha,air}}{(dE/dx)_{H,air}} = \frac{1}{4} \cdot \frac{4}{1} = 1 \qquad (39)$$

$$\therefore \quad \rho_H = \rho_\alpha \qquad \text{if} \qquad V_H = V_\alpha \qquad (40)$$

Using Mano's[35] measurements of stopping powers, the results for a few substances are depicted in Figure 14. ρ is given as a function of particle velocity. In the figure the atomic stopping power 1 is arbitrarily chosen to represent 1/2 the "air molecule".

One may assume the chemical formula of the foil material to be of the form $[CH_2O]^n$ whence 1/15 of the weight is due to H, 6/15 to C, and 8/15 to O. The differential stopping power, referred to the "air atom", of these substances for an alpha particle of velocity 1.0 x 10^9 cm/sec [2.07 Mev energy] is obtainable in part from Figure 14. The stopping power for 1/2 O_2 is 1.04, that for C [not shown in the figure] is.91, and that for 1/2 H_2 is .23. The total stopping power of the substance $[CH_2O]^n$ is therefore .95.

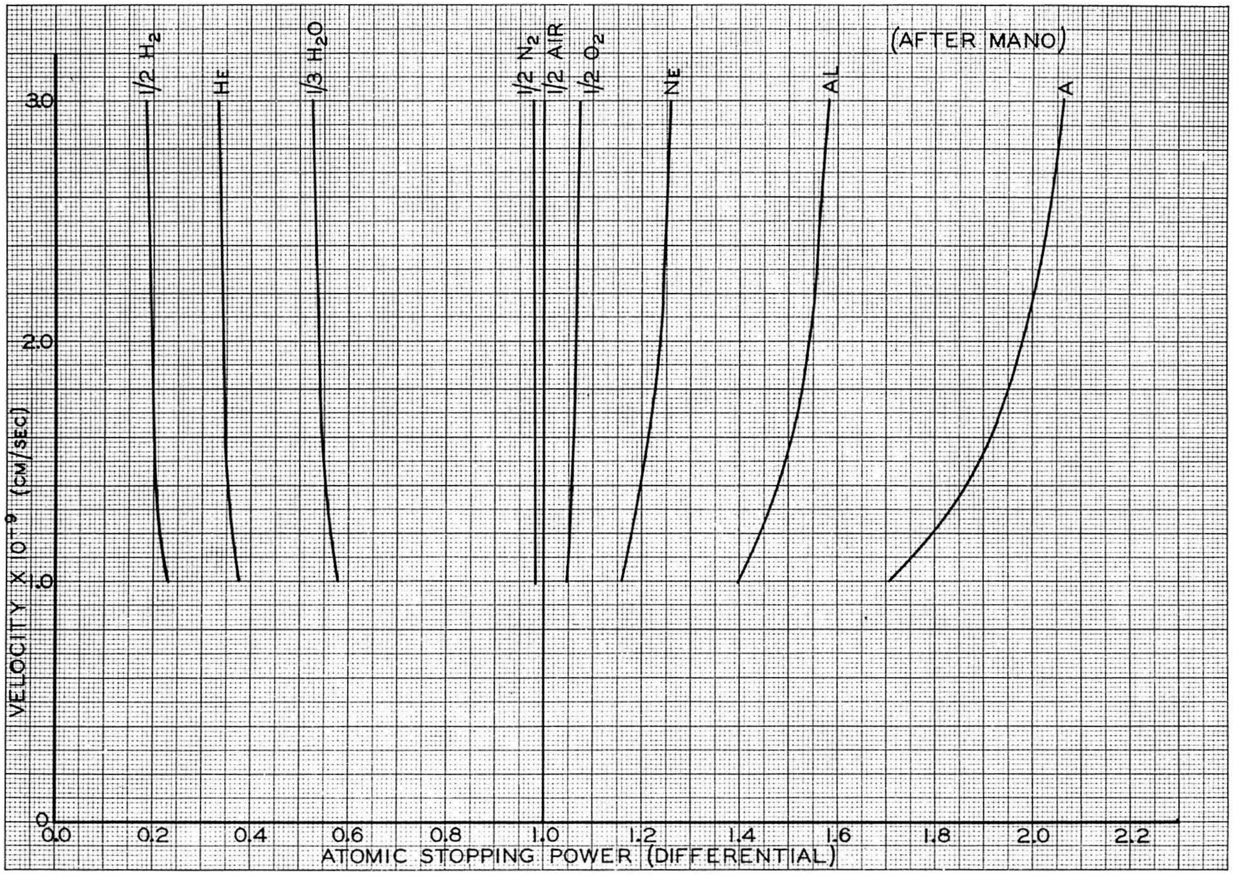

Figure 14. Differential atomic stopping power as a function of particle velocity for various substances.

The weight of the foil was found to be 1.52 mg for 4 cm^2 of the material. Since air at 15 degrees Centigrade and 760 mm Hg weighs .00124 gms/cc one sees that under the above mentioned conditions of temperature and pressure, by weight alone the foil is equivalent to 3.0 mm of air. However due to the fact that the stopping power of the foil substance is but .95, the effective air equivalence of the window is 2.85 mm. Taking a rough mean between the value obtained in this way, and that obtained with the previous method one may assume as a good approximation to k the figure 2.5 mm air equivalence of the foil for 2 Mev alpha particles.

Using the lithium data again the stopping power of the chamber is now determined to be .145 when the contents of the chamber were He and H_2O vapor at 50 cm Hg pressure. It will be shown later, in the discussion of sources of error, that the discrepancy in computed Q's for the fluorine particles will be negligibly affected by small variations in k and ρ.

In order to have an accurate means of computing Q from the observations it is necessary that the stopping power of CaF_2 be known. Since this had not been measured a close approximation to it was estimated by a consideration of Mano's measurements. The atomic stopping powers of Ca [Z = 20], and of F [Z = 9] were computed by combining and interpolating between the values for A [Z = 18] and Al [Z = 13], and for O [Z = 8] and Ne [Z = 10]. Sets of values were given for the last four mentioned elements by Mano, and are depicted in Figure 14.

Since the stopping power is linearly proportional to the atomic number we may write:

$$\rho(Ca) = \rho(A) + \frac{2}{5}\left[\rho(A) - \rho(Al)\right] \tag{41}$$

$$\rho(F) = \rho(\tfrac{1}{2}O_2) + \tfrac{1}{2}\left[\rho(Ne) - \rho(\tfrac{1}{2}O_2)\right] \quad (42)$$

Combining:

$$\rho(CaF_2) = \rho(\tfrac{1}{2}O_2) + \rho(Ne) + \tfrac{7}{5}\rho(A) - \tfrac{2}{5}\rho(Al) \quad (43)$$

The results computed in this way are shown in Figure 15, where $\rho[CaF_2]$ is given as a function of both v and of E.

The same target arrangement employed for the lithium was used for the fluorine. Figures 16a 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 the pressure inside the expanded chamber was 35 cm Hg, and the vapor used was H_2O. Figure 16a comprises 141 tracks, while the curve of part b of this figure is deduced from 20 tracks.

Figure 17a depicts the structure observed under 910 kev bombardment. The peak then 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 represents 219 tracks, obtained from about a thousand pictures.

Figure 17b is 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.

