Construction of a Pressure Van de Graaff Generator and its Application to Nuclear Physics

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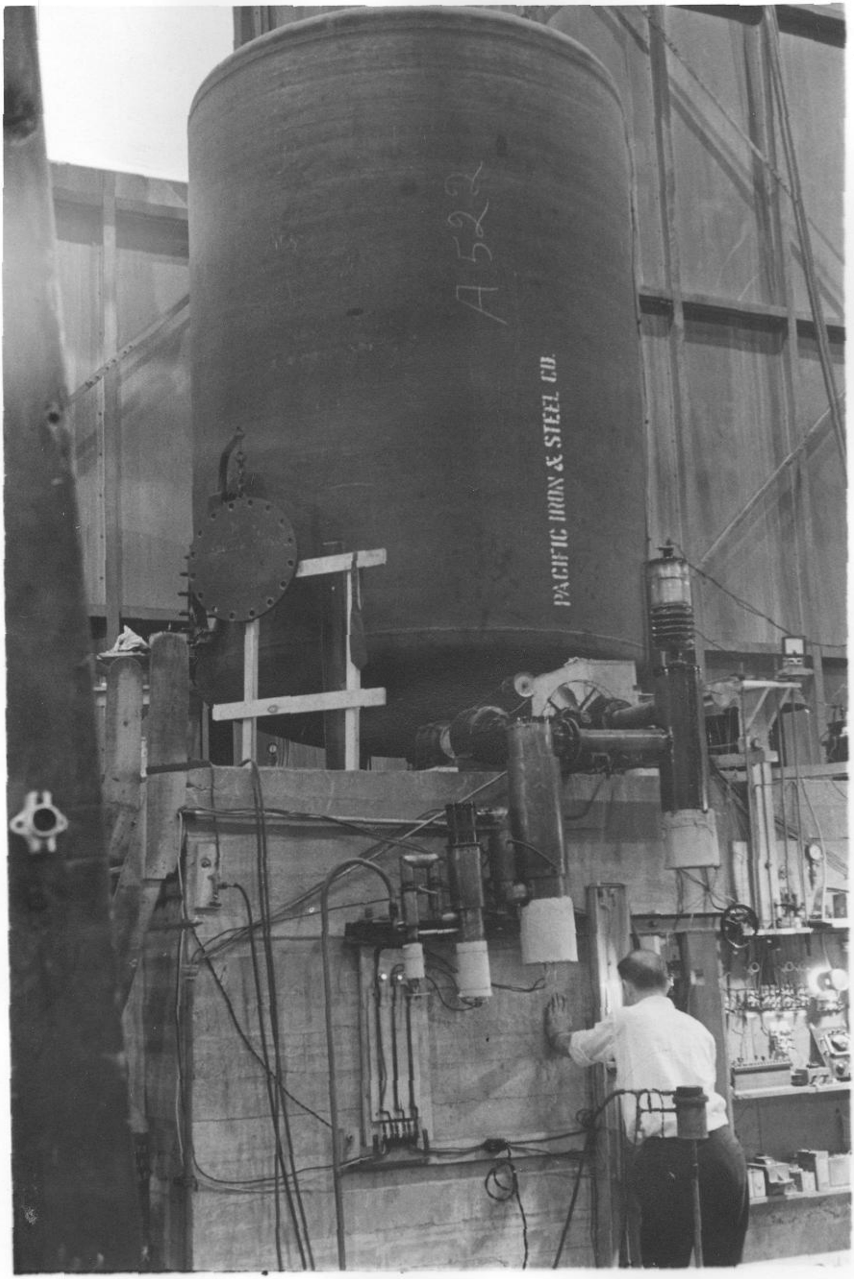

General View of Installation, showing tank, pumps and control panel

ABSTRACT

An electrostatic generator of the Van de Graaff type has been constructed in a pressure tank in combination with an accelerating tube designed to produce one to two million volt ions. Tests with the high potential terminal negative have indicated that the installation might be a practical compact source of high voltage x-radiation for possible therapeutic application. With the terminal positive, it is possible to obtain and to focus on a target five to ten micro-amperes of positive ion current with proton or deuteron currents of the order of 5 - 10% of the total,homogeneous in energy to one percent, or better.

The machine has been used to study the resonance reactions of Fluorine under proton bombardment at two energies, 0.334 and 0.927 Mev., by measuring the gamma ray energies in a cloud chamber at both values. From the fact that the energy difference of nearly 0.6 Mev. does not appear in the gamma ray, it is concluded that it results from a transition in O^{16}, from a level excited to 6.3 Mev. to the ground state, and that the triplet state of $(Ne^{20})^*$ formed by the capture of the resonant protons must drop to $(O^{16})^*$ with emission of a short range alpha particle. The possibility that the gamma ray may result from the transition to a level in Ne^{20} preceding the emission of the alpha particle is considered to be ruled out by this evidence. Some indication for an additional gamma ray line at about 10 Mev., amounting to two or three percent of the total radiation is found at the higher resonance, but is not considered as established, and the general character of the reaction at the high resonances is certainly the same as that of the lowest one. The experimental facts are found to be not inconsistent with theoretical expectations, but the theory is still far from giving a complete picture of the situation. Further work, both experimental and theoretical, is indicated on the problem.

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I. Introduction

The developments of nuclear physics during the past five years have made increasingly apparent the need for sources of positive ions of energies greater than one million electron-volts, not only because the number of nuclei which can be disintegrated with particles of lower energy is limited, but also because of indications that the reactions may exhibit quite radical differences when the energy of the bombarding particle reaches values comparable with the barrier height. In addition, the discovery of "resonance" effects at energies just corresponding to stationary states of the nuclear system has emphasized the value of a high degree of homogeneity in the energy distribution of the ions.

Of the types of apparatus commonly used in the acceleration of positive ions, the most practicable seem to be four in number:

1. Cyclotron
2. Transformer-kenotron set and tube
3. Cascade transformer set and tube
4. Van de Graaff generator and tube.

