SHORT RANGE ALPHA PARTICLES FROM THE BOMBARDMENT OF FLUORINE WITH PROTONS

Thesis

by

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CHAPTER I

INTRODUCTION

The gamma rays from fluorine were originally detected by McMillan(13). It has been shown that resonance occurs in the yield at 330 Kv(10)(12) and at several higher voltages(11). If it is assumed that the reaction producing this radiation is

$$F^{19} + H^1 \rightarrow Ne^{20} + h\nu$$

then the energy available as shown by the mass values is 12.89 Mev. The quantum energy of the radiation has been measured(6)(7) by the analysis of pairs observed in a cloud chamber and the energy spectrum found to consist of a single line near 6 Mev.

Alpha particles from the bombardment of fluorine by protons were first observed by Cockcroft and Walton(15). Henderson, Livingston, and Lawrence(14) obtained a value of the extrapolated range of 6.95 centimeters for a bombarding voltage of 1.69 Mev. This range corresponds to a reaction energy of 8.15 Mev. Burcham and Smith(5) have also investigated this reaction and have observed alpha particles of mean range 5.90 centimeters at a bombarding voltage of .85 Mev. They give 7.95 Mev. as the reaction energy. The energy available in the reaction

$$(1) \qquad F^{19} + H^1 \rightarrow Ne^{20*}_{A} + O^{16} + He^4 \quad (5.90\ \text{cm.})$$

as calculated from the mass values is 8.14 Mev. This energy is just that needed for the observed alpha particle and hence there can be no gamma ray associated with this reaction.

Three reactions have been proposed to account for the gamma rays.

$$(2)\qquad F^{19} + H^{1} \rightarrow Ne^{20*}_{B} \rightarrow O^{16*} + He^{4} \rightarrow O^{16} + He^{4} + \gamma$$

$$(3)\qquad F^{19} + H^{1} \rightarrow Ne^{20*}_{B} \rightarrow Ne^{20*}_{C} + \gamma \rightarrow O^{16} + He^{4} + \gamma$$

$$(4)\qquad F^{19} + H^{1} \rightarrow Ne^{20*}_{B} \rightarrow Ne^{20*}_{C} + \gamma \rightarrow Ne^{20} + \gamma + \gamma'$$

where A, B, C refer to different excited states of the Ne^{20} nucleus.

According to the uncertainty principle the product of the time a state exists by the uncertainty in the energy is proportional to $\hbar$.

$$\Delta t \, \Delta E \approx h$$

If the energy levels are narrow (i.e. ΔE small) then the time a state will last is long or its probability of disintegration is small.

In calculating the yield of disintegration products by the use of the dispersion formula (see appendix) it is useful to consider the half width of the yield curve of the reaction as the uncertainty or breadth of the energy level. This breadth is usually measured in electron volts and is denoted by Γ. By the principle of the conservation of energy Γ is also the breadth of the distribution in energy of the products of the reaction if the range of bombarding voltages used is greater than this width.

The alpha particles do not show resonance therefore the energy levels in the Ne^{20}_A nucleus in reaction (1) are not well defined and the time the nucleus lasts will be short. Since the gamma rays are only produced by protons of sharply defined energy, the energy levels in the Ne^{20}_B nucleus which takes part in the reactions (2), (3), and (4) must be well defined and hence this nucleus must last a long time (i.e. have a small disintegration probability). It must have, therefore, different properties from the nucleus which produces the long range alpha particles. The Ne^{20}_B cannot be responsible for both the long range alpha particles and gamma rays because if it were it would decay with emission of an alpha particle long before it had a chance to emit a gamma ray. The Ne^{20}_B must then have some property which slows down the disintegration giving long range alpha particles.

A feature of nuclear forces which is a result of the fact that the velocities of protons and neutrons is small compared to the velocity of light is that the total spin of the neutrons and protons and the total angular momentum will vary only slowly with time(16). The coupling between them which causes them to vary is of the order $(V/C)^2$. Since the conversion of spin into orbital angular momentum is proportional to the square of the coupling energy a disintegration which involves a change of spin should be of the order of $(C/V)^4$ slower than one which does not. For an alpha particle of 7 Mev. energy this factor is of the order of 10^4.

The alpha particle and O^{16} both have zero spins. Therefore the Ne^{20}_{A} nucleus which decays rapidly with the emission of an alpha particle must also have a spin of zero. F^{19} must then have a spin of 1/2 which would be expected since it is made up of an odd number of particles. It would be logical to assume that the Ne^{20}_{B} nucleus which is responsible for the gamma rays is a triplet state formed by a proton whose spin adds to that of the F^{19}. Such a state could decay into an alpha particle and unexcited O^{16} only at a rate 10^4 slower than the Ne^{20}_{A} nucleus.

The number of gamma ray quanta produced is at least 10 times as great as the number of alpha particles at voltages below 1 Mev. To account for such a large yield assuming reactions (3) and (4), the probability that Ne^{20}_{B} disintegrate into a gamma ray must be at least ten times as great as the probability that a long range alpha particle be produced. Since the formation of long range alpha particles shows no resonance over a range of bombarding voltages of 10^6 volts, the singlet-singlet transition must have a Γ_α of at least 10^6 volts. The triplet-singlet transition is 10^4 slower than this or it has a Γ_α = 100 volts. This would mean that the probability of a disintegration producing gamma rays must be represented by a Γ_γ = 1000 volts. This is much larger than the widths usually found for nuclear gamma rays and is considered(18) to be too large to be probable(16). If reactions (3) and (4) are ruled out by the above considerations, the only remaining possibility is that the gamma rays originate according to the reaction (2). In this case the short range alpha particle would be emitted without change in spin but would have an energy lower than the barrier so that its probability of disintegration would be decreased by the Gamow factor for the penetration of the barrier (see appendix). For a particle of about 1.5 Mev. the probability of disintegration would be large enough to compete successfully with the long range alpha particles slowed down by the spin change but still small enough to give sharp resonance.

The reaction (2) assuming a particle of about 1.5 Mev., Q = 1.9 Mev., satisfies the energy balance since the gamma ray takes 6 Mev.[6] and the total available energy is 7.95 Mev.[5] If it is assumed that the products of the disintegration are two gamma rays of 6 Mev. the energy balance is off by about 1 Mev.

Previous attempts to detect these short range particles both here and elsewhere[5] have not been successful. It was felt that this might be due to the use of too high bombarding voltages causing the scattered protons to obscure the alpha particles. This investigation was begun with a desire to eliminate this difficulty by bombarding at a voltage very little above the resonance value.

CHAPTER II

APPARATUS

GENERATOR AND TUBE

The apparatus for producing the protons of 350 Kv. energy needed in the following experiments consists of a vacuum accelerating tube and an electrostatic generator of the Van de Graaff type. The tube consists of two glass cylinders a foot in diameter and twenty-eight inches high.

In order to focus the protons which leave the ion source upon the target some sort of electrostatic lens system is needed. The first arrangement tried consisted of thirteen steel discs, one-eighth inch thick and eight inches in diameter, supported on three glass rods. They were spaced at equal intervals along the tube and had one inch holes in the center to form a path for the protons. In order to prevent these discs from becoming charged it was found necessary to drill holes in the cylinders and insert steel plugs which would provide an electrical connection between the discs and the outside of the tube. It was found that this arrangement gave very little focusing.

The holes in the center of the discs were accordingly enlarged and short sections of one and one-half inch tubing inserted to form gaps of the type used successfully by Hafstad and Tuve(1), and whose focusing properties have been rather thoroughly investigated(2).

This arrangement gave satisfactory results although the motion of the cylinders (about one-eighth inch) permitted by the supporting rods causes the focal spot to shift with vibration.

The tube is connected by a short section of six inch pipe to an eight inch two stage oil diffusion pump(3). The two stages consist of two forty-five degree cones both of which direct oil jets downward. The top cone has a clearance of one-half inch from the pump wall and the bottom cone one-eighth inch. The pumping speed as measured by admitting air at a known rate directly to the top of the pump was two hundred liters per second for the best setting of jet openings and heater current. The pumping speed was again measured after the pump was in place on the tube by determining the rate at which the pressure in the tube was decreased. The pressure in a one hundred liter volume changed from 3×10^{-3} to 10^{-6} in sixty seconds, giving a pumping speed of 13.4 liters per second. This value is probably a measure of the speed of flow of the gas in the tube leading to the McLeod gauge.