Figure 18 shows the effect of bombarding at a slightly higher voltage. This was at 936 kev, just above the 927 kev resonance. The structure on the high-energy side of the peak was thought to be due to the alpha particles

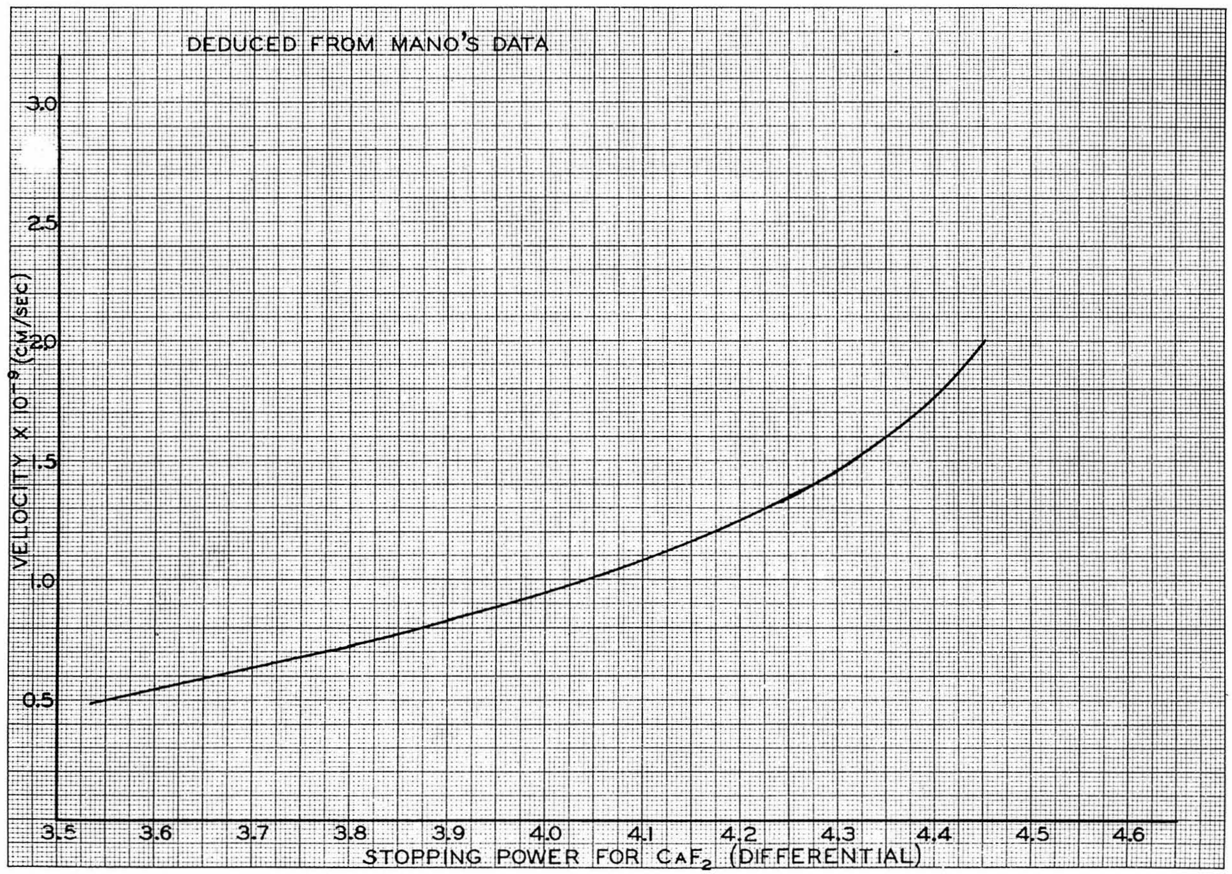

Figure 15. Differential atomic stopping power as a function of particle velocity for calcium fluoride.

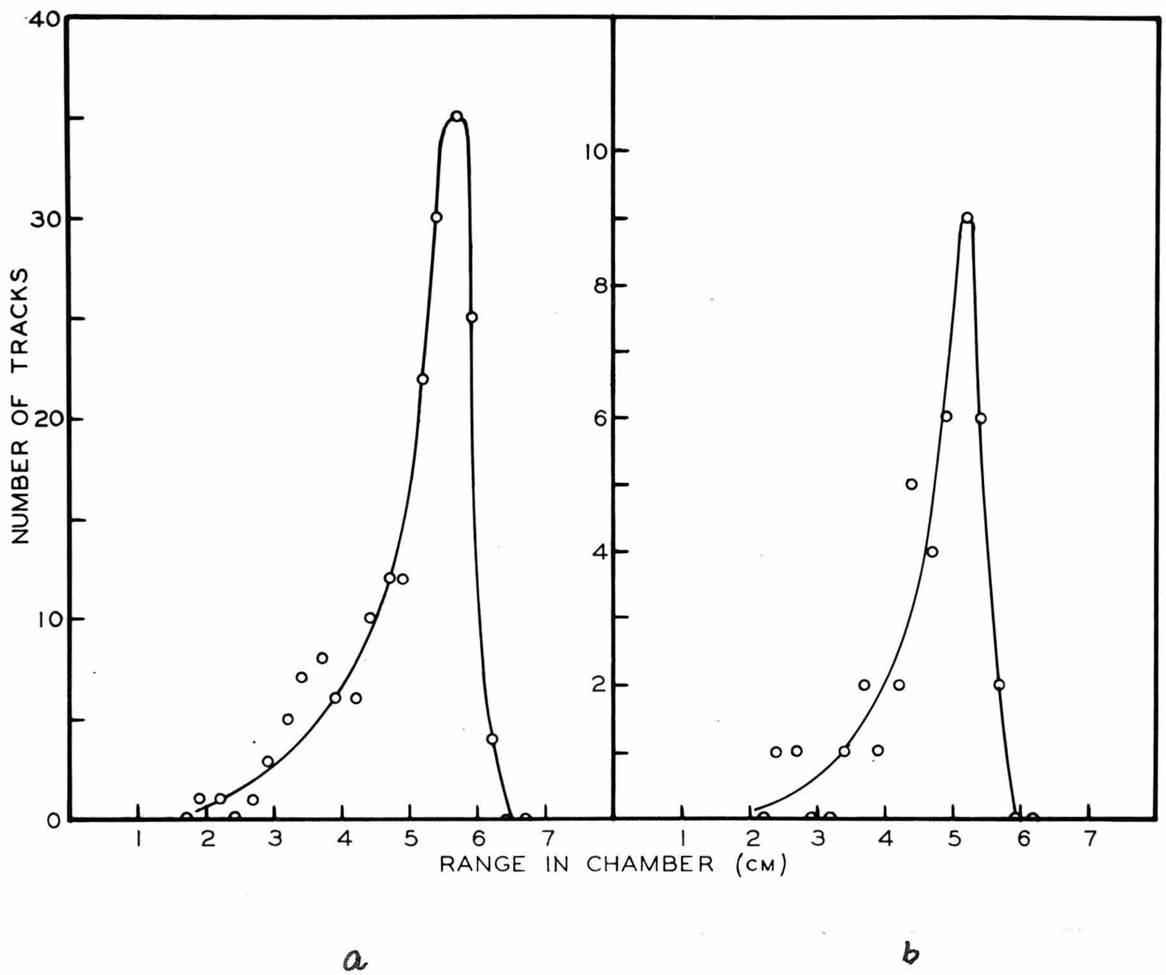

Figure 16. Alpha particles observed when bombarding a thick fluorine target with [a] 364 kev protons [ρ= .105], and [b] 390 kev protons [ρ= .105].