The Cyclotron - extensively developed at the University of California[1] - has proved very useful for obtaining extremely high energies with considerable currents: Several hundred microamperes at ten million electron-volts have been obtained. Particularly if one makes use of the so-called "phantom current", which circulates in the chamber without coming out, one may produce very large quantities of radioactive isotopes of known elements which are of great value, both in physical and biophysical investigations. The fact, however, that the ion energies range as much as 10% below the maximum tends to offset these advantages for the types of investigations which it was desired to carry out here.

Transformer-kenotron sets have been used at several laboratories[2,3,4] with a great deal of success. Installations of greater than one million volts capacity are quite expensive, and, at least in their present development, inconveniently large, because of the great clearances required.

Considerable experience has been gained in this laboratory[5] and at Ann Arbor, Michigan[6] with the cascade transformer and tube. This type of apparatus has proved very useful, particularly in the investigation of gamma ray spectra where high intensities are required. It would seem, however, that the extension to two million volts would be attended with some difficulty, again because of the need for a large space, and also because of the great power loss in charging current which occurs in alternating current high voltage installations. The inhomogeneity of the ion beam is also a serious disadvantage, but might perhaps be lessened by synchronizing the admission of ions into the accelerating tube with the voltage or by precise magnetic analysis. Another difficulty is the large background of X-radiation, produced on the alternate half-cycle, which interferes greatly with measurements of weak radiations.

The development by Tuve at Washington[7], and by Herb, Parkinson and Kerst at Madison, Wisconsin[8] of the Van de Graaff generator in a form suitable for application to an accelerating tube has shown the great value of this instrument in nuclear physics. Operated, in Herb's form, in a pressure tank five and a half feet in diameter and twenty feet long, this apparatus is capable of delivering over a microampere of ions with energies up to 2.5 Mev. and homogeneous to one-half or one-fourth percent. The beam comes through a pipe in one end of the tank, can be focussed on a spot only a few mm. in diameter, and is readily accessible for auxiliary apparatus. The freedom from extraneous X-radiation is also a recommendation of some weight. The relative simplicity of the machine makes it especially adaptible to a somewhat limited budget, inasmuch as most of the parts can be constructed on the spot and need not be purchased.

In view of the advantages of the Van de Graaff machine, it was decided to construct a plant similar to that at Wisconsin at this laboratory to supplement the present apparatus and to extend the available energy to 2 Mev. To gain practical experience in the construction and operation of the Van de Graaff machine, a small plant was first built by W.B. McLean and J.F. Streib[9] and somewhat later, the large machine, of which the first part of this Thesis is a description, was begun by C.C. Lauritsen, W.A. Fowler, and the author.

II. The Generator at the California Institute

A. Design:

In principle, the Van de Graaff machine consists of an insulated conductor which is charged by a mechanically driven conveyor belt. The potential so obtained is used to accelerate ions in an evacuated tube where they are focussed on a target at the low potential end.

The problems in an electrostatic generator roughly divide themselves into four parts which will be discussed in order:

Insulating system

Charging system

Voltage measurement and control system

Tube

1. Insulating system

Having once decided voltage and current requirements for the apparatus, one must determine the necessary dimensions and the best geometrical arrangement of terminal, charging belts, and tube. From considerations of simplicity and ease of construction, the best arrangement seemed to be that shown in Figure 1: a cylindrical structure containing the tube and belts in a vertical position, capped by a hemisphere and enclosed in a cylindrical air pressure tank with standard belled ends.