The charge is accumulated on a hemispherical dome thirty-six inches in diameter. The bottom edge of this dome is protected from corona and the potential drop down the tube given cylindrical symmetry by a series of five-eighths inch Dural rings. (See Plate I). Several spacings of these rings were tried in an attempt to determine an optimum value. No largest value was found except that with no rings most of the current was lost as corona from the bottom edge of the dome. When the spacing was less than the diameter of the rings, sparking

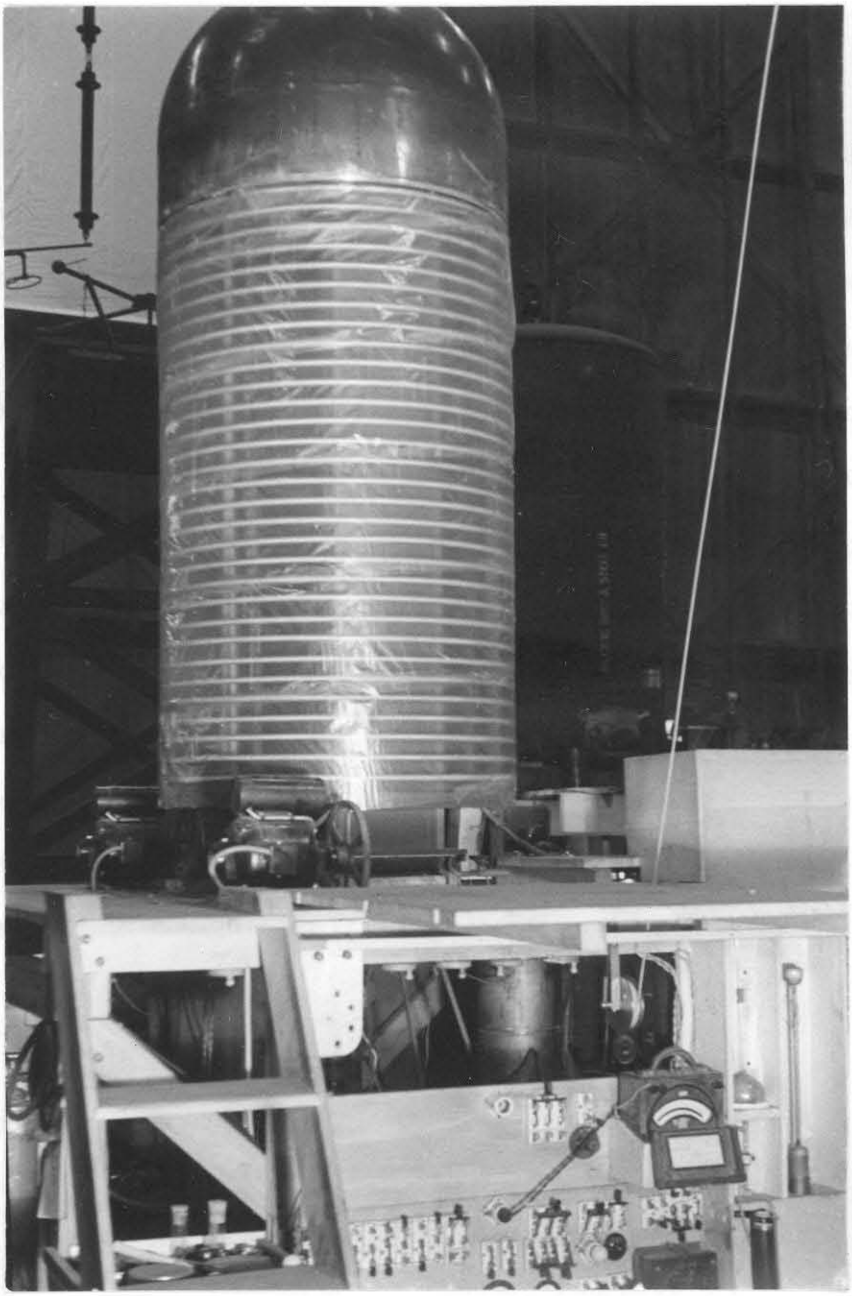

Plate I. The ion accelerating tube showing the rings used to distribute the voltage and the charging belts.

occurred between the rings. When it was greater, the voltage was limited by sparking along the tube.

The charging belts are made of rubber hospital sheeting eleven and one-half inches wide. It was found necessary, in order to keep the belts from leaving the rollers during starting and stopping, to cement a three-fourths inch strip of the same material along each edge of the belt. One belt runs at a speed of 3400 feet per minute and the other at 4400 feet per minute. The slower belt normally delivers 180 microamperes current and the faster belt delivers 200 microamperes. Both belts are charged by the same spray voltage of twenty-seven kilovolts. An increase in this voltage does not produce an increase in the current carried. The theoretical carrying capacity of the belts can be calculated by assuming that the maximum field is that between the belts, and is the sum of the fields due to the positive charge carried up and the negative carried down.

$$E = 2\pi\sigma_{up} + 2\pi\sigma_{down}$$

The current to the dome is given by

$$I = (\sigma_{up} + \sigma_{down})vw$$

where v = belt velocity

w = belt width.

If the air becomes conducting when $E = 30{,}000$ volts per cm. the maximum theoretical currents for the slow and fast belts respectively are 223 microamperes and 290 microamperes. The actual currents are therefore about eighty per cent and seventy per cent of the theoretical values. It was found that a bakelite covering on the bottom roller increased the current carried by the belts as it allowed them to be in a stronger spray field, whereas a similar covering on the top roller tended to become charged and produce fluctuations in the current.

The charging and collecting combs are made of ordinary pins spaced at one-fourth inch intervals. Closer spacings do not produce any larger currents. The position of the combs around the rollers influenced the current strongly while the distance of the combs from the rollers did not.

Several methods of measuring voltage were tried. The generating voltmeter method was not feasible because of the great amount of non-conducting material distributed about the laboratory. All of this material became charged and produced fields, in addition to the field caused by the charge on the dome, of such magnitude that the zero of the voltmeter sometimes shifted by as much as fifty per cent. A sphere gap was tried but discarded since it was not continuously recording and each reading of the voltage upset the electrical equilibrium of the tube and it required a short time for the voltage to redistribute itself. A glass tube of about one sq.cm. area filled with a mixture of xylol and alcohol was used as a high resistance in series with a galvanometer. This had two disadvantages. One was that the resistance of the mixture changed with time and the current carried. The other was that an appreciable amount of current was gained as corona from various projections. The first difficulty was eliminated by using the column as a potentiometer. The chance of corona losses was reduced by surrounding the tube with a second glass tube containing more xylol mixture in order that the potentials inside and outside the glass might be nearly the same. A ground wire was introduced into the outer column to remove current flowing in this column.

The voltmeter as finally adopted is shown diagrammatically in Figure I. It consists of two concentric glass tubes filled with xylol and alcohol. The liquid is pumped up the inner tube and allowed to return between the tubes, thus maintaining the homogeneity of the mixture. If the negative potential applied to the bottom electrode is adjusted until no current flows through the galvanometer then this potential is proportional to that of the high potential electrode. The voltmeter was calibrated to read the potential at the top of the tube by using the gamma ray resonance at 330 Kv.[13] in the reaction $F^{19} + H^{1}$. This arrangement has been satisfactory and gives consistent results even though the specific resistance of the xylol and alcohol changes by a factor of 100.

The ion source is of the hot filament type developed by Crane, Lauritsen, and Soltan[4]. The power to operate the source is supplied by a 500 cycle 110 volt generator driven by a twelve foot V-belt. The filament is a seven turn helix of thirteen mil tungsten