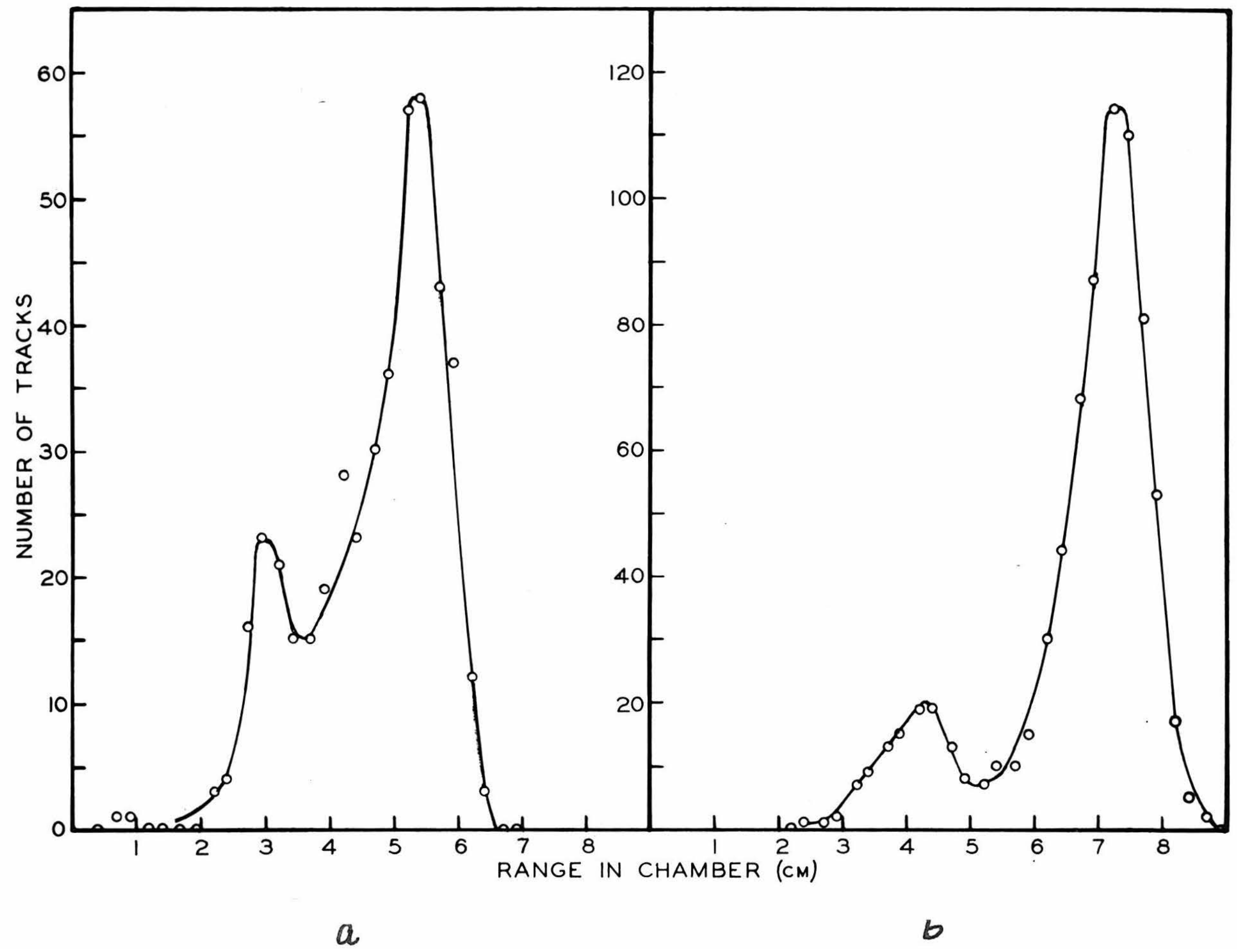

Figure 17. Alpha particles observed when bombarding a thick fluorine target with 910 kev protons. [a] $\rho = .145$, [b] $\rho = .105$.

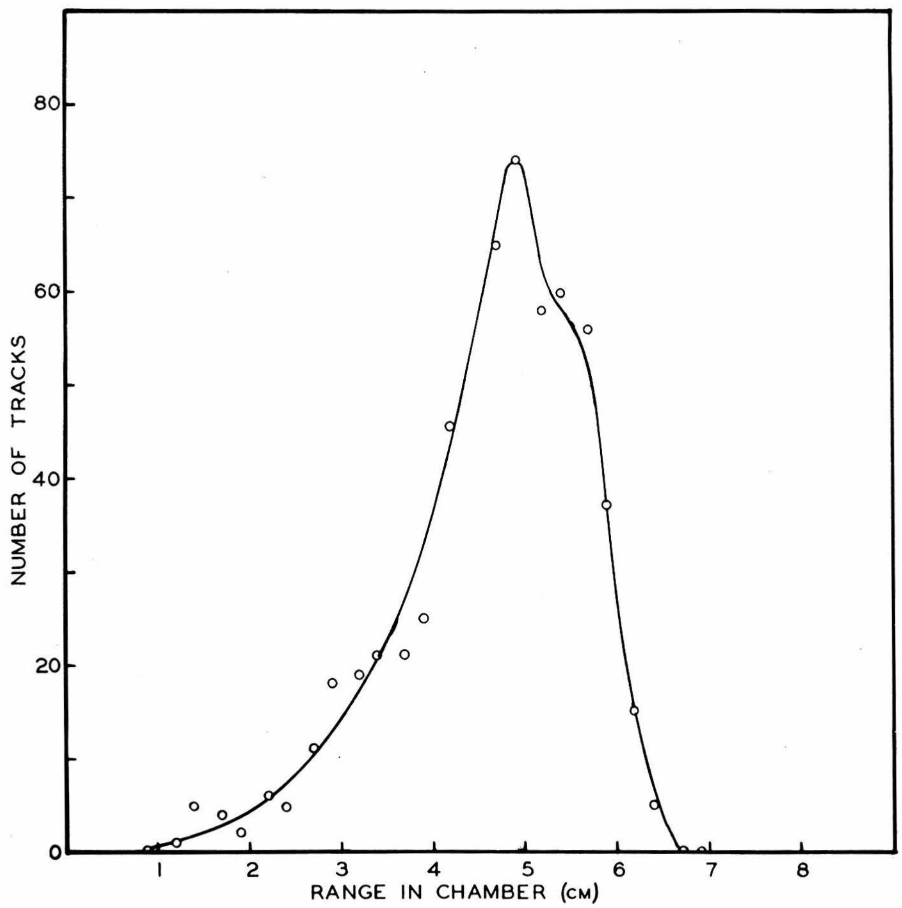

Figure 18. Alpha particles found as a result of the bombardment of a thick fluorine target with 936-kev protons.

arising from the 927 kev resonance, and that the main body of the alpha particles originates at the 867 kev threshold. The intensity due to the upper level is less than that due to the lower because at this bombarding voltage the full width due to the former is not realized. The curve represents 305 acceptable tracks, and was obtained from about 750 stereoscopic photographs.

The result of bombardment at 987 kev is represented in Figure 19. This is well above both the 867 and 927 kev resonances. The alpha particles emanating from both levels are clearly resolved. That the two peaks are separated is due to the fact that the stopping power of the target material for the alpha particles differs considerably from that for the protons. This fact is insured by the greater energy of the alpha particles in the experiment, over that of the protons. 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.

Figure 20a depicts the alpha particles obtained under bombardment by 1389 kev protons. The particles emitted were from the 1363 kev resonance. The curve represents a total of 107 tracks, and was deduced from about 250 photographs. This increase, beyond that given above, in the number of particles per picture, is to be expected in view of the appearance of the gamma-ray yield curve of Figure 1.

The next figure, 20b, shows the results of raising the bombarding voltage slightly, to 1414 kev. Some 500 pictures were taken at this energy, yielding a total of 251 tracks. The broadness of the base of the peak seems to confirm the existence of the satellite at 1335 kev.