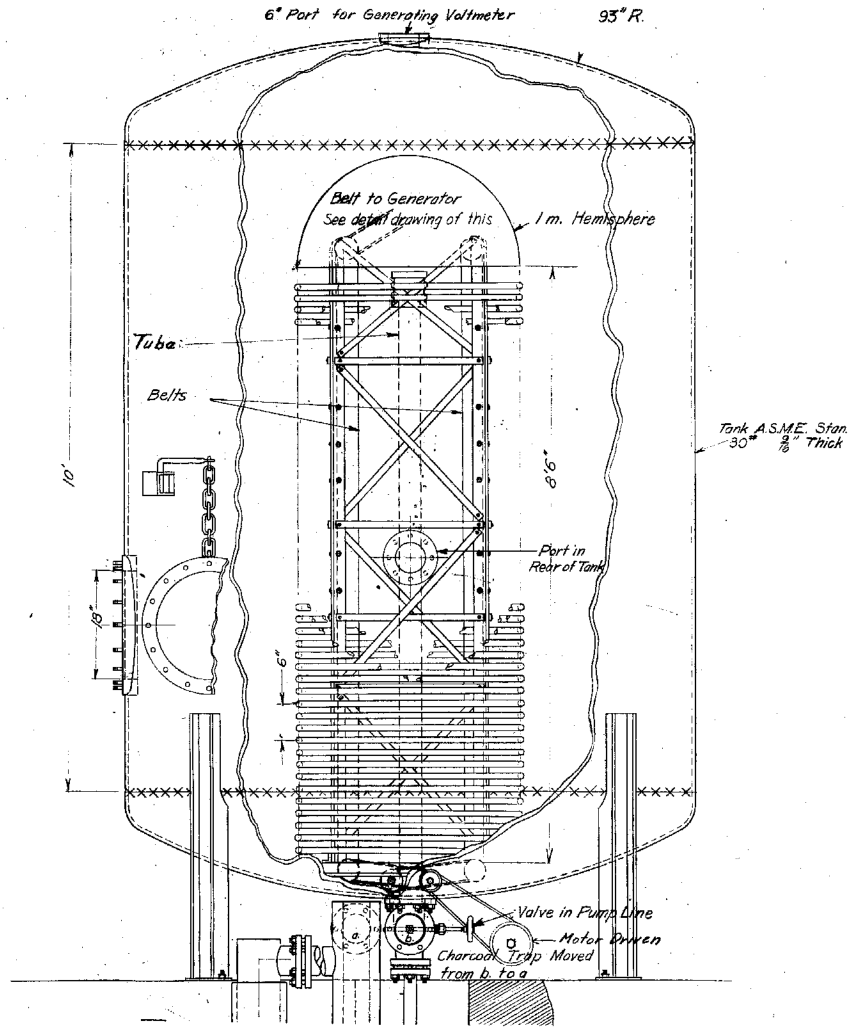

Fig. 1 Assembly Drawing of Generator and Tube

The equipotentials in the ideal case would be expected to be somewhat pear-shaped, the extension at the bottom being governed by the spark-over strength of the supporting members and the top roughly hemispherical about the high potential terminal. From the best estimates available, it was decided that a tube length, belt length and support member length of about eight feet should be sufficient for 2 Mev. at five or six atmosphere's pressure. From a consideration of the electrostatic problem of a sphere within a sphere, simple computation shows that the minimum field at the surface of the inner sphere is obtained when the ratio of the radii is 1:2, and that at this value the field is twice that for a single, free sphere. Since the breakdown field is 30,000 volts per cm. of radius for a free sphere at atmospheric pressure, and since one would expect a nearly linear increase for the first few atmospheres, a 25 or 30 cm. radius should be sufficient for about 2 Mev. However, in view of the fact that one rarely gets within 50% of the theoretical breakdown expectations, because of the high fields at minor irregularities, an inner hemisphere of 50 cm. radius was finally adopted. Because of the fact that the field does not depend critically on the ratio of the radii near the minimum point, a distance of 60 cm. from the terminal to the top of the tank, dictated by convenience, was specified. From experiments with grounded walls arranged around the smaller outfit constructed in open air[9], the conclusion was reached that the critical point would probably be at the junction to the cylindrical section, so the distance at this point was made 70 cm. For convenience in construction, the tank was made cylindrical, rather than pear-shaped, with standard dimensions of eight feet diameter and ten feet shell length, thirteen and a half feet in overall length, with an eighteen inch manhole in the side near the bottom. The hemisphere was put in before the head was welded on; all other parts were put in through the manhole.

It is a well-known phenomenon in insulating materials subjected to a potential gradient along their lengths, that they tend to break down progressively: the field concentrates at certain points and initiates a discharge, liberating ions which travel and cause breakdown along the remainder of the length. For this reason, it is essential to have a voltage distribution system on all insulating members, including the tube. In the present construction, all parts of the apparatus, except the tube, are supported on a square bakelite tower - see Figure 1 - and the potential distribution is taken care of by a series of rings whose potentials are fixed by a controllable corona current down them and which serve to define equipotential surfaces in the interior of the column. It was at first considered sufficient merely to have the rings near to the insulating members, but experience showed the necessity of having actual contact to the surface. In the construction finally used the rings were supported on nails driven in the bakelite. The determination of the best ring size and spacing is not amenable to precise calculation, but by considering the conditions between adjacent rings as similar to those between infinite cylinders, one finds that a ratio of diameter to spacing of as high as 2:1, making the total air path about 80 cm., is permissible. The desire to reach the ideal of an infinite number of rings at infinitesimal spacing must be balanced with convenience of construction and maintenance, so, following again the experience of Herb,[8] and McLean,[9] the rings were made of 5/8" aluminum tubing spaced 1-1/8" apart. To keep the edges of the bakelite members from projecting into the field, the rings were spaced 3/8" away. It was not considered necessary to tie in the diagonal members, in view of their length.

The amount of corona current between rings required to keep them at equal potential differences depends, of course, on the magnitude of stray currents - corona from rough spots, insulator leakage, and discharges in the tube -

tending to change their potentials. These adverse currents depend on the voltage at which the generator is running, the pressure and humidity of the air and the condition of the tube, and, since the total current available is limited, the control current must be made variable. This adjustment is effected by moving a set of needles, one for every four rings, mounted on the tube, with respect to a set of fixed smooth electrodes by means of a screw and crank mechanism operated from outside the tank. The separation can be varied from 2 to 5 cm.. In order to secure stable control, the points are made negative with respect to the smooth electrodes, since, for this combination the corona currents vary relatively slowly with voltage and spacing. Positive points have very steep characteristics and are extremely unstable near the sparking potential. The maximum current which can be drawn in point-to-plane corona before breakdown occurs is of the order of 200 microamperes, for either sign.

The needle holders were designed to take up to eight needles each, spaced symmetrically around the tube to allow for controlling large currents if necessary. Some attention was paid to keeping the needles close to the tube in the thought that the spray of ions on the porcelain surfaces would make them sufficiently conductive to prevent the accumulation of surface charges. Connections were all made with springs to minimize vibration of the tube.

2. Charging system

From the best estimates available, it seemed that currents of the order of 200 to 300 microamperes would be necessary to give sufficient stability in the generator to permit a drain of several microamperes in the tube. Also, since there seemed reason to believe that such an outfit had possibilities for conversion into an X-ray installation for yielding therapeutically useful quantities of radiation, an effort was made to give all the current capacity possible, consistent with reasonable clearances, int~~o~~ the system. A convenient arrangement was with two 24" belts, symmetrically arranged about the center, and a linear speed of about 4000 feet per minute was specified. Assuming again, a breakdown field of 30,000 volts per cm. at the surface of the belt, one finds a saturation value of 2.7×10^{-9} coulombs per square cm., giving a theoretical expectation of about 600 microamperes per belt at atmospheric pressure, if the belt carries charge both up and down. Again, up to a few atmospheres, this value should increase almost linearly with pressure.

The belts are charged by means of a set of spray combs, consisting of a row of pins, spaced at 1/4" intervals across the width of the belt, facing the metal roller on which the belt runs, and 1/4" away. The combs are excited with 5000 to 20,000 volts d.c. which is brought in through an insulated lead-in bushing from a source outside the tank. In the original design, the rollers were covered with 1/16" bakelite sleeves on the theory that the high resistance of the bakelite would act to stabilize the pin current, giving a more uniform spraying. These sleeves were later discarded.(see below).

A diagram of the system for charging the down-going side of the belt is shown in Figure 2. This so-called "doubling system" was first used by M.A.Tuve[7] and has the effect of doubling the current-carrying capacity of the belt. Positive charges sprayed on at the bottom spray comb A are carried up by the motion of the belt and some of them are drained off by the sharp points of the "pickup comb" B connected to the metal roller. The current flowing across the resistance R - ordinarily the leakage resistance of the insulating parts or a corona point - causes the roller to assume a potential of several thousand volts with respect to the terminal. The spray comb C, then, being negative with respect to the roller, gives off charge to neutralize any positive charge remaining and to saturate the belt with negative charges. The amount of charge going down may be regulated by means of an adjustable corona gap between the roller and the frame connected to the terminal.