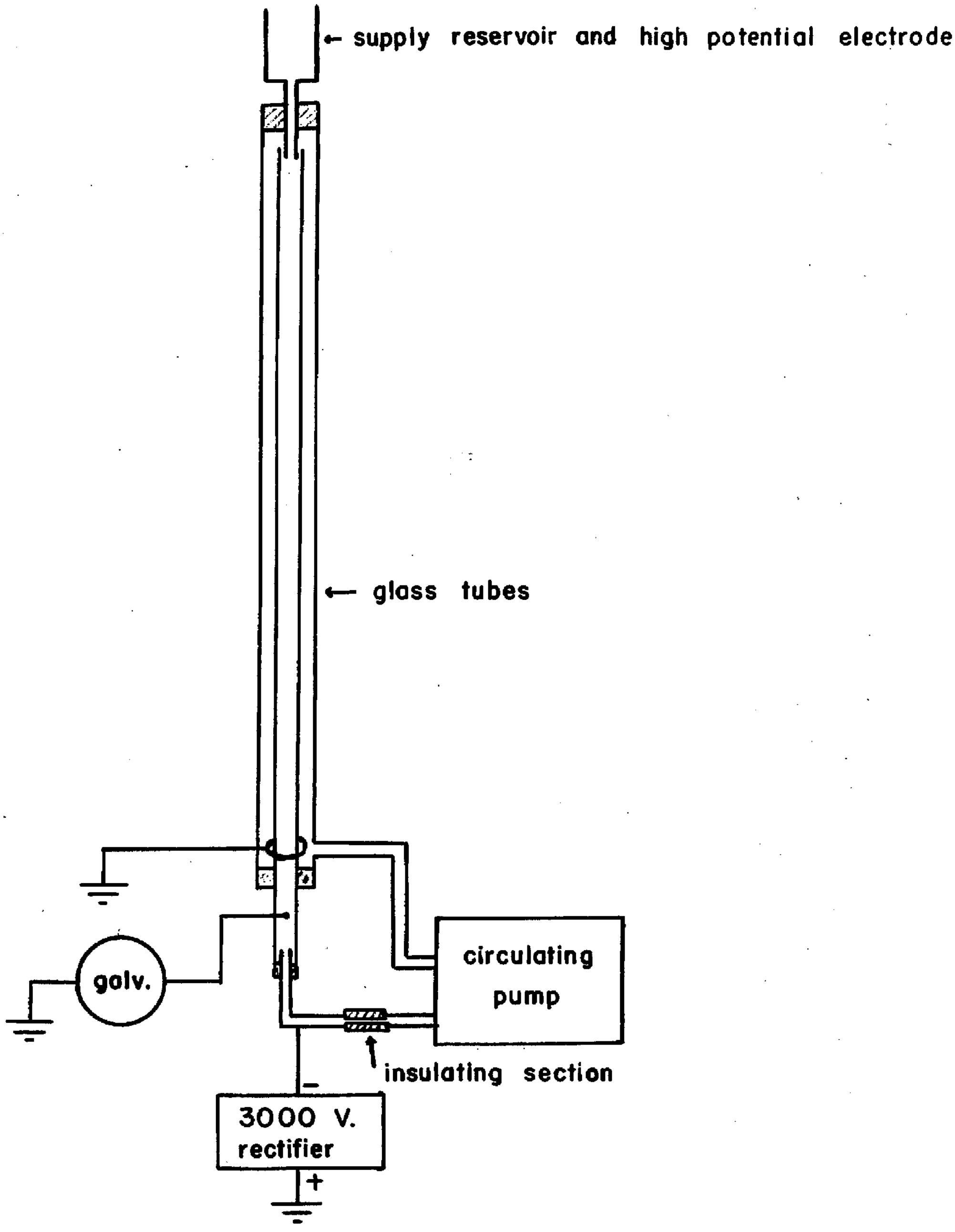

FIGURE I. DIAGRAM OF VOLTMETER

wire and carries ten amperes at six volts. This ion source will deliver up to 600 microamperes when the pressure in the tube is 7×10^{-4}. Under normal operating conditions the current to the bottom of the tube is between 100 and 300 microamperes. The amount of this current which can be focussed on the three-fourths inch diameter target varies between 10 and 100 microamperes. The presence of air in the tube causes the operation to be unsteady and the focusing poor. The amount of current striking the target can sometimes be greatly increased by flushing out the tube with hydrogen.

The voltage is controlled by a set of corona points whose distance from the dome is variable. A glass tube of one inch diameter filled with a mixture of xylol and alcohol is used to distribute the potential uniformly between the rings and thus down the tube. Contact is made to the liquid by means of tungsten electrodes inserted at the proper points. Another xylol column with three segments of variable length is placed across the first three focusing gaps as a means of varying their potential.

CLOUD CHAMBER

The products of disintegration in the reaction studied were observed in a low pressure, helium filled cloud chamber. The stopping power of this chamber was approximately one tenth that of air.

Both mica and lacquer films, mounted on small mesh copper grids, were used as windows to admit the particles to the cloud chamber.

The mica was discarded after half of the tracks had been obtained because of the possibility that an abrupt change in thickness might produce the appearance of a group of particles with a distinct range. The second window was made of Egyptian lacquer which is rather more slow drying than ordinary lacquer and produces uniform and tough films whose stopping power is equivalent to that of about three millimeters of air.

The target consisted of a layer of CaF_2 powder applied to a copper base by moistening with alcohol. The surface made an angle of forty-five degrees with the direction of the incident particles. The products of disintegration were observed in one case at an angle of $90^\circ \pm 9^\circ$ with the incident beam and in another case at $90^\circ \pm 6^\circ$.

It was found necessary to operate the ion source continuously in order to keep the voltage on the tube steady. A shutter just above the target protected it from bombardment except when the chamber was expanded. The timing of the shutter was adjusted so that particles were allowed to enter the chamber only after the cloud chamber was fully expanded to insure that the stopping power of the chamber be the same for all the particles observed.

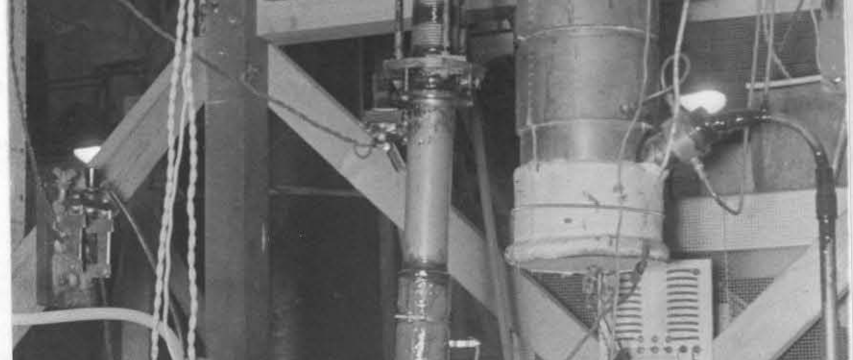

Plate II. The target tube and cloud chamber.

CHAPTER III

SHORT RANGE ALPHA PARTICLES FROM $F^{19} + H^{1}$

In order to determine the possibility of observing alpha particles from $F^{19} + H^{1}$ in the presence of protons of energy greater than 330 Kv., their expected range was calculated from the known energy available, and the known gamma ray energy.

The alpha particles which take all the energy available in the reaction

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

have a mean range of 5.90 centimeters at a bombarding voltage of .85 Mev.(5) The energy available in the reaction is thus 7.95 Mev. Since the single gamma ray has a quantum energy of 6 Mev.,(6),(7) an alpha particle associated with the gamma ray should have an energy of $1.95 \times \frac{16}{20} + .33\ \frac{15}{20} = 1.79$ Mev. at a bombarding voltage of 330 Kv.

The yield of gamma rays shows a sharp resonance at a bombarding voltage of 330 Kv. It would be expected, according to the theory of their origin discussed in Chapter I, that the yield of short range alpha particles should show the same resonance properties. Hence, for higher bombarding voltages, the reaction will occur deeper in the target, and the particles will have a shorter residual range. The observed range of the protons corresponds, however, to the maximum energy particles scattered from the surface. The ranges of the scattered protons and alpha particles for different energy protons are shown in the following table:

Bombarding voltage	Scattered Proton range	Residual Alpha particle range
330 Kv	.32 cm	.95 cm
350	.34	.92
400	.41	.83
450	.48	.73
500	.58	.63
550	.67	.51

This shows that the maximum difference in range to be expected is 6.3 millimeters, and occurs just at resonance, while just above 500 Kv. the range of the protons becomes equal to that of the alpha particles. An accelerating potential of 350 Kv. was chosen to insure that in spite of fluctuations the voltage would remain above the resonance, and yet not be so high as to cause the scattered protons to obscure the alpha particles.

The operation of the tube and cloud chamber was checked by bombarding LiCl with protons. This reaction yields two groups of alpha particles whose ranges are near to that of the group to be expected in the bombardment of fluorine, and therefore affords a good calibration of the window thickness and stopping power of the chamber.

The reaction involved is $Li^6 + H^1 \rightarrow He^3 + He^4 + (Q = 3.72 \pm .08$ Mev.). Bethe[8] has shown that the energy of a particle emitted at 90° to the direction of the incident beam is given in terms of the Q for the reaction and the bombarding energy by the equation

$$E_2^o = Q \frac{M_3}{M_3 + M_2} + E_1 \frac{M_3 - M_1}{M_3 + M_2}$$

where E_2^o = energy of the emitted particle at 90
E_1 = energy of the bombarding particle
Q = reaction energy
M_1 = mass of the bombarding particle
M_2 = mass of the observed nucleus
M_3 = mass of the recoil nucleus.

This gives 2.28 Mev. for the energy of the He_3 nucleus, and 1.70 Mev. for that of the He_4 at a bombarding voltage of 350 Kv.

The range of particles ejected at angles less than 90^o increases so that the component of the range of a particle ejected at an angle slightly less than 90^o is longer than the range of a particle coming out at 90^o. The tracks in these experiments were not measured stereoscopically so that the observed range is the component of the true range in a direction making an angle of 90^o with the incident beam. The angle between the direction of the particles which have the greatest component of range and the direction of the incident beam varies for different reactions, being larger for the light elements. Bethe(8) denotes this angle by θ_o and employs it as a criterion for good and poor geometry. Good geometry is an arrangement wherein particles ejected at an angle of θ_o are not observed while in a case of poor geometry particles ejected at an angle of θ_o are observed. The cosine of this angle can be determined by:

$$\text{Cos } \Theta_0 = n \frac{(M_1 M_2)^{1/2}}{M_2 + M_3} \left(\frac{E_1}{E_2^0}\right)^{1/2}$$

where M_1, M_2, M_3, E_1, and E_2^0 are masses and energies as previously denoted

$n = 2 \frac{d(\log R)}{d(\log E)}$ and is plotted for different energy particles.

In the reaction $Li^6 + H^1 \rightarrow He^3 + He^4 + 3.72$ Mev. the value of Θ_0 is 76° 40' for the He^3 particles, and 75° for He^4. While in the reaction $F^{13} + H^1 \rightarrow O^{16} + He^4 + h\nu + 1.65$ Mev., it is 84° 50'.

Two different arrangements of target, window and cloud chamber were used in these experimments. With the mica window the angle of the particles was limited to 90° ± 6°. When the mica window was replaced by a lacquer film it was somewhat easier to obtain larger films and to take advantage of this a larger opening was used. The new opening limited the particles to 90° ± 9°. Therefore both arrangements constitute good geometry for the lithium reaction, and poor geometry for the fluorine reaction.

The mean ranges for the two alpha particle groups from lithium can be determined from an experimental range energy curve. The curve used in this case was that published in 1938 by Holloway and Livingston(9). The mean range of a He^4 particle corresponding to an energy of 1.70 Mev. is .90 centimeters. The range of a particle in terms of the energy is given by the equation:

$$R = \frac{m}{Z^2}\Psi\left(\frac{E}{m}\right)$$

where m = mass of the particle
E = energy of the particle
Z = atomic number of the particle.