In Figure 21 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

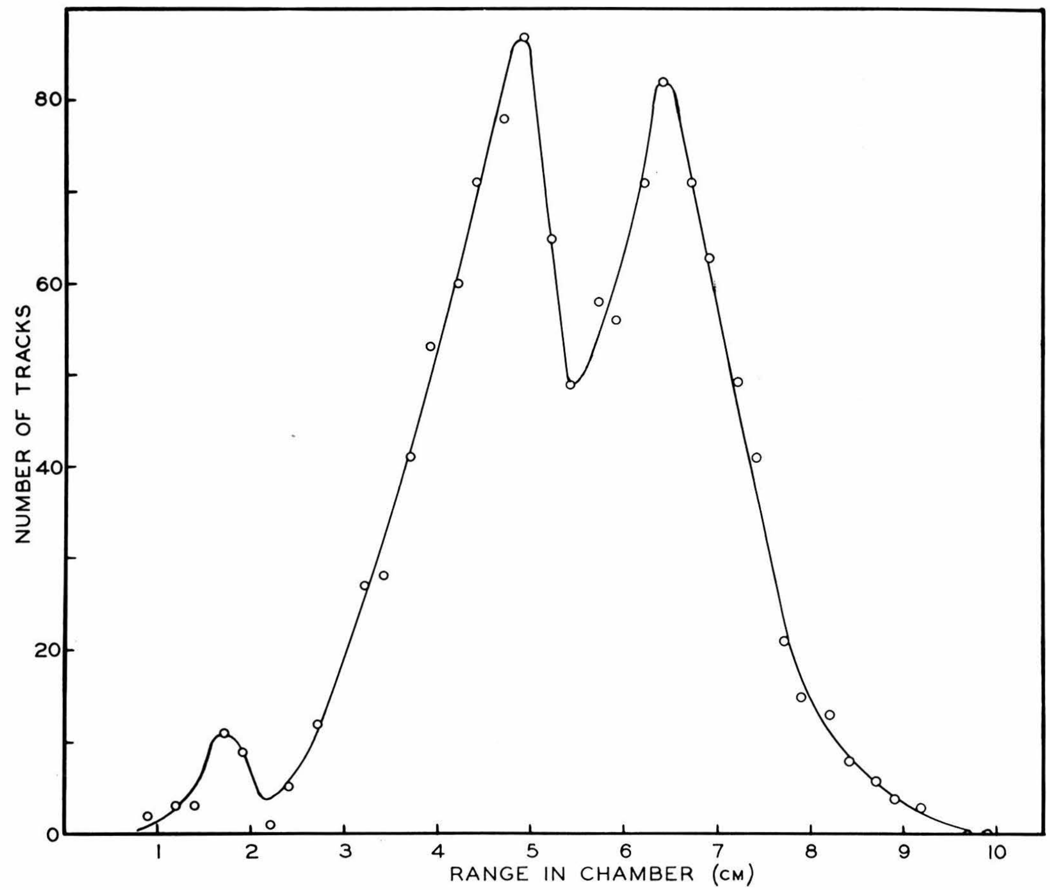

Figure 19. Two groups of alpha particles observed as a result of the bombardment of a thick fluorine target with 987 kev protons.

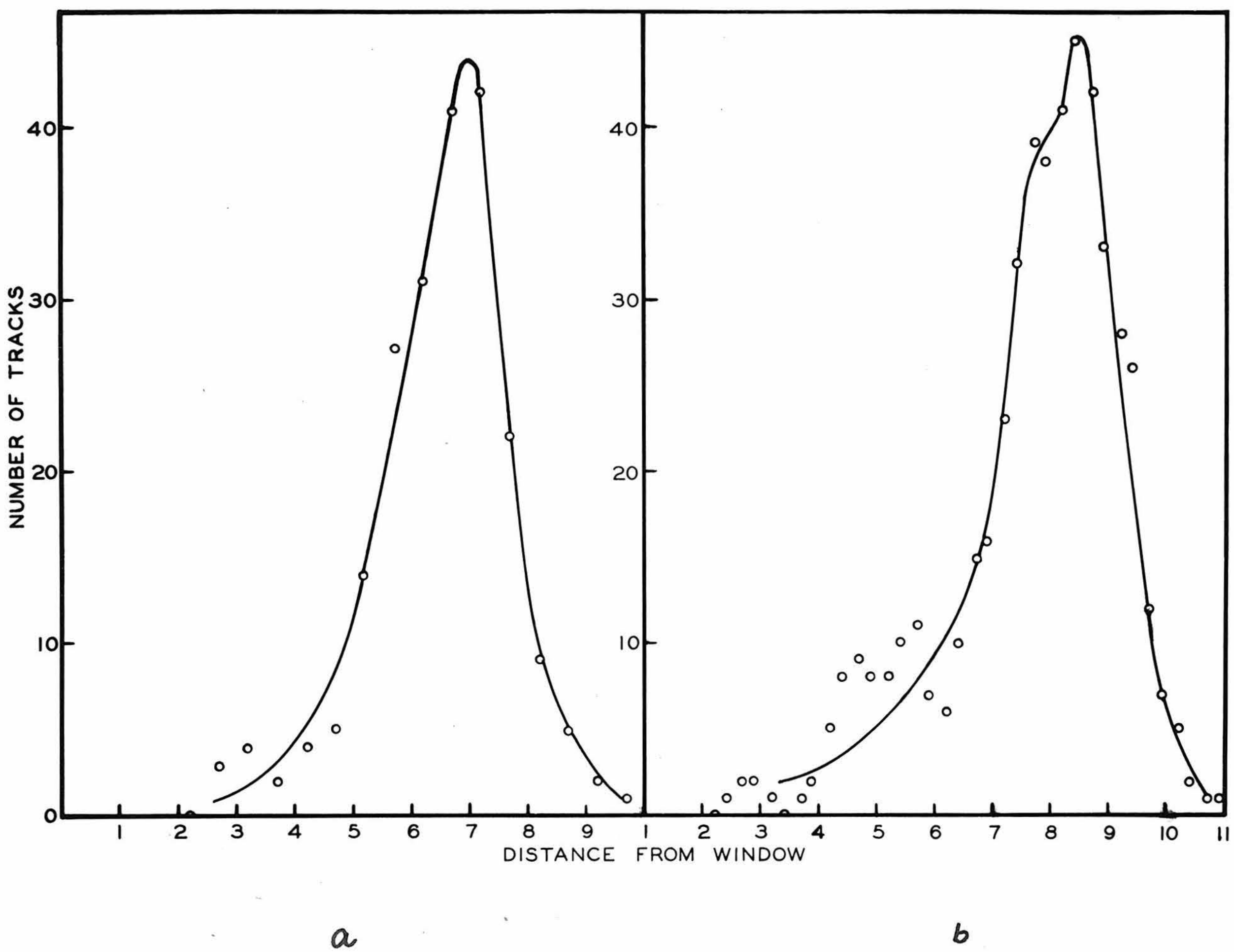

Figure 20. Alpha particles observed as a result of the bombardment of a thick fluorine target with [a] 1389 kev protons [$\rho = .145$], and [b] 1414 kev protons [$\rho = .105$].

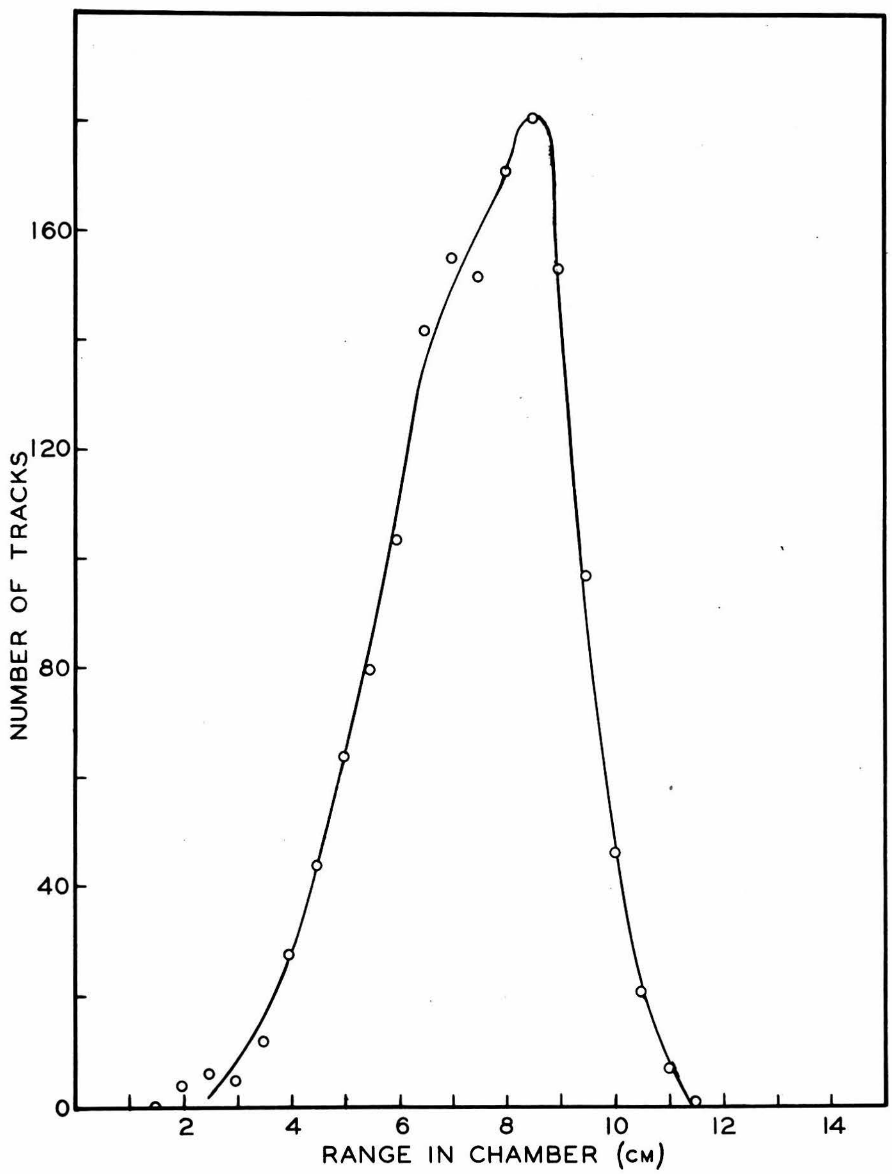

Figure 21. Alpha particles found as a result of the bombardment of a thick fluorine target with 1274-kev protons.

having been taken, yielding 737 acceptable tracks.