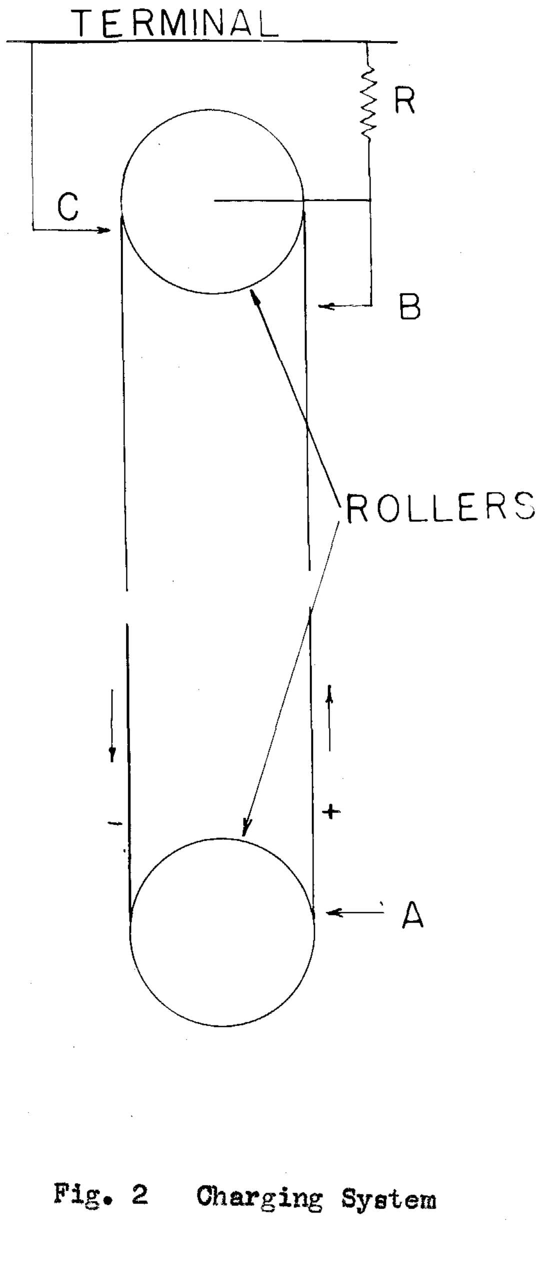

Fig. 2 Charging System

The mechanical problem of running such a wide belt required some care. The eventual solution was a crowning of about 1/2 degree for two inches at each end of the roller and doubling over the edge of the belt for one inch at each edge. Provision was made for adjusting the tension and alignment on both top and bottom rollers. The rollers were made of 4" brass tubing with steel end plugs which carried ball bearings running on a fixed shaft mounted on adjustable hangers. Careful balancing was found to be necessary to prevent excessive vibration. Power is transmitted to the bottom rollers by means of serrated vee belts from jack shafts which run through packing glands and were driven each by two one horsepower motors outside the tank. The belt tension is usually about 500 pounds.

Considerable attention was given to the matter of belt material. Canvas, electrical insulation paper, hospital rubber sheeting, and balloon fabric all gave roughly the same current, but mechanically the last two seemed best. The canvas, having a rough surface and relatively large stretching, was difficult to drive at high pressure because of air friction; while the paper, having almost no flexibility, was unstable on the rollers. Hospital rubber sheeting with vulcanized joints at forty-five degrees was used for some time, but balloon fabric, because of its lighter weight and greater tensile strength, was finally adopted.

3. Voltage measurement and control

In view of the great importance of accurate and reproducible voltage measurement in some of the experiments for which the generator was intended, some care was taken in designing the voltmeter. Of the several possibilities, the generating electrostatic voltmeter seemed the best, because of its zero current drain and its proven reliability.[8] The design finally adopted is shown in Figure 3 (2): a grounded semicircular sector, driven by a (an induction) synchronous motor, alternately covers and uncovers an insulated semicircular plate in the