Therefore the range of a He^3 particle is 3/4 that of a He^4 particle of 4/3 the energy(8). The mean range of a He^4 particle of 2.28 x 4/3 = 3.04 Mev. is 1.75 centimeters, giving as the mean range of the He^3 particles 1.75 x 3/4 = 1.31 centimeters.

In the case of a thick target and a reaction which is not resonant some disintegrations take place below the surface of the target so that the shape of the range number curve is altered. The mean range does not then correspond in general with the peak of the curve which represents the most probable range. It lies near the most probable range if the penetration into the target is small (i.e., a rapid decrease in the disintegration probability with depth). On the other hand it is near the extrapolated range if the penetration is large.

The amount of penetration is determined by:

$$\beta = \frac{\left[zZ\left(\frac{M_1}{E_1}\right)^{1/2} + 4\right]\frac{S_2}{R_2}}{\frac{R_1}{R_2}n_1 + \frac{E_1}{E_2}\,\frac{M_3 - M_1}{M_2 + M_3}\,n_2}$$

where z = the atomic number of the incident particle
Z = the atomic number of the nucleus
S = total straggling
n = range exponent

In the case of good geometry the variation of range with angle can be treated as straggling of the range of amount

$$\gamma = R_o \frac{a}{b} n \frac{(M_1 M_2)^{1/2}}{M_2 + M_3} \quad \frac{E_1}{E_2}^{1/2}$$

where the notation is as above and the beam is considered defined by two circles of radius "a" placed a distance "b" apart. The largest value of $\frac{\gamma}{R_o}$ in these experiments occurs for the He^3 particles emitted from the lithium reaction in which case it is .0205 for the larger window.

The theory of range straggling is not very accurate for low energy particles and hence Bethe has not calculated the straggling for particles of range less than 3 centimeters. However an extrapolation of his curve would indicate that for particles of around 1 centimeter range the straggling might be about 6%.

The total straggling is the geometric sum of the range straggling and the angular straggling. If s' denotes the total straggling then

$$s'^2 = s^2 + \gamma^2 \qquad .06^2 + .02^2 = .063$$

Since the total straggling is not known very well in this case the angular straggling could be neglected. However the method of successive approximations by which the straggling is determined from the experimental curves in the following paragraphs determines the total straggling directly.

In order to obtain the approximate magnitude of the penetration

β can be calculated in terms of $\frac{S}{R_o}$.

For He^3 (particle energy 2.28 Mev., 0.35 Mev. bombarding voltage)

$$\beta = \frac{1 \times 2 \left(\frac{1}{.35}\right)^{1/2} + 4 \frac{S}{R_o}}{\frac{.55}{1.31} 2.3 + \frac{.35}{2.28} \frac{3}{7} 2.41} = 6.56 \frac{S}{R_o}$$

If $\frac{S}{R_o}$ is .06, then $\beta = .39$ and is not small enough so that the mean range of these particles may be considered as equal to the experimental extrapolated range, however, in order to determine an approximate value of the stopping power of the chamber and foil this will be considered to be true.

From Figure 2A it can be seen that the measured extrapolated ranges of the two groups of alpha particles using the mica window, and helium, water, and alcohol in the chamber are 5.15 centimeters and 8.83 centimeters. If the stopping power of the chamber is denoted by σ, the equivalent thickness of the window by δ and it is assumed that for the particles involved the ratio of the stopping power of the gas in the chamber to that of air is a constant, then:

$$R_{He^3} = 1.31 = 8.83\,\sigma + \delta$$

$$R_{He^4} = 0.90 = 5.15\,\sigma + \delta$$

$$\sigma = \frac{.41}{3.68} = .111$$

$\delta = 0.33$ centimeters air equivalent.

Figure 2B is the curve obtained using the lacquer window with only helium and water vapor in the cloud chamber. As in the above case

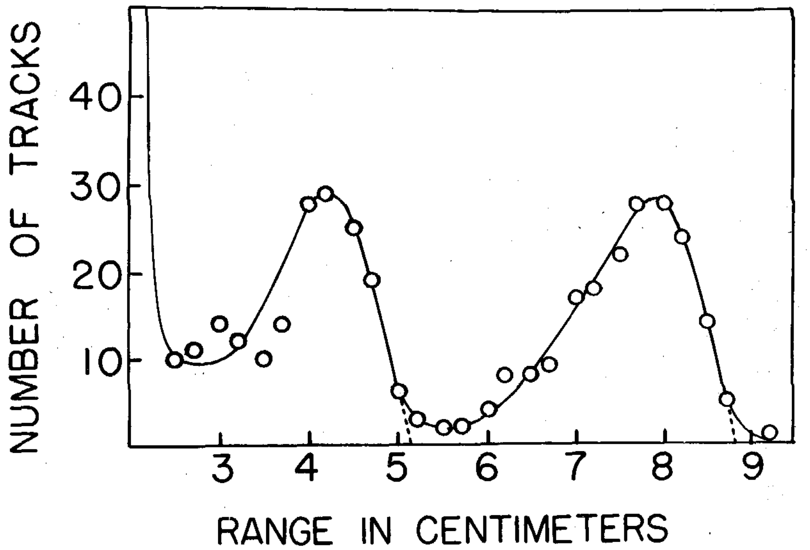

Figure 2A. The number of alpha particles from the reaction $Li^6 + H^1 \rightarrow He^3 + He^4$ plotted as a function of their observed range in centimeters in the cloud chamber. This curve was used to calibrate the mica window and the stopping power of the gas in the chamber.

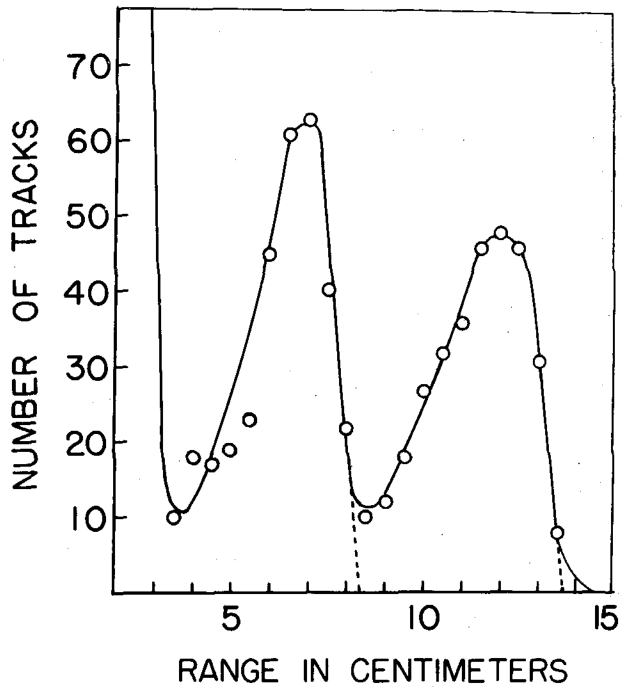

Figure 2B. A similar curve to Figure 2A except that the mica window was replaced by a lacquer window and no alcohol was used in the cloud chamber.

$$R_{He^3} = 1.31 = 13.7\,\sigma + \delta$$

$$R_{He^4} = 0.90 = 8.3\,\sigma + \delta$$

$$\sigma = .076$$

$$\delta = .27 \text{ centimeters air equivalent.}$$

Using the provisional values of the stopping powers of the gas in the cloud chamber calculated above, it is possible to obtain a value of the straggling from the shape of the curves in Figures 2A and 2B. Bethe gives the difference between the most probable range and the extrapolated range as $s(X_{extr} + X_o)$ where s is the total straggling. X_{extr} and X_o are functions of β and may be determined from Figure 38, page 286 of Bethe's paper(8). From Figure 2A the difference between the most probable and the extrapolated range is 0.95 x 0.111 = 0.105 centimeters. If   = 0.39, then X_{extr} = 0.34 and X_o = 1.0. Therefore

$$0.105 = s(1.0 + .34)$$

$$s = 0.079 \text{ centimeters} = 6.0\%\ R_o$$

Hence in this case the assumption of 6% straggling was justified. A similar calculation for the He^3 peak in Figure 2B gives

$$s(X_{extr} + X_o) = 1.7 \times .076 = 1.29$$

$$s = .096 \text{ centimeters} = 7.4\%\ R_o$$

If these values are used to determine a new β and this again used to determine the straggling from the experimental curves the revised values are 6% and 7.7% which are sufficiently close to the first values so that another approximation is unnecessary.

The straggling for the group of particles of mass four can be determined in a similar manner. In this case

$$\beta = \frac{1 + 2\left(\frac{1}{35}\right)^{1/2} + 4\,\frac{s}{R_o}}{\frac{.55}{.90}\,2.3 + \frac{.35}{1.70}\,\frac{2}{7}\,2} = 5.3\,\frac{s}{R_o}$$

If $\frac{s}{R_o} = 6.7\%$ the average in the case of He^3 then $\beta = 0.35$. From Figure 2A

$$s(X_{extr} + X_o) = .90 \times .111 = .10 \text{ centimeters}$$

$$s = \frac{1.0}{1.37} = .073 = 8.1\%\ R_o$$

From Figure 2B

$$s(X_{extr} + X_o) = 1.6 \times .076 = .122$$

$$s = \frac{.122}{1.37} = .089 = 9.9\%\ R_o$$

The next approximation using the new values of the straggling to determine β gives values of 8.5% and 10.5% which are close enough to the first values to make another approximation unwarranted.