Figure 22 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, provided one believes the recoil nucleus to be helium rather than hydrogen, and the initial track to have been caused by an alpha particle, and not a proton scattered by the grid. A great many such forks were observed throughout the present series of experiments.

Since the end of the range was greatly magnified in thechamber due to the low stopping power there, much detail for this portion of the tracks was observed. The majority of the alpha tracks observed possessed the spurious curvature exhibited by the short track in Figure 23. The theory for this type of behavior in a cloud chamber has been developed by E. J. Williams[36]. 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 Figure 1 there is a resonance maximum for the higher energy particles in this region. It is noticeable, in the picture, that the deflection is less for the longer range particle.

In Figure 24 is presented a photograph taken at 1274 kev, just above the 1220 kev pair resonance. The alpha particle is presumably one which had left an O^{16} nucleus in a state which subsequently decayed with the emission of an

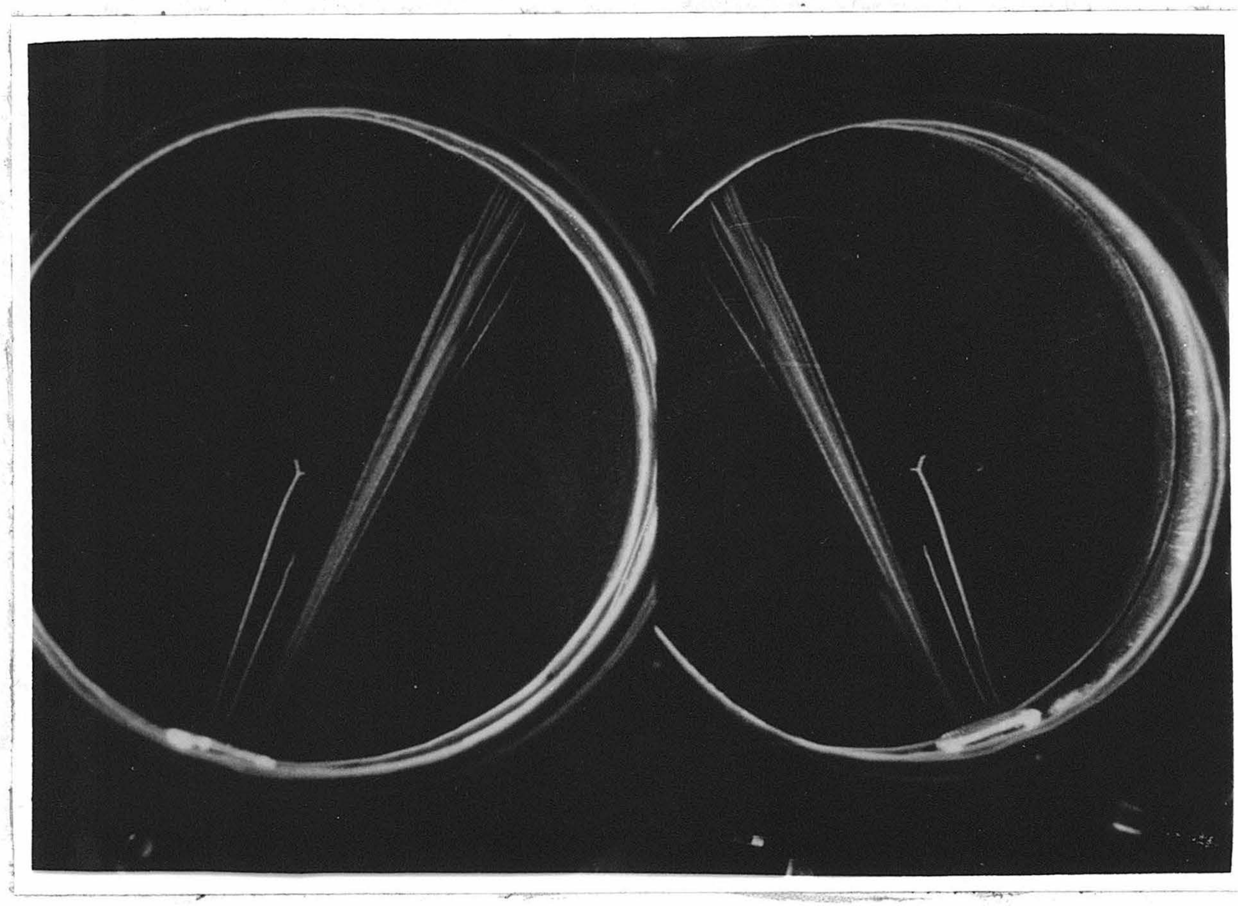

Figure 22. Stereoscopic views of two short-range alpha particles observed at 987 kev bombarding voltage. The longer-range particle has suffered a 90 degree collision with a helium nucleus in the chamber.