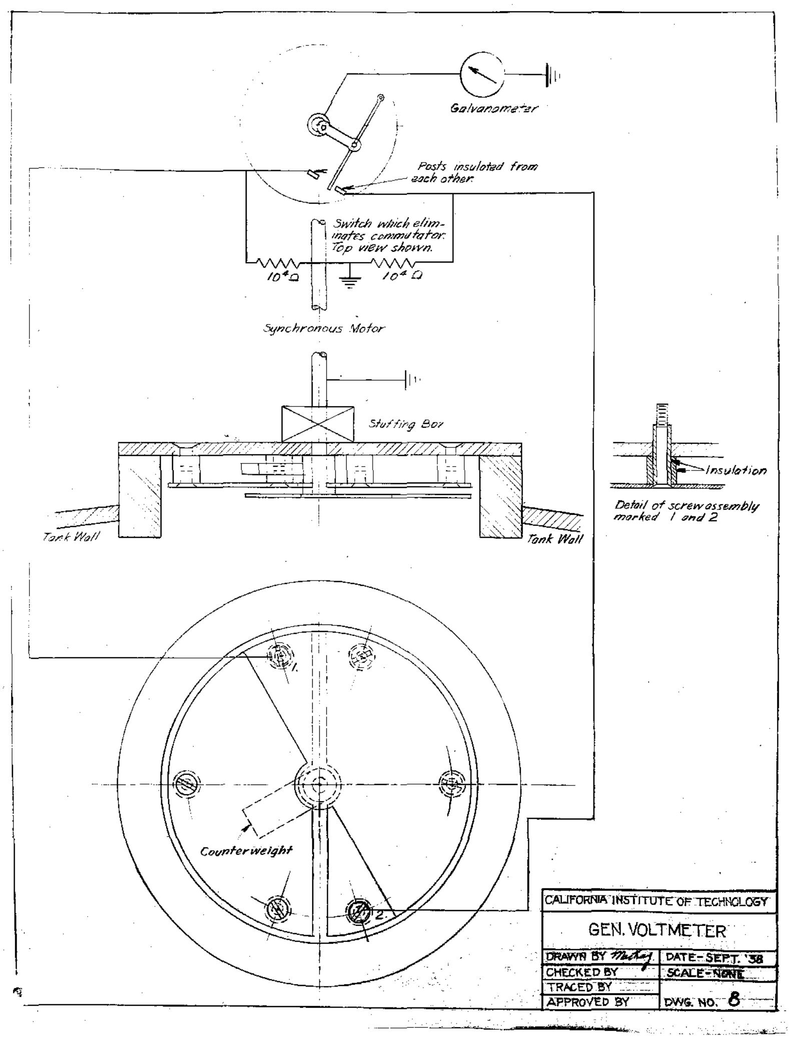

Fig. 3 Generating Voltmeter

top of the tank facing the terminal hemisphere. The current so induced is rectified by means of a cam operated breaker point and is balanced on a bridge circuit, the null being indicated by a galvonometer on the control panel. To insure recharging of the stationary plate on the off half-cycle, a 10,000 ohm resistor is permanently connected between it and ground. The galvonometer resistance is low enough so that its sensitivity is not impaired by this shunt. The time and duration of contact were adjusted for maximum and found not to be very critical: it seems that with the circuit conditions indicated, the current flows in a single pulse, rapidly damped out, so the duration of contact may be varied over wide limits without affecting the galvonometer reading. Careful shielding of the leads and contact system was necessary, but the use of a make and break rectifier eliminated all the usual stray currents found in rotating comutators.

Voltage control is effected by varying the voltage applied to the spray combs, and hence the charging current. The voltage may also be controlled by adjustment of the corona gaps on the tube and by varying the load in other ways. For large changes in voltage it is preferable to change the tank pressure.

4. Tube

In the selection of the type of tube to be used, again an appeal was made to previous experience. The use of the short ion path tube in this laboratory has shown its advantages of less critical focussing and comparatively large ion currents because relatively few of the ions suffer collisions in the residual gas in the tube, even when the vacuum is not perfect. The difficulty in the electrostatic generator ~~Van de Graaff type of machine~~ of distributing the potential in the tube would tend to offset these advantages however: excessively large tube diameter would be required to provide for the necessary telescoping full length shields. The long ion path tube, on the other hand, having a large number of small steps in voltage, is readily adaptable to this construction where the steps are available and space is at a premium; and the experience of Herb and Tuve has shown that focussing is not such a problem as was formerly thought.

The determination of the best number of accelerations for such a tube is rather arbitrary: for minimum aberration in the lenses, the requirement is that they be long in comparison with their diameters, and it did not seem likely that the beam would be held smaller than a few cm. in diameter if one used the full angular spread of the beam emerging from the ion source. Accordingly, the focussing sleeves were made 2" in diameter, $5\frac{1}{2}$" long, and spaced ~~1/2"~~ 3/8" apart in 6" tube sections. To secure maximum possible pumping speed consistent with clearance from the outside of the tube to the belts, an inside diameter of 4" was specified for the tube. The sections were made of porcelain, with annular corrugations on the outside, smooth on the inside and glazed all over. Joints were made with Picein wax, without gaskets. Figure 4 is a detail drawing of the tube and ion source.

The ion source used was copied from the type formerly used at this laboratory on other tubes [11]. In it the electrons emitted from the hot filament are drawn by a potential of several hundred volts through a region at relatively high pressure - of the order of 10^{-3}mm. of Hg. - in the gas to be ionized, and the ions so formed drawn out by a probe at a negative potential of a few thousand volts. A canal in the probe allows some of the ions to get out into the tube where they are accelerated by the main field. For focussing, two small accelerations are provided, controllable from outside the tank by means of adjustable needle gaps. To bridge between the 1/8" diameter of the canal and the 2" diameter of the sleeves in the tube, the first focussing sleeve was made 1" in diameter and connected to the first ring below the terminal. The second accelerating shield was connected to the second ring. The remainder of the gaps are connected to every succeeding fourth ring.

Power for the ion source is supplied by two transformer rectifier sets excited by a 500 cycle, 500 watt airplane generator which is driven by a long serrated vee belt. The filament, a seven turn helix of 0.013" tungsten, is heated by means of a low voltage transformer, and its temperature, controlled

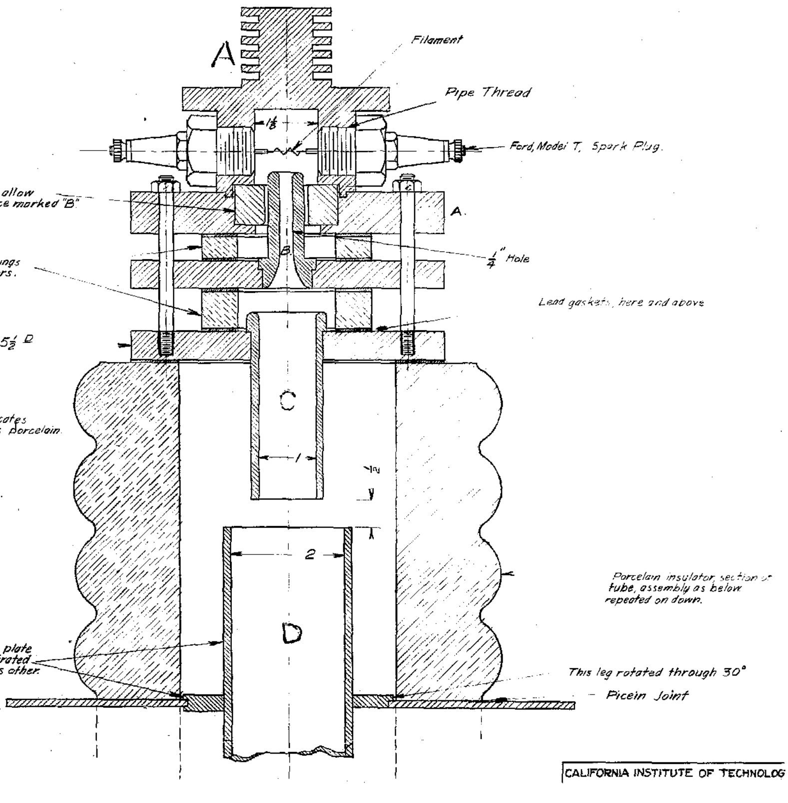

Fig. 4 Ion Source

from outside by means of a rheostat, determines the current at given gas pressure. Gas is supplied from a small tank at high pressure and controlled from outside by a rubber disc valve. All controls are brought down by 3/4" bakelite rods with steel extensions passing through packing glands in the tank. Rod was chosen in preference to tubing because of the possibility of sparking down the inside of the tubing.