The fact that the curve in Figure 2B gives higher straggling for both groups of alpha particles may be due to greater variations in window thickness in the case of lacquer films than in the case of a mica window. Considering the errors involved in determining the most probable range, however, it may not have any significance.

The measured extrapolated range is given in terms of the mean range and the straggling by $R_{extr} = R_{mean} + s\, X_{extr}$. The results for the two groups of particles and the two windows are tabulated:

	He^3		He^4	
	Mica	Lacquer	Mica	Lacquer
R_{mean}	1.31	1.31	0.90	0.90
β	0.39	0.40	0.44	0.54
X_{extr}	0.33	0.38	0.36	0.39
s'	0.082	0.098	0.076	0.094
$s'X_{extr}$	0.027	0.037	0.027	0.037
R_{extr}	1.337	1.347	0.927	0.937

The stopping power of the chamber and the windows can now be calculated more accurately.

For the mica window; with water and alcohol vapor, and helium in the chamber:

$$1.337 = 8.83\sigma + \delta$$

$$0.927 = 5.15\,\sigma + \delta$$

$$\sigma = .111$$

$$\delta = .357 \text{ centimeters air equivalent}$$

For the lacquer window; with only water vapor and helium in the chamber:

$$1.347 = 13.7\,\sigma + \delta$$

$$0.937 = 8.3\,\sigma + \delta$$

$$\sigma = 0.076$$

$$\delta = 0.307 \text{ centimeters air equivalent.}$$

Since the stopping power of the chamber is the same for this calculation as it was when the mean range was considered equal to the extrapolated range it is not necessary to apply any correction to the difference between the most probable and the mean ranges as determined from Figures 2A and 2B.

When a target of CaF_2 powder was bombarded with protons, particles whose ranges were definitely longer than those of the scattered protons were obtained in the cloud chamber. Pictures of these particles are shown in Plates III and IV. Plate III shows two short tracks and a long track which does not end in the chamber and which is presumably due to the alpha particles which take all of the energy available in the reaction. Plate IV is a picture taken at a lower bombarding voltage than III and shows that while the alpha particle tracks remain about the same length or are slightly longer, since at lower voltages they are produced nearer the surface of the target, the protons have become shorter. This would not be true if the tracks observed were due simply to exceptionally long protons. Several forks such as that shown in Plate V have been obtained. Since the gas in the chamber consists largely of helium this is further evidence that the particles are alpha particles. However it is not completely conclusive since some hydrogen is also present in the chamber. The density of the tracks would also indicate that they are caused by a more heavily ionizing particle than those present in the scattered brush of protons.

One hundred forty four tracks were obtained using the mica window with helium, alcohol, and water in the cloud chamber. The bombarding voltage was 350 Kv. The resulting number range curve is shown in Figure 3A. The number of tracks obtained in 0.5 centimeter overlapping intervals is plotted as a function of the range. One hundred eighty one tracks were also obtained at the same bombarding voltage but with the lacquer window and without any alcohol in the chamber. The range number curve for these particles is shown in Figure 3B. Since the stopping power in this case was smaller it was found better to plot this curve as well as that in Figure 2B by using the number of tracks occurring in one centimeter overlapping intervals in place of the 0.5 centimeter intervals used for curves 2A and 3A.

The angular straggling for alpha particles from $F^{19} + H^{1}$ is of the order of 0.7% and hence may be neglected in determining the mean range from the number range curve.

Since the group of particles comes from a resonant reaction it would be expected that the ranges should be distributed symmetrically about the mean range. The observed asymmetry of the curves might be explained by considering that the resonance has some width ($\approx$ 4 Kv.) In this case the shorter range particles will be formed deeper in the target and hence suffer greater straggling, since the straggling in the target is greater than in helium. This would tend to spread out the backside of the curve. Another explanation could be that there existed another group which was not resolved. Any irregularities in the window thickness could also produce this result.

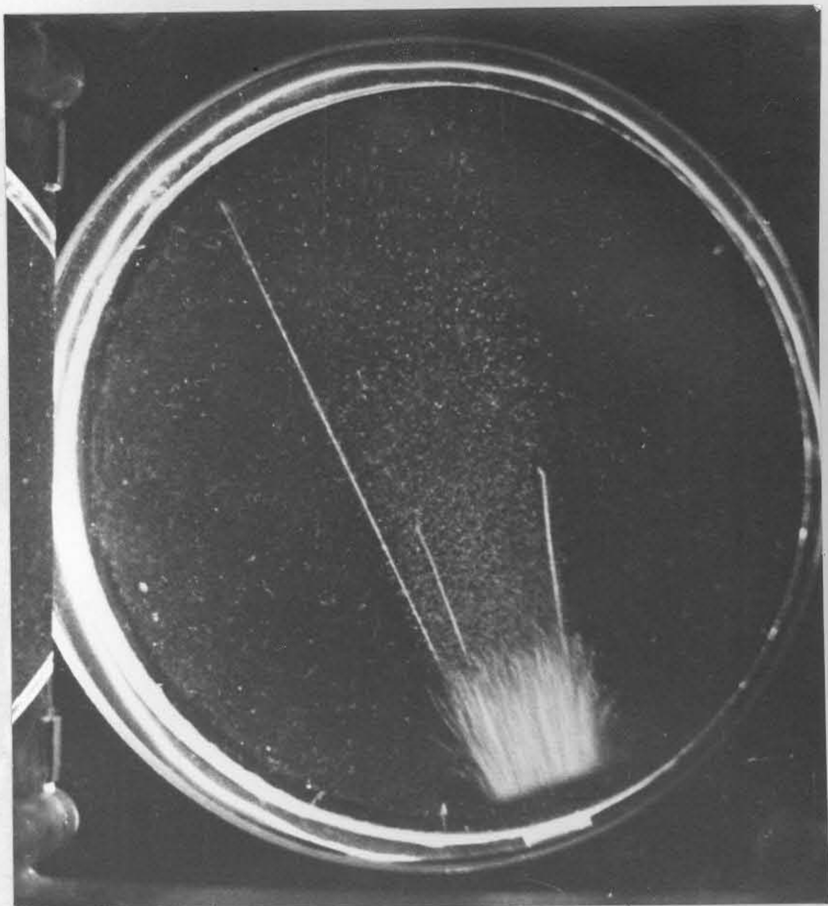

Plate III. Two particles from the reaction $F^{19} + H^1 \rightarrow O^{16} + He^4 + \gamma$ and one from the reaction $F^{19} + H^1 \rightarrow O^{16} + He^4$. The band of small drops extending across the center of the cloud chamber are due to soft x-rays produced in the target. These x-rays are produced when the extranuclear electrons are excited by the protons. Their adsorption coefficient can be measured by counting the number of drops per square centimeter at different points along the path.

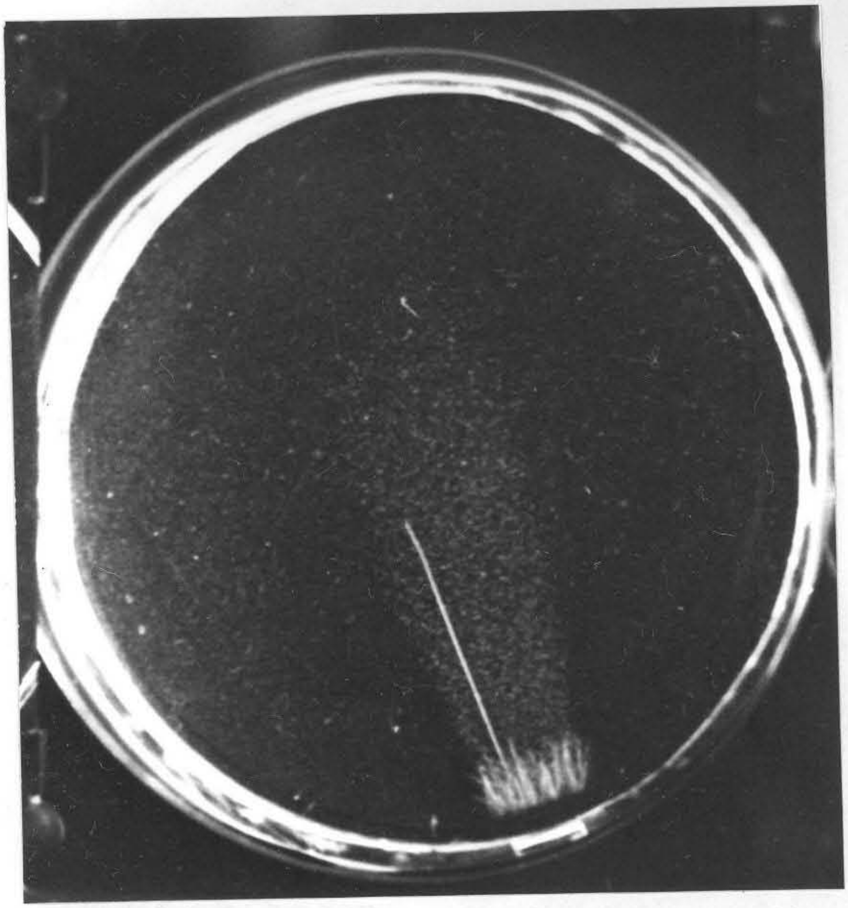

Plate IV. A track from $F^{19} + H^1$ at a lower bombarding voltage than that used in Plate III.