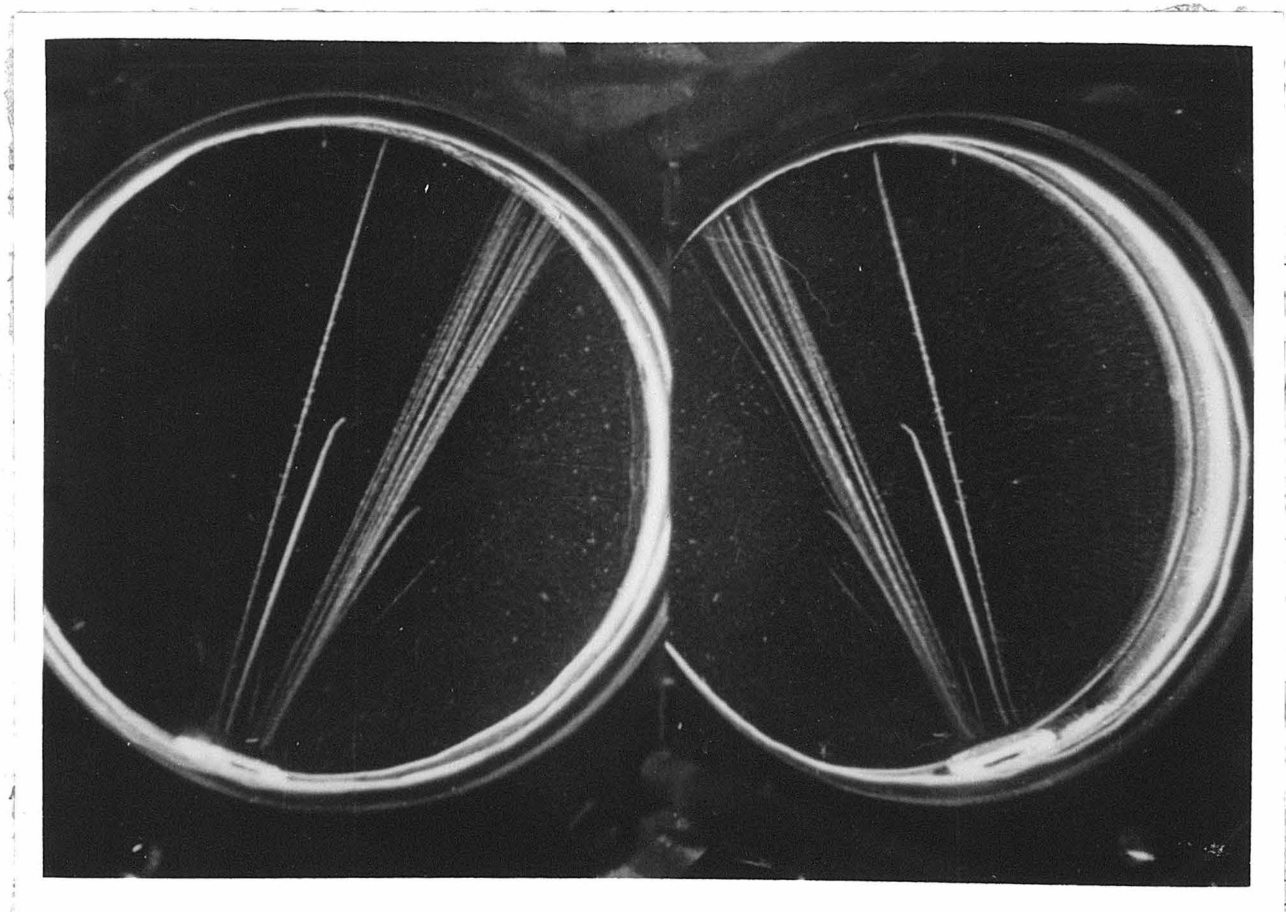

Figure 23. Stereoscopic views of a long and a short-range alpha particle observed at 1414 kev bombarding energy.

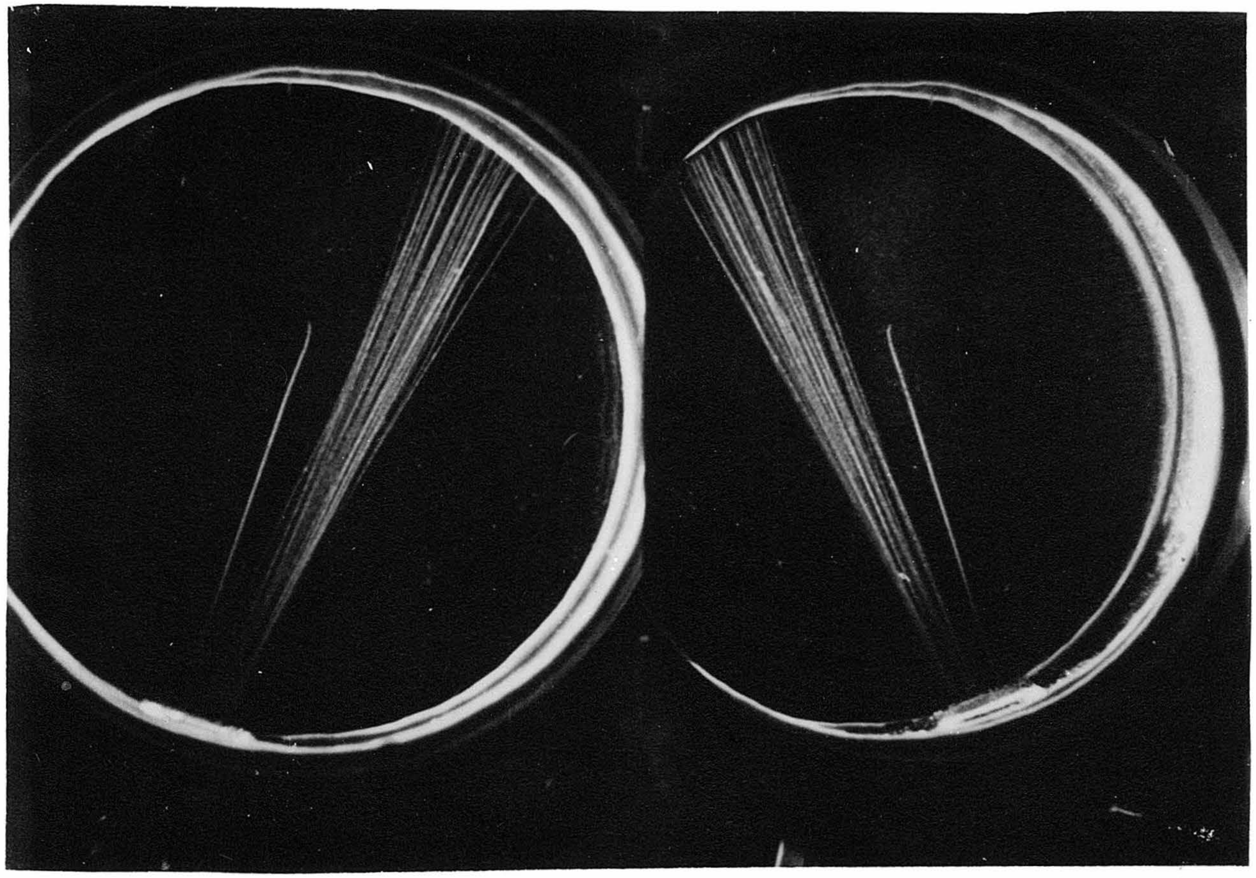

Figure 24. Stereoscopic views of a short-range alpha particle observed at 1274 kev bombarding energy.

electron pair. In the picture there is a slight curvature near the end of the range for the alpha particle.

The computation of the Q of the short-range alpha particles at each of the resonances was performed using the stopping power of .145 measured (with the lithium alpha particles) for 50 cm pressure in the chamber. In order to obtain that for the case of 35 cm pressure in the chamber use was made of data that had been obtained with both pressures, at the voltages 1220 and 1250 kev. The simple assumption was made in each case that the apparent range in the chamber was proportional to the stopping power. The mean value for the two cases gave ρ for 35 cm pressure of He plus water vapor to be .105.

As a sample calculation of Q one may take the example of Figure 16a. 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 .415 cm. When the proton energy has decreased to 334 kev the mid-point of the resonance is reached. Since the range of 334 kev protons is .36 cm one finds a penetration of the target equivalent to .055 cm of air at the above mentioned conditions of temperature and pressure.

$$\Delta R_H = .415 - .36 = .055 \text{ cm} \qquad (44)$$

Now the average velocity of the proton in traversing this thickness of target material is $.8 \times 10^9$ cm/sec. The energy of the emitted particle is about 1.7 Mev, giving a velocity of $.87 \times 10^9$ cm/sec. From Figure 15 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 not quite 45 degrees, compelling the alpha particles to traverse but .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:

$$\Delta R_\alpha = .92 \frac{3.935}{3.875} .055 = .051 \text{ cm} \qquad (45)$$

Furthermore, since the air equivalence k of the window was taken to be .25 cm we have the true mean range $\bar{R}$:

$$\bar{R} = 5.7 \cdot .105 + .25 + .051 = .899 \text{ cm} \qquad (46)$$

whence the energy of the emitted particle was 1.71 Mev. Now, from Bethe, Q is found to be:

$$Q = \frac{M_2 + M_3}{M_3} E_2 - \frac{M_3 - M_1}{M_3} E_1 \qquad (47)$$

Substituting the values in the present experiment for the quantities in the above equation we have Q = 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.

The results of the computations for the remainder of the curves are assembled in Table I. The column headed ΔR_H is the depth of target, in cm of air, which the protons must have penetrated before their energies 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.

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

Table I

Stopping power of chamber	Resonance energy	Bombarding energy	Apparent mean range	ΔR_H	ΔR_α	True mean range	Energy of alpha particles	Q	No. of tracks
	kev	kev	cm	cm of air	cm of air	cm of air	Mev	Mev	
.105	334	390	5.2	.10	.093	.889	1.69	1.79	20
.105	334	364	5.7	.055	.051	.899	1.71	1.82	141
.105	334	368	5.7	.06	.056	.904	1.72	1.83	54
.145	867	910	5.25	.15	.132	1.138	2.12	1.83	219
.105	867	910	5.7	.15	.132	1.138	2.12	1.83	387
.145	867	936	4.65	.24	.211	1.131	2.11	1.81	305
.105	867	987	4.7	.435	.381	1.125	2.10	1.80	} 594
.105	927	987	6.6	.22	.192	1.135	2.12	1.77	
.145	1363	1389	6.95	.12	.104	1.355	2.475	1.81	107
.105	1363	1414	8.45	.235	.204	1.341	2.455	1.78	251
.105	1220	1274	8.5	.23	.201	1.343	2.46	1.93	737

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.