B. Operation:

Actual construction work on the generator took about three months. As was expected, many features of the original design required improvement, and a good deal of the time - ten months - since has been devoted to gaining operating experience and to making the indicated changes. Particular attention was given at first to the problem of obtaining the high currents necessary for an X-ray source, and subsequently studies were made of the factors affecting the terminal voltage and the tube performance.

1. Charging current

The maximum charging current obtained, measured with the terminal grounded, was 360 microamperes per belt, at atmospheric pressure, representing about 60% of the theoretical expectation. This current was obtained with 24" hospital sheeting belts, on bakelite rollers. At fourteen pounds gauge pressure in the tank, a value of 600 microamperes was obtained. No attempt was made to go to higher currents as the attraction between the upgoing and downgoing sides of the belts caused severe rubbing, and the 1.2 milliampere total was considered ample. The voltage used on the spray combs was about 10,000 volts at atmospheric pressure, and increased roughly linearly with increasing pressure.

A useful measure of the behavior of the belt and doubling system is the current drawn by the bottom spray combs: in a good belt, this current is just equal to the terminal charging current except near saturation. When the doubler is shorted, the spray current shows a decided decrease, because it must neutralize the charge brought down by the belt. Some of the charge is lost to grounded metal parts near the bottom roller before it gets to the comb, but the remainder is read on the spray current meter. A plot of terminal current against spray current appears in Figure 5.

The charging current delivered by a belt varies to some extent with the dryness of the air. At humidities higher than 50%, the current is low and sometimes unsteady. It seems, however, that the surface recovers rapidly on drying: unless the exposure to humid air has been more than a few hours, an hour or so suffices for drying. Tests on surface leakage, made with a condenser-electrometer arrangement, indicated that the recovery of surface resistivity is not so rapid, taking in some cases a matter of days. Also, it has been found that belts of relatively high leakage along their lengths may still carry as much as half the maximum current: on one occasion a belt which had gotten some calcium chloride solution on it by accident was found to deliver over 100 microamperes, in spite of the fact that it could not maintain more than a few thousand volts along its length. The leakage was clearly seen in a series of streamers, extending from top to bottom and illuminating the whole belt. These facts force one to the conclusion that the charging current does not depend a great deal on the surface resistivity of the belt. The fact that a canvas belt, having a very rough surface, gives nearly as much as a smooth rubber belt seems to indicate that the character of the surface is also not very important in this respect.

Considerable trouble was encountered with the bakelite sleeving on the rollers. It was found that at extremely low humidity, less than 20%, the belts completely ceased to charge, and would not draw current on the spray combs, regardless of the spray voltage applied. Letting in moist air did not help unless it was allowed to remain so for a day or more. Wiping the bakelite with damp hands produced immediate, but not complete, cure. The conclusion was reached that the bakelite became dried out to such an extent that it remained charged in such a way as to prevent charges from leaving the spray comb and charging the belt, effectively neutralizing the spray voltage. It was found that a wire stretched over the top of the roller in