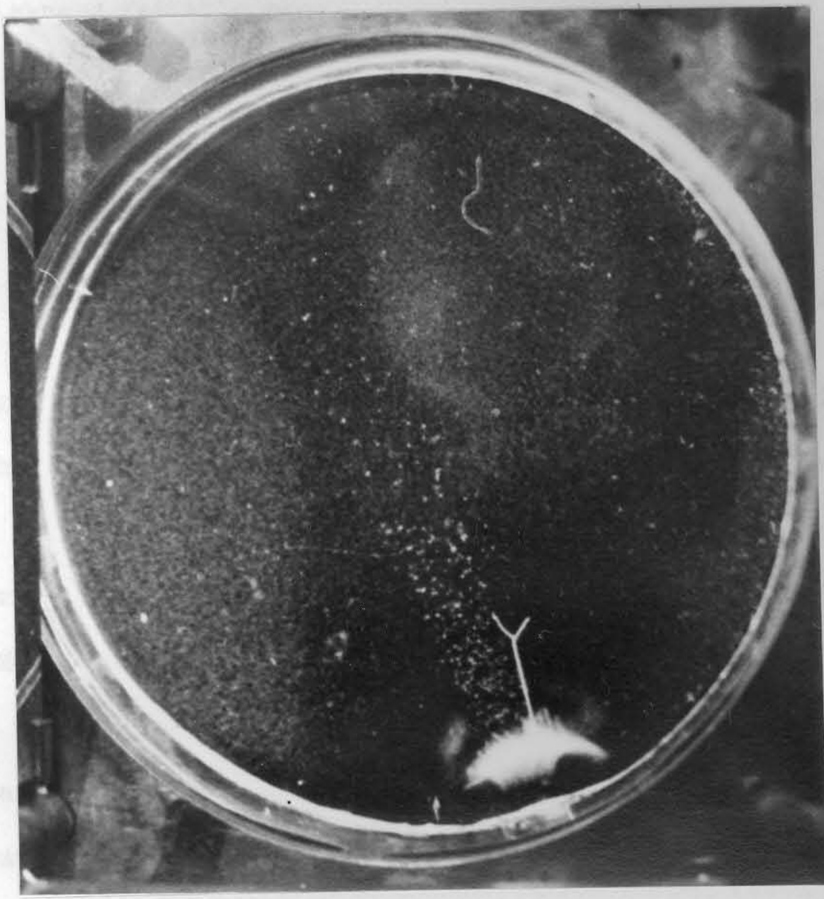

Plate V. A fork produced in helium by the particles from $F^{19} + H^{1}$.

The measured mean range in the cloud chamber from Figure 3A is 4.4 centimeters. From the stopping power of the chamber and the window thickness for this case

$$R = 4.4\,\sigma + \delta = 4.4 \times .111 + .357 = .847 \text{ centimeters.}$$

For the curve in Figure 3B

$$R = 7.0\,\sigma + \delta = 7.0 \times .076 + .307 = .837 \text{ centimeters.}$$

The average measured mean range is therefore .84 centimeters in air.

The reaction does not take place at the surface of the target since the protons of .35 Mev. must penetrate the target until they are slowed down to an energy of .33 Mev. The difference between the range of a .35 Mev. proton and that of a .33 Mev. proton is 0.4 millimeters. Since the target is at an angle of 45° the alpha particles must penetrate an amount of material equivalent to 0.4 millimeters of air in getting out of the target. In order to get the true mean range 0.4 millimeters must be added to the observed mean range, giving a range of .88 centimeters.

The two sets of tracks have been combined and plotted as a function of the true range in Figure 4. In this figure the scattered protons have a range which is apparently too great since the .04 millimeter correction for penetration of the target was made by shifting the origin of the graph. This makes the correction apply to all tracks but the protons of maximum range are those scattered from the surface of the target.

Since for the reaction $F^{19} + H^1 \rightarrow O^{16} + h\nu + He^4$ the geometry was what Bethe classifies as poor geometry, the particles which were emitted at an angle θ_0 are allowed to enter the cloud chamber. The range measured is therefore the component, in a direction perpendicular to the incident beam of the range of these particles. If the energy of these particles is known the total energy released in the reaction can be calculated by the formula (ref. 8, eq. 773, page 179)

$$Q = \frac{M_2 + M_3}{M_3} E_2^m + E_1 \frac{M_1}{M_3} \left(1 - n \frac{M_2}{M_2 + M_3}\right) - E_1$$

where the subscripts 1, 2, 3, refer to the bombarding observed, the recoil nuclei respectively

n is the range exponent

E_2^m is the energy corresponding to the range of the observed particle.

The energy of an alpha particle of 8.8 millimeters range is 1.66 Mev.[10]

$$Q = \frac{20}{16} 1.66 + .35 \frac{1}{16} \left(1 - 1.98 \frac{4}{20}\right) - .35$$

$$Q = 1.74 \text{ Mev.}$$

The error in this determination is due chiefly to errors in determining the extrapolated range from the range number curves for $Li^6 + H^1$. Extreme values of the extrapolated ranges, for the curve in Figure 2A, which still lie within the probable errors of the points, give a value for the mean range of the fluorine alpha particles of

7.8 millimeters in place of 8.4 millimeters. Since there are two observations each with about this error the probable error should be .67 x .6 = .4 millimeters. The statistical error in the determination of the mean range of the alpha particles, from the curve in Figure 4, is the half width divided by the square root of the number of tracks or $\frac{1.25}{325}$ = .07 millimeters. The sum of these two statistical errors gives a probable error of about 0.5 millimeters. This corresponds to a probable error of .10 Mev. in the value of Q for the reaction.

Other errors may have been caused due to the fact that in order to change from a LiCl target to a CaF_2 target, it was necessary to allow the pressure in the cloud chamber to return to atmospheric pressure. This change of the gas in the chamber might cause a variation in the stopping power if the amount of air impurity changed or if the pressure and temperature were not exactly reproduced. That these errors were probably small is shown by the fact that the two determinations of the range agree well within the statistical error.

If the alpha particles arise in the same reaction as the gamma rays they must show resonance at the same voltage. In an effort to confirm this, 1250 cloud chamber pictures were taken at various voltages while the current to the target was kept as constant as possible. Variations in target efficiency and current fluctuations were spread out among the various voltages as much as possible by changing the voltage frequently. Runs at voltages above the gamma ray resonance were separated by runs at voltages below this resonance. Since only the relative yields at the various voltages were important this procedure minimized any errors due to fluctuations in the efficiency of the apparatus (target, ion source, current, etc.).

The length of the scattered proton brush was measured on each picture. In Figure 5 the number of tracks appearing per 100 pictures containing proton brushes of a particular length is plotted as a function of the proton length. The interval used is 3 millimeters of proton length as measured in the cloud chamber.

The proton ranges were converted to voltmeter readings by using the mean of the ranges obtained during runs when the voltage on the tube was particularly steady. The proton range as a function of the voltmeter reading is shown in Figure 6. Figure 7 shows the yield of gamma rays (solid curve) and the yield of alpha particles (dotted curve) plotted as a function of the voltmeter reading. The ordinates have been adjusted to give both curves the same maximum value. The probable errors shown in Figure 5 do not include current fluctuations. Such variations will probably account for the large errors in the high voltage region where relatively few pictures were taken. The results indicate that the alpha particles and gamma rays both show resonance in their yield at the same bombarding voltage within the experimental error. This resonance voltage is known to be 330 Kv.[10],[11],[12]

An attempt was made to measure the relative yields of gamma rays and short range alpha particles simultaneously. For cloud chamber

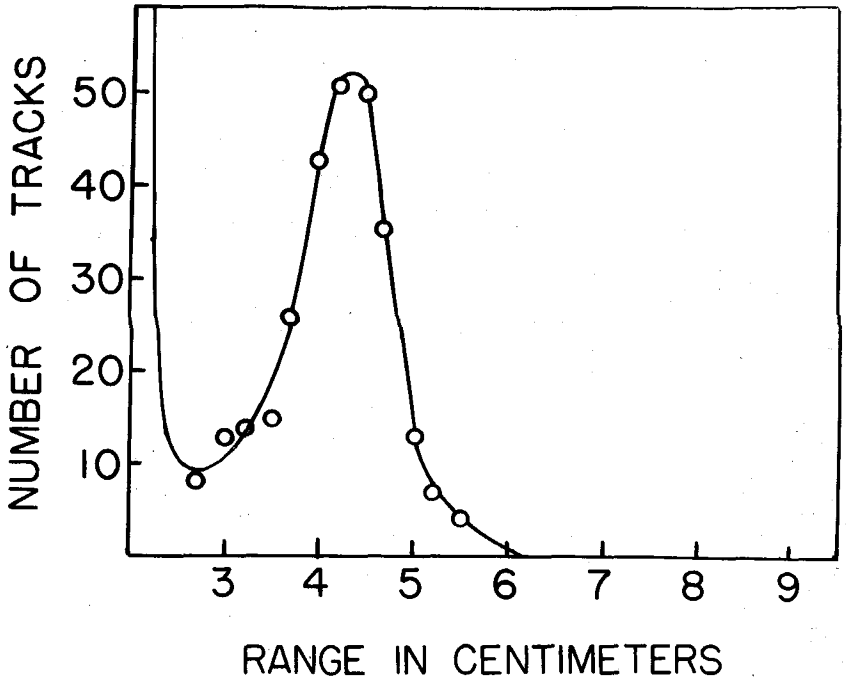

Figure 3A. The number of tracks from the bombardment of F^{19} with protons of 350 Kv. energy plotted as a function of the observed range in the cloud chamber. These particles were admitted through a mica window to a cloud chamber containing a pressure of -17 inches of helium, water, and alcohol vapor. The points represent the number of tracks in 0.5 centimeter overlapping intervals.