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 again after a lapse of about three months. The observations are summarized graphically in Figure 25, 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 seen to be 5.7 cm, yielding a value of 1.83 Mev for Q, in very good agreement with the preceding measurements.

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 26 shows a sketch idealizing the conditions of the problem at this voltage. Two gaussian peaks, each of half-width b, are depicted having a true separation a. Due to the proximity of the two peaks the observed separation will be some quantity $a - 2x_1$, where $x_1 << a$.

Let $y_1 = e^{-\frac{x^2}{c^2}}$ and $y_2 = e^{-\frac{(x-a)^2}{c^2}}$

Superposing:

$$y = y_1 + y_2 = e^{-\frac{x^2}{c^2}} + e^{-\frac{(x-a)^2}{c^2}} \tag{48}$$

Now, finding new maxima where dy/dx = 0, we have:

$$\frac{dy}{dx} = -\left(\frac{2x}{c^2}\, e^{-\frac{x^2}{c^2}} + 2\frac{(x-a)}{c^2}\, e^{-\frac{(x-a)^2}{c^2}}\right) = 0$$

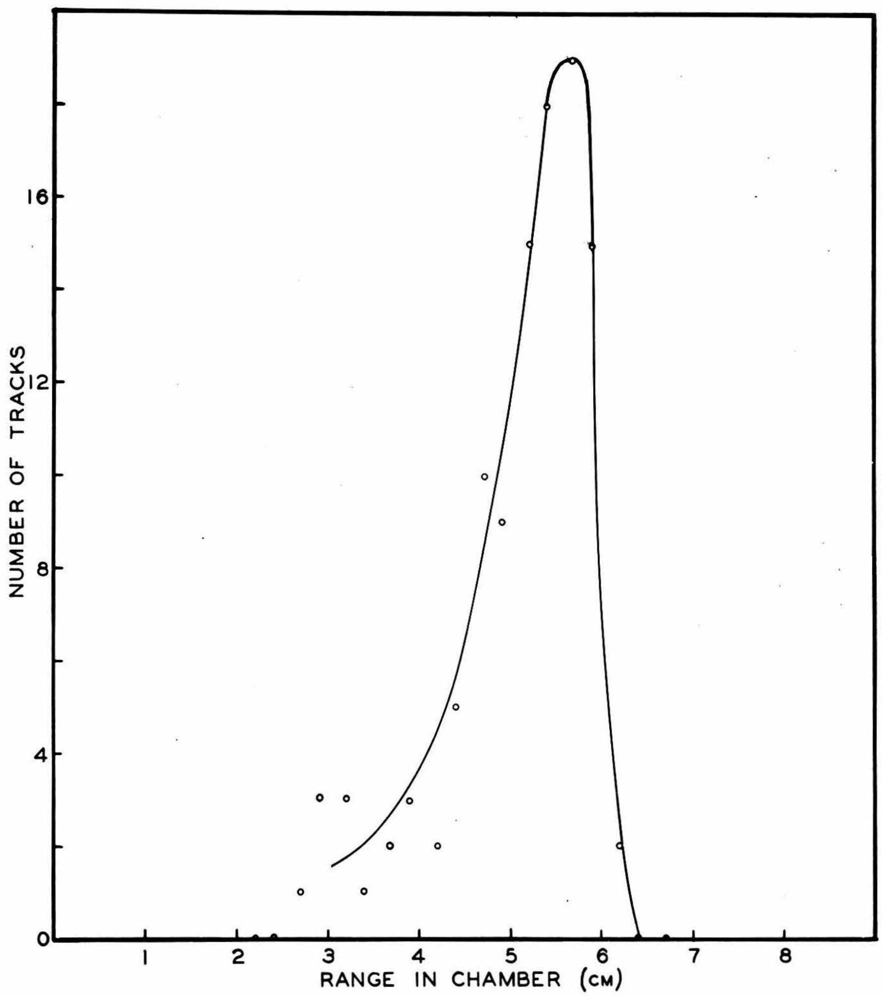

Figure 25. Alpha particles found as a result of the bombardment of a thick fluorine target with 368-kev protons.

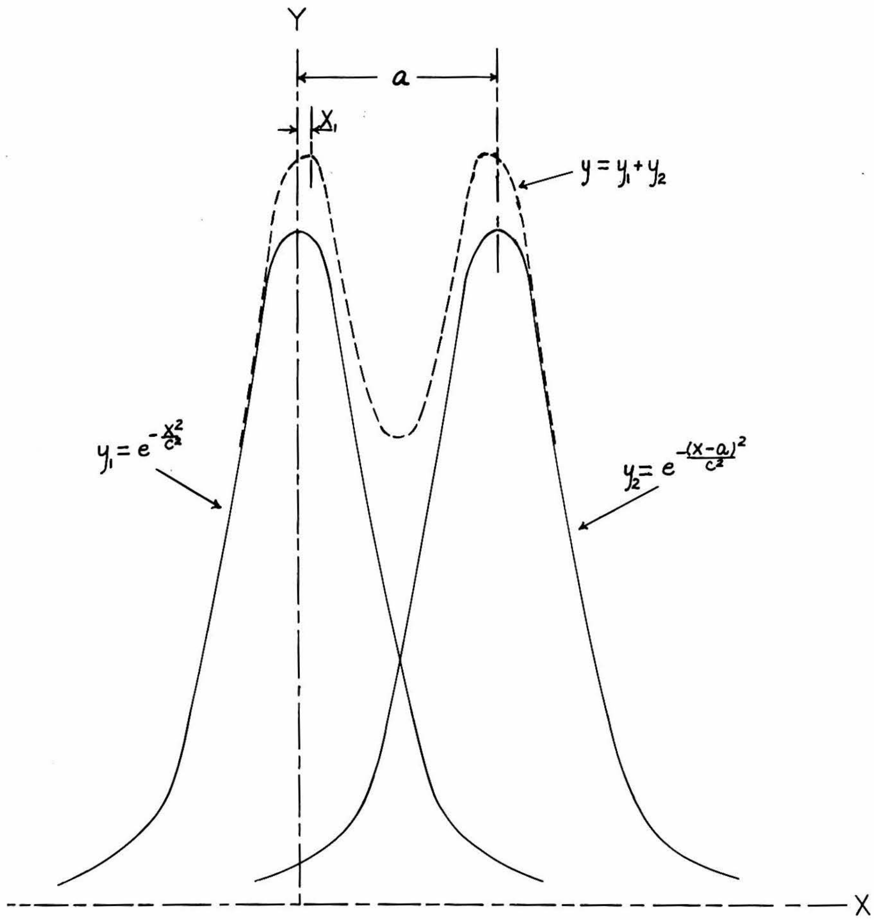

Figure 26. Sketch showing the shift of two gaussian peaks due to their proximity to each other.

or

$$x e^{-\frac{x^2}{c^2}} + (x-a) e^{-\frac{(x-a)^2}{c^2}} = 0 \tag{49}$$

Again consulting Figure 19, evidently a good approximation will be obtained if a = b = 1.66c. A root of equation (49) is then to be found at 2x/a = .2, namely, an apparent shift in the total separation of, 20 per cent. Accordingly the locations of the apparent mean ranges were taken as 4.7 and 6.6 cm, rather than at 4.9 and 6.4 cm. Similar shifts were made for Figures 17 and 18, taking into account that some of the alpha particles on the front slopes may have been due to the upper resonance. From Table I it is clear that within a possible error of 30 kev the two resonances exhibited in Figure 19 possess identical values for Q.

It is worthy of note that due to the fact that the expected alpha-particle ranges are very close to those used in calibrating the apparatus the errors in calculated Q's, arising from errors in ρ or k will be very small. This may be seen as follows:

Let

$$R_0 = k + \rho R + \alpha \tag{50}$$

where R_0 is the true mean range for a fluorine alpha particle, k is the air equivalence of the foil, ρ is the stopping power, and α is the contribution due to passage through a finite target thickness.