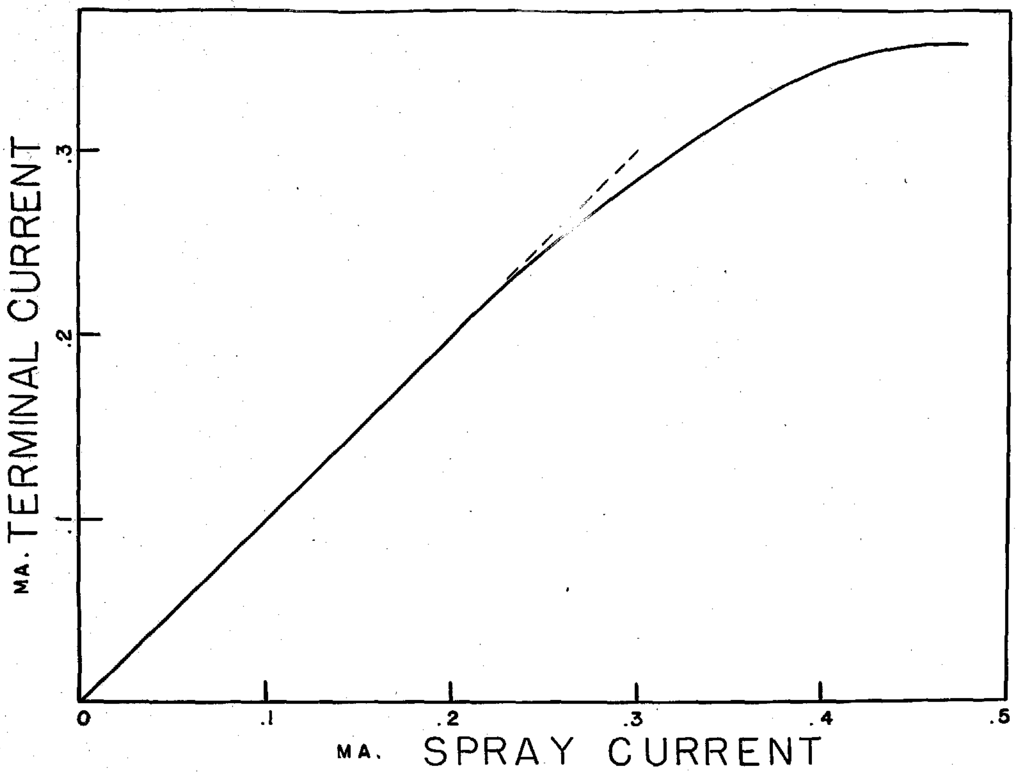

Fig. 5 Terminal Current vs. Spray Current

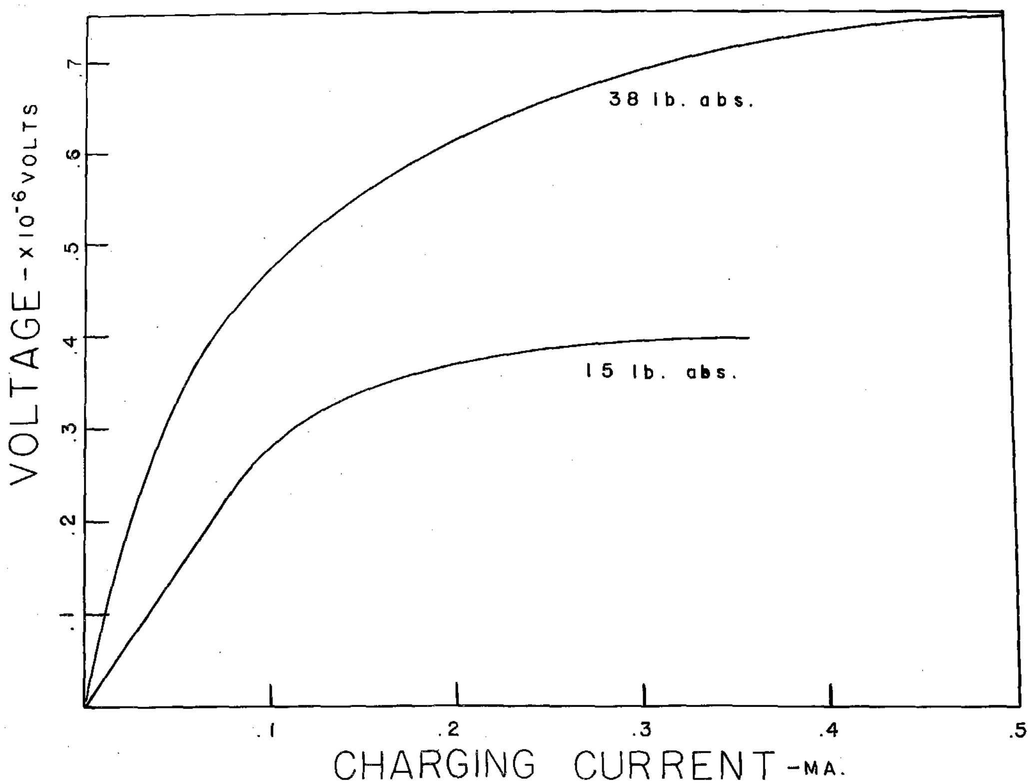

Fig 6 Terminal Voltage vs. Charging Current

such a way as to collect this surface charge as the roller rotated made it again possible to charge the belts. Removing the bakelite completely cured the trouble and it has never recurred, regardless of the humidity in the tank. With bare metal rollers, it was necessary to raise the spray comb slightly above the point of tangency to prevent the charge from leaking through the belt. With this arrangement on both top and bottom, the maximum current obtained is 280 microamperes per belt. The spray voltage required is, of course, very much lower, about 5000 volts.

A large amount of the original difficulty in obtaining consistent charging was found to be due to electrical leakage in the doubling system. Because of the rather high voltage - 5000 to 10,000 volts - necessary, corona from sharp points on the doubler assembly or the frame connected to the terminal was a definite limitation until the points were filed off. It was also found that the bakelite insulation was not good enough and hard rubber was substituted. Tests with a "megger" delivering about a thousand volts, showed the resistance to be as low as 20 megohms, while, to maintain 10,000 volts with a current of 100 microamperes, a resistance of 100 megohms is necessary. In order to pick up the requisite current, it proved necessary to move the pickup combs several inches below the point of tangency on the roller. With these modifications, the doubler operated quite consistently without outside control, as long as the current was over 100 microamperes.

2. Voltage

Something about the stability of the generator and the possible current drain can be learned from the plot of terminal voltage against charging current shown in Figure 6. It is to be observed that the first linear rise is typical of an ohmic resistance load, while the abrupt flattening is indicative of the onset of corona. The plateau from about 200 microamperes to the maximum value of 600 represents the current which can be drawn - for example, down the tube - without seriously affecting the voltage, and in this region, variations in the current affect the voltage only slightly, giving a high degree of stability to the system.

The maximum voltage obtained at atmospheric pressure is about 600 k.v. and seems to be limited both by flashing from the terminal to the tank and down the corona gaps. As the pressure is increased, the voltage increases at first, but comes to a limit at two or three atmospheres of from 1. to 1.2 m.v. At pressures higher than that required just to prevent flashing to the tank, considerable sparking is observed between the top rings and along the bakelite members. It is thought probable that the bakelite is charred in the joint of the angle section and that non-uniformity of the potential distribution causes the unsteadiness. The remedy will probably be to clean the bakelite, eliminate the crack with spacers and put in horizontal grooves filled with aquadag to take care of the potential distribution. *

At high charging, the limiting factor on the voltage is sparking down the belt. With rubber sheeting belts, this effect seemed to set in around 1 m.v., with currents higher than 200 microamperes per belt, and led to the adoption of balloon fabric which is much better. Herb has circumvented the difficulty in his machine by using unfiltered rectified alternating current on the spray combs, on the theory that the charge is put on in lines, with uncharged spaces between. A brief trial revealed no such effect here: the charge merely spread on the belt and the effective spray voltage was much reduced. It has been suggested that this sparking down the belts may give an upper limit to the voltage to be obtained by the Van de Graaff principle and the suggestion made that it may in the future be necessary to try to use a stream of charged dust particles instead of a belt.[12]

*Subsequent examination of the bakelite showed that sparking and burning has occurred inside the material, along splits between the laminations. Replacement with porcelain columns is now in progress.

The effect does not seem yet to be serious in apparatus used for nuclear physics where large currents are not necessary, but may be quite important in X-ray installations. In the present outfit, most satisfactory operation is obtained with a current of about 200 microamperes, with one belt.