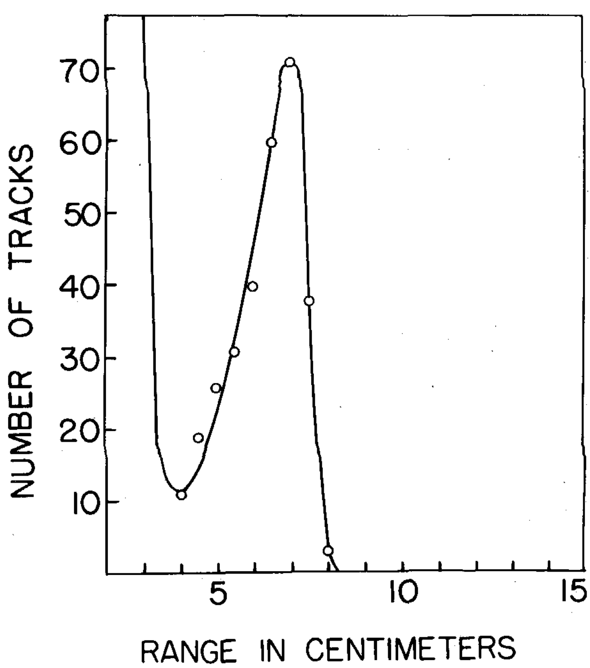

Figure 3B. This curve differs from the above in that the mica window was replaced by a lacquer window and the alcohol eliminated from the cloud chamber. Because of the lowered stopping power 1 centimeter overlapping intervals were used in plotting the points.

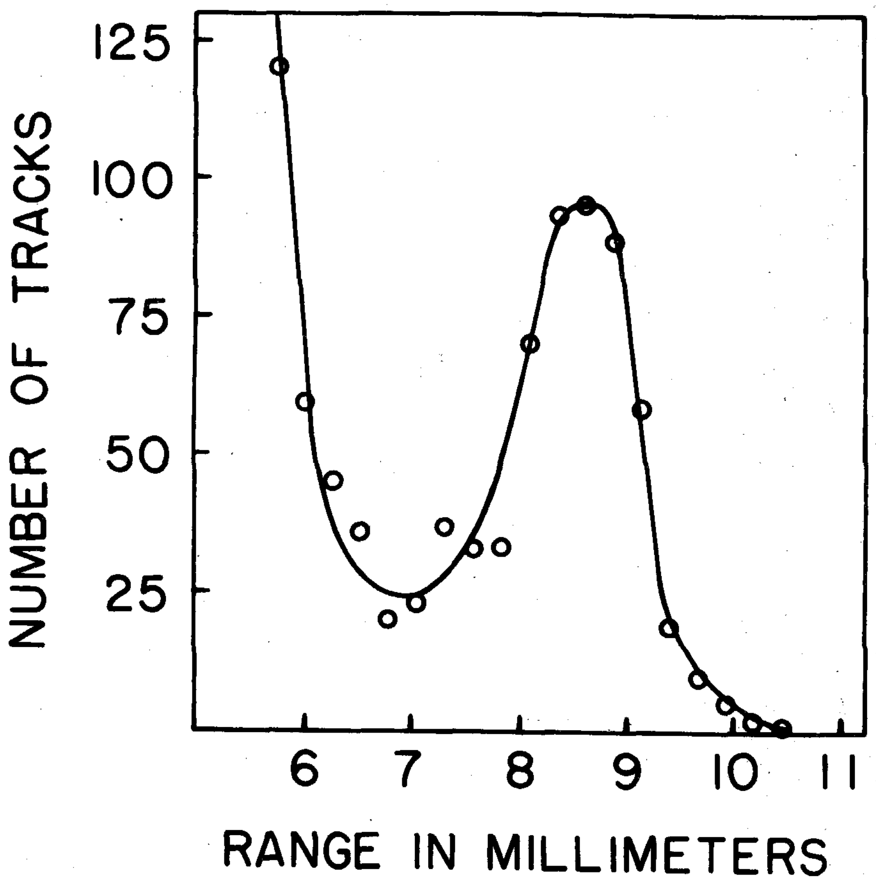

Figure 4. The combined tracks from the curves in Figures 3A and 3B plotted as a function of the corrected range in millimeters of air. The points represent the number of tracks in 0.5 millimeter overlapping intervals.

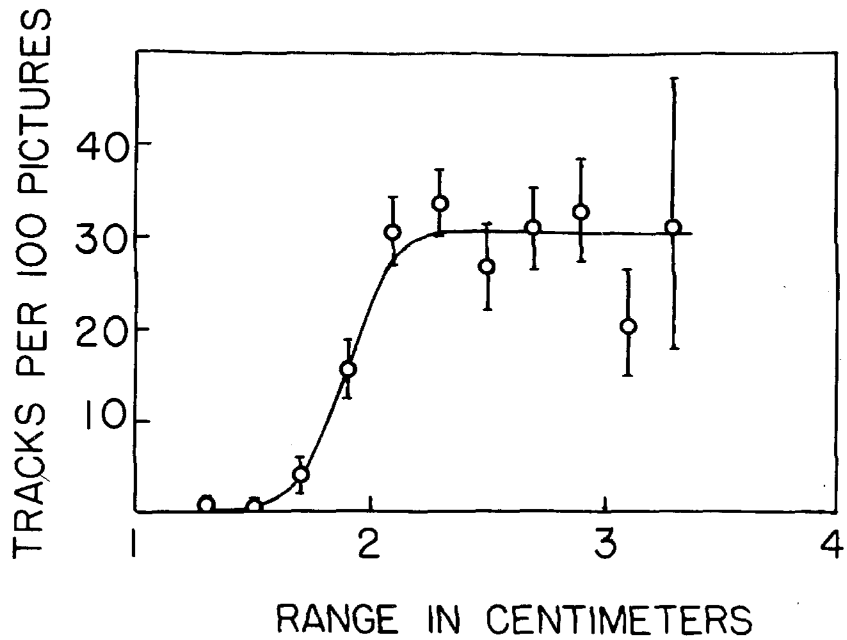

Figure 5. The number of short range alpha particle tracks appearing on 100 pictures is plotted as a function of the range of the scattered protons. The probable statistical error is shown.

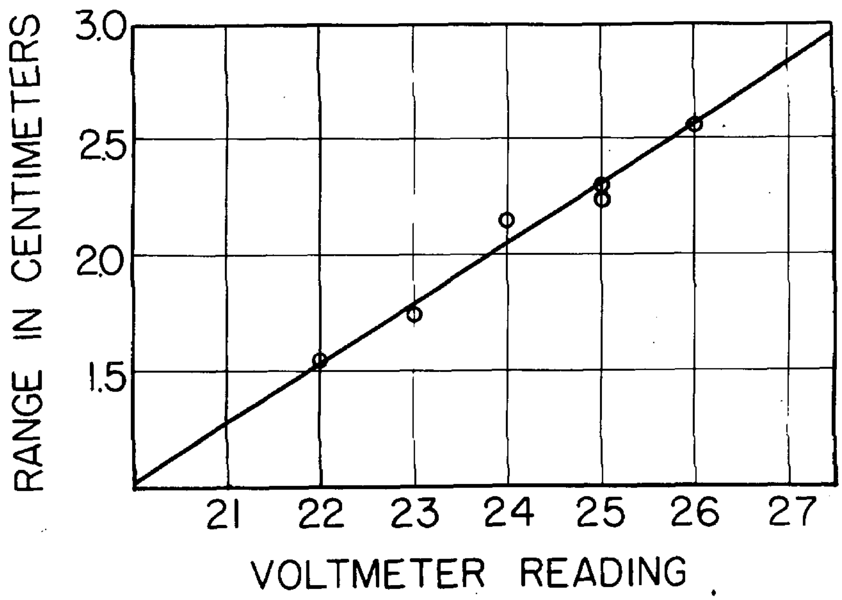

Figure 6. The range of the scattered protons is plotted as a function of the voltmeter reading in arbitrary units. The points were obtained from runs during which the tube was exceptionally steady.