Now the variation in R_0 due to variations in k and ρ will be:

$$dR_0 = dk + R d\rho \tag{51}$$

A relation between dk and $d\rho$ is determined by accepting the absolute value of the range of one of the lithium particles as known and equal to c_1.

Thus:

$$k + \rho c = c_1 \tag{52}$$

whence

$$dk = -c d\rho \tag{53}$$

$$dR_o = R d\rho - c d\rho = [R - c] d\rho \tag{54}$$

but since the average of the two lithium ranges is very nearly the same as the range of a fluorine particle we have:

$$c \cong R \qquad \text{and} \qquad R - c = dR$$

thus:

$$dR_o = d\rho \cdot dR \tag{55}$$

so that the variation of R_o is a quantity of the second order.

For example, let $d\rho = .01$, an amount larger than the variations actually encountered by making various corrections to the lithium curve. Corresponding to this the variation dR in R will be .2 cm, a quantity well within the accuracy of the experiment. From this we see that $d\rho \cdot dR = .002$ cm, corresponding to a shift in Q of but 3 kev.

To eliminate errors due to films having been deposited on the target, the latter was changed after several hours of continuous bombardment. However, in actual fact the error due to such a film would be small, since it would depend on the ratio of the stopping power for the alpha particles to that for the protons. If the substance had an atomic number reasonably near the mean assumed for air this ratio would be unity. A further consideration is that the alpha particles involved possessed energies of from 2.5 to 4 times those of the protons here used, and since $\rho = \rho(v)$ the stopping power of a substance for a proton is the same as that for an alpha particle of four times the energy of the proton. Similar arguments apply to the calibration experiment, using a lithium target. The chief danger there was the possibility of an oxide coating. The effect due to this would cancel out when one considered both the porton and the alpha particle because the stopping power of oxygen is very close to unity.

The target area was scrupulously limited to the size of the area actually bombarded in order to minimize effects due to the accumulation of charge on the target surface. That errors due to this were small was demonstrated by the clustering of the Q values, representing aging of the target surface of from one to several hours, permitting varying degrees of deposition of conducting material on the target.

Not the least important is the fact that small-period variations in the running conditions of the experiment were negligible because of the long times involved in the accumulation of such cloud-chamber data.

It was concluded, finally, that the accuracy of the experiment was limited chiefly by insufficient precision in the voltmeter calibration.

IV--Theoretical Discussion--The small peak on the low-energy sides of Figures 17 and 18 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 6.0 Mev radiation of $F^{19} + H^{1}$.

It is of importance to notice the difference in the relative height of the two peaks in Figure 19 from that in the corresponding part of Figure 1. Due to the comparatively long lifetime [about 10^{-15} seconds] 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[37] that the fluorine gamma radiation at three bombarding voltages, 370, 900 and 1000 kev possesses a spherically symmetric angular 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 possessed zero angular momentum, if the compound nucleus possessed zero angular momentum, or if the emitted particle possessed 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 19 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 kev, or 40 kev greater than the magnitude obtained when using the slightly greater value for the resonance voltage. We thus see that the computed Q is very sensitive to the precise value for the resonance energy. 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 Figure 1. In Figures 20 and 21 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 $\pm$ .04 Mev. The probable error is but .01 Mev. However, due to a possible systematic discrepancy the error is quoted as being .04 Mev. In Figure 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 resonances 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 Figures 17 and 19 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 the alpha particles 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 but a single resonance level, but suggested 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 due 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 be 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 Figure 1 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 Figure 22 for the pair resonant alpha particles one obtains a Q value of $1.93 \pm .07$ Mev, given in Table I, for the bombarding energy of 1274 kev. The error is somewhat larger in this case, firstly 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 pair emission proceeds 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 an assumption. Further evidence is indicated by the similar structure of the alpha-particle group to that of the pair peak shown in Figure 1.

The above results indicate a separation for the two states of O^{16} to be about 0.12 $\pm$ .1 Mev.

An explanation of the small peak in Figures 17 and 19 could be the existence of a pair peak at about 750 kev. Some evidence for this was obtained with one of the excitation curves. This is not indicated in Figure 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. Due to 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.

The sincere thanks of the author are due Professors Lauritsen and Fowler who kindly directed the work. The author is indebted, also, to Dr. J. F. Streib who generously assisted in the preparation of the figures.

References

1. J. D. Cockroft and E. T. S. Walton, P. R. S., 137, 229 (1932).

2. M. L. E. Oliphant and Lord Rutherford, P. R. S., 141, 259 (1933).

3. E. O. Lawrence and M. S. Livingston, Phys. Rev., 44, 316A (1933).

4. M. A. Tuve, L. R. Hafstad and O. Dahl, April 1934 meeting of the American Physical Society.

5. M. C. Henderson, M. S. Livingston and E. O. Lawrence, Phys. Rev., 46, 38 (1934).

6. W. E. Burcham and C. L. Smith, P. R. S., 168, 176 (1938).

7. Edwin McMillan, Phys. Rev., 46, 325A (1934); Phys. Rev., 46, 868 (1934).

8. H. R. Crane, L. A. Delsasso, W. A. Fowler and C. C. Lauritsen, Phys. Rev., 46, 531 (1934).

9. W. Heitler, "Quantum Theory of Radiation", Oxford University Press, 1935.

10. L. A. Delsasso, W. A. Fowler and C. C. Lauritsen, Phys. Rev., 51, 39 (1937); Phys. Rev., 51, 527 (1937).

11. J. Halpern and H. R. Crane, Phys. Rev., 55, 258 (1939).

12. P. I. Dee, S. C. Curran and J. E. Strothers, Nature, 143, 759 (1939).

13. T. Lauritsen, C. C. Lauritsen and W. A. Fowler, Phys. Rev., 59, 241 (1941).

14. L. R. Hafstad and M. A. Tuve, Phys. Rev., 47, 506 (1935); Phys. Rev., 48, 306 (1935).

15. L. R. Hafstad, N. P. Heydenburg and M. A. Tuve, Phys. Rev., 50, 504 (1936).

16. R. G. Herb, Kerst, McKibben, Phys. Rev., 51, 691 (1937).

17. E. J. Bernet, R. G. Herb and D. B. Parkinson, Phys. Rev., 54, 398 (1938).

18. N. P. Heydenburg, L. R. Hafstad and M. A. Tuve, Phys. Rev., 56, 1078 (1939).

19. W. E. Burcham and S. Devons, P. R. S., 173, 555 (1939).

20. J. F. Streib, W. A. Fowler and C. C. Lauritsen, Phys. Rev., 59, 253 (1941).

21. T. W. Bonner, P. R. S., 174, 339 (1940).

22. T. Lauritsen, W. A. Fowler and C. C. Lauritsen, Phys. Rev., 56, 858A (1939).

23. W. B. McLean, R. A. Becker, W. A. Fowler and C. C. Lauritsen, Phys. Rev., 55, 796 (1939).

24. W. E. Burcham and C. L. Smith, Nature, 143, 795 (1939).

25. E. Gaerttner and H. R. Crane, Phys. Rev., 52, 582 (1937).

26. J. Halpern and H. R. Crane, Phys. Rev., 55, 260 (1939).

27. W. A. Fowler and C. C. Lauritsen, Phys. Rev., 56, 840 (1939).

28. M. S. Livingston and H. A. Bethe, Rev. Mod. Phys., 9, 277 (1937).

29. Gilbert J. Perlow, Phys. Rev., 58, 218 (1940).

30. Hugo Neuert, Physik. Zeits., 36, 629 (1935).

31. L. Alvarez and R. Cornog, Phys. Rev., 56, 613 (1939).

32. Sanborn C. Brown, February 21, 1941, meeting of Amer. Phys. Soc.

33. M. G. Holloway and M. S. Livingston, Phys. Rev., 54, 18 (1938).

34. D. B. Parkinson, R. G. Herb, J. C. Bellamy and C. M. Hudson, Phys. Rev., 52, 75 (1937).

35. G. Mano, Jour. Phys. and Rad., 5, 628 (1934).

36. E. J. Williams, Phys. Rev., 58, 292 (1940).

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