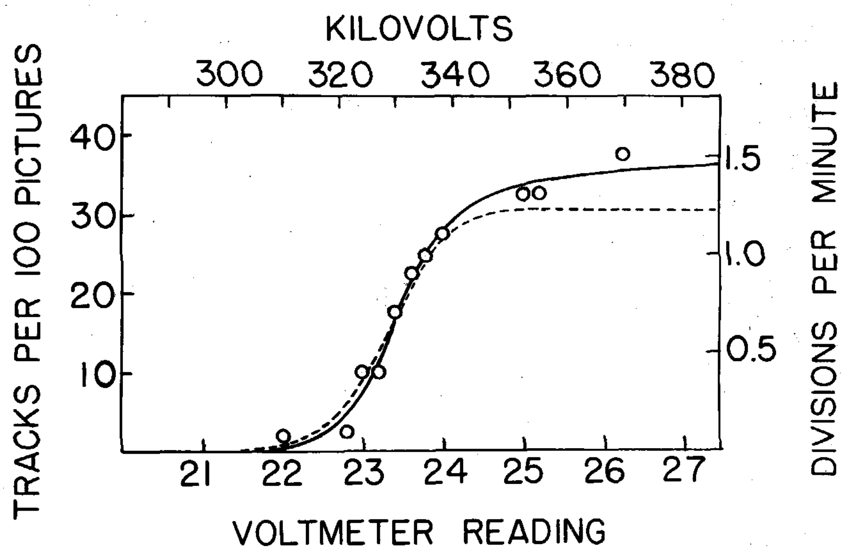

Figure 7. The dotted curve is the alpha particle yield in Figure 5 plotted as a function of the voltmeter reading as determined from Figure 6. The solid curve and points represent the yield of gamma rays as ~~a function of~~ determined by the electroscope reading. The voltmeter calibration as calculated from this curve is given in the top scale.

operation it was necessary that the proton beam strike the target only during an expansion, however these short periods of bombardment did not produce enough gamma rays to cause the electroscope deflection to be appreciably above its background. Since this direct method of determining the ratio of the yields was not applicable, an attempt was made to find the relative number of gamma rays and short alpha particles indirectly by comparing each with the yield of long range alpha particles.

On all the pictures taken of the reaction $F^{19} + H^1$, a total of 21 tracks occur which do not stop in the chamber and are presumably the alpha particles of 5.90 centimeter range produced in the reaction. The total number of short tracks occurring on the same pictures is 537. The ratio of the number of short tracks to long ones at $\sim$ 350 Kv. is 26 ± 5. This ratio may be too small since fluctuations in voltage above 350 Kv. would tend to increase the relative number of long tracks, while if the bombarding voltage fell below 330 Kv. no short tracks would be produced.

The yield of long range alpha particles has been determined as a function of the voltage by Henderson, Livingston, and Lawrence.(14) They give an equation derived from the Gamow theory which fits all but one of their points. The number of alpha particles per 10^9 protons is

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

where $S = \dfrac{8.92}{V^{\frac{1}{2}}} \quad \dfrac{28.3}{(8.2 + V)^{\frac{1}{2}}}$ and where V is in Mev.

If $k = .608\, e^{20}$ then N will be the number of disintegrations per 10^9 protons. For 0.35 Mev

$$N = .00195 \text{ alpha particles per } 10^9 \text{ protons}$$
$$= 1.95 \text{ alpha particles per } 10^{12} \text{ protons.}$$

The minimum yield of gamma ray quanta from the resonances in fluorine below 750 Kv. has been estimated as 5×10^{-9} quanta per incident proton.(17) From the yield curves of Bernet, Herb, and Parkinson(11) it can be estimated that approximately one third of this yield would be due to the resonance at 330 Kv. if only protons were effective in producing it. However, the molecular ions will also produce activity at the 330 Kv. resonance. The target current has been estimated as being about one third protons. Since hydrogen molecules have two nuclei for every charge, there are five times as many particles producing disintegrations at 330 Kv. as at the higher resonances. Taking these two factors into account the ratio of gamma rays from the 330 Kv. resonance to those from the other resonances below 750 Kv. must be 5 to 2. Therefore the yield of gamma rays from the 330 Kv. resonance is $5/7 \times 5 \times 10^{-9} = 3.5 \times 10^{-9}$ quanta per incident proton.

The ratio of gamma rays to long alpha particles is 1800 from these computations. This does not agree very well with the assumption that all the gamma rays are produced according to the reaction

$$F^{19} + H^1 \rightarrow Ne_B^{20*} \rightarrow O^{16*} + He^4 \rightarrow O^{16} + He^4 + \gamma$$

where one gamma ray is produced for every short range alphs particle. It is always difficult however to compare yields obtained in different laboratories under different conditions. The yield of long range alpha particles may have a large error due to the extrapolation of the yield curve to such low energy. Oliphant and Rutherford(18) have measured the yield of long range alpha particles up to bombarding voltages of 200 Kv., Henderson, Livingston, and Lawrence(14) from 450 Kv. to 1650 Kv., both curves showing an exponential increase of the yield with voltage. It may be possible however that the Γ_α for the suppressed transition from the triplet Ne^{20}_{B} to O^{16} + He^{4} (5.90 cm.) is large enough to add an appreciable number of long range alpha particles showing resonance at 330 Kv. to those to be expected from the non-resonant reaction. The yield in the region around 330 Kv. has not been investigated and it is only here that such a deviation would be noticed. The fact that all of the long range alpha particles observed occurred at voltages above the resonance value would lend support to such an explanation of the low ratio of short to long range alpha particles.

It may also be that the angular distribution of the short range alpha particles is anisotropic with a minimum at 90° in which case too few of them would have been observed.

Recent work(21) has shown that the energy of the gamma rays is the same whether they are produced by protons entering the nucleus at the 330 Kv. level in F^{19} + H^{1} or at the 862 Kv. level. This can only be true if alpha particle transitions occur between these levels and an excited state of O^{16}. If any gamma ray transitions occurred from these levels the resulting gamma rays would have different energies. Thus it seems probable that a short range alpha particle must be produced before the emission of a gamma ray quantum in spite of the apparent discrepancy between the ratios of gamma rays to long range particles and short to long range particles.

Determinations of the angular distribution of the short range alpha particles and the yield curve for the long range alpha particles in the neighborhood of 330 Kv. will probably show that the number of short range particles is equal to the number of gamma ray quanta.

CHAPTER IV

SUMMARY

Short range alpha particles from the bombardment of CaF_2 with protons of .35 Mev. energy have been observed and their mean range determined to be 0.88 ± .05 millimeters. The energy release is calculated to be Q = 1.74 ± .10 Mev. The yield of these particles shows resonance at the same bombarding voltage as the yield of gamma rays from the same reaction. It is concluded that the production of short range alpha particles is to be associated with the production of gamma rays according to the equation:

$$F^{19} + H^1 \rightarrow Ne^{20*} \rightarrow O^{16*} + He^4 \rightarrow O^{16} + He^4 + \gamma$$

A recent determination(21) of the quantum energy of the gamma rays by observation on pairs ejected in a cloud chamber gives a value of 6.3 ± .1 Mev. The mass of F^{19} calculated using this value for the energy of the gamma ray and the above determined value for the energy of the alpha particle is 19.00440 ± .00016. This is in good agreement with the value of 19.0043 obtained from the long range alpha particles by Burcham and Smith(5) and with the mass spectroscopic value of 19.00452 ± .00017 obtained by Aston.

APPENDIX

The cross section or the probability that a nuclear state will disintegrate, producing a product i is given in terms of the mutual energy of the bombarding particle and the nucleus, and the probabilities of the different possible modes of disintegration by the formula:

$$\sigma_i = \pi \lambda^2 \omega \frac{\Gamma_p \Gamma_i}{(E_R - E)^2 + \frac{1}{4}\Gamma^2} \tag{1}$$

where $E = \dfrac{M_n}{M_p + M_n} E_p^{obs.}$

M_n = mass of nucleus
M_p = mass of bombarding particle
E_p^{obs} = observed energy of protons in laboratory coordinates.

$$\lambda^2 = \frac{\hbar^2}{2ME} = \frac{\text{De Broglie wave length}}{2\pi}$$

$$M = \frac{M_n M_p}{M_p + M_n}$$

$$\omega = \text{statistical wt.} = \frac{2J + 1}{(2S + 1)(2i + 1)}$$

J = angular momentum of compound nucleus
S = spin of incident particle
i = "spin" or total angular momentum of bombarded nucleus

E_R = energy at which the compound nucleus has a resonance level.

Γ_p = partial width for re-emission of a proton.
Γ_i = " " " emission of an α-particle or quantum.
$\Gamma = \Gamma_p + \Sigma \Gamma_i$ = total width of the level.

The partial width $\Gamma_i = G_i \gamma_i$ is due to two factors. One corresponds to the time required for a particle to form, and cross the nucleus. For alpha particles and protons, in the case of allowed transitions, this is of the order of 10^{-22} sec. giving a $\gamma_i \approx 1$ Mev. The other is the probability that the particle will penetrate the coulomb barrier. This probability is the Gamow factor:

(2) $$G_i = \exp\left[-0.76\sqrt{\frac{M_1 Z_1}{Z M^{1/3}}} \; F\left(\frac{E}{E_{barrier}}\right)\right]$$

$$F(x) = x^{-\frac{1}{2}} \arccos x^{\frac{1}{2}} - (1-x)^{\frac{1}{2}}$$

$$E_{barrier} = 0.70 \frac{Z_1 Z (M_1 + M)}{M^{4/3}} \text{ Mev.}$$

From equation (1) it can be seen that σ will have half the resonance value if $|E - E_R| = \frac{1}{2}\Gamma$. Therefore Γ is the width of the resonant level at half maximum.

If the total width of a level or nuclear state, Γ, is small then the particles or gamma rays emitted from such a level will show resonance in their yield. If Γ is large compared to the range of bombarding voltages used this resonance will be too broad to produce a noticeable effect.

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