It seems quite important in operation near the limiting voltage at a given pressure, that the current drain be fairly steady. Such things as discharges in the tube due to poor vacuum, sparking between rings or unsteadiness in the corona gaps can easily set off a discharge at some critical point. The system can usually be stabilized by draining current down the corona gaps and often this current drain has the effect of increasing the voltage. Ordinarily the voltage recovers in a few tenths of a second after a flash-over, but the flapping induced in the belt may cause unsteadiness for some time.

The voltage is controlled largely by changing the charging current, but it is sometimes necessary to change the drain on the corona gaps. It is possible to change the voltage by about 50% before unsteadiness occurs, without changing tank pressure.

The generating voltmeter is calibrated from time to time by going over the resonance levels at 330 kv. and at 860 kv. in the gamma ray production from the Fluorine-proton reaction,[18] and seems linear and reproducible to a few percent or better. Typical thick and thin target curves are shown in Figure 7.

3a Tube - X-rays

As has been indicated, some time was spent in investigating the possibilities of the installation as a source of X-rays. For this purpose, the ion source was connected in such a way as to emit and focus electrons, rather than positive ions. Since, according to the theory of ion optics,[13] focussing depends only on the relative voltages on the lenses, and not at all on the ~~character~~ mass of the ions, the main lens system of the tube is suitable either for electrons or positive ions.

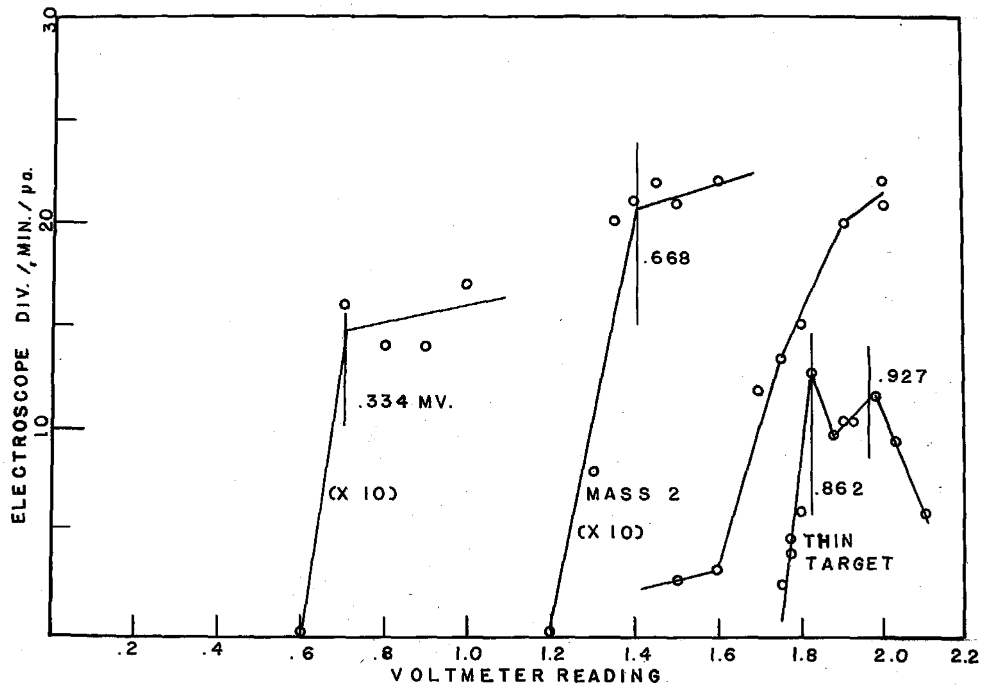

Fig. 7 Voltmeter Calibration

In the first accelerations, however, in the source itself, some differences appeared, presumably because, at the beginning of their path, the ions diverge considerably, and the conditions of the theory do not obtain.

It was found, for example, that the voltages on the first and second gaps, marked C and D in Figure 4, should be reversed for best operation, and that, unless these voltages were fixed by a power supply, electron bombardment would change them and the focal spot would pulsate.

The arrangement found best was as follows:

filament and filament holder (A in Figure 4) at 0 volts

probe (B) at 200 volts

first shield (C) at 600 volts

second shield (D) at 200 volts

A voltage of - 45 volts, to force electrons toward the probe, was tried on the filament case without any definite effect. The probe voltage is not critical and serves largely to determine the maximum current: at voltages less than 100 volts, only 50 microamperes could be drawn out, at 200 volts up to 400 could be obtained. The voltage on the first shield is also not critical except in so far as it must not be allowed to fluctuate: 1200 volts was also tried and found to be satisfactory.

It seems definite, however, that the acceleration from the first to the second shields should be negative. When 1200 volts was tried on the second gap, the focussing was quite poor.

The remainder of the gaps were at the voltage naturally taken up by the corresponding tube sections and did not greatly affect the focussing. With electrons, once the voltages were set, the focussing was quite automatic: no controls were necessary and the spot remained very nearly the same in size and in position from day to day. As the spot was only observed by means of a fluorescent screen on the under side of the target, no precise measurement of its size could be made, but it was certainly less than 5 mm. in diameter.

Because of the fact that electrons have a relatively long mean free path, it was possible to obtain high currents and good focussing without much trouble with tube vacuum. Apparently satisfactory operation can be obtained at pressures of several times 10^{-5} mm. of Hg. Considering that the electrons must travel nearly twelve feet, it would not be surprising if a large fraction of the beam were lost. Actually, on some occasions, as much as 300 microamperes of electrons hit the 2" target - mostly within a .5 cm spot - with a belt charging current of 600 microamperes at something over 500 kv. The most consistent performance, however, was with about 100 microamperes of electrons at a maximum voltage estimated to be about 1.5 m.v.

The X-ray output, using a gold target, was measured by means of a thimble chamber calibrated against an open air chamber. The maximum output, at 1.5 m.v. and 100 microamperes, was 17. roentgens per minute at 60 cm. with 1 mm. Cu.and .5 mm. Au.filtration. Points taken at other voltages indicated that the output per unit current follows roughly a square law as would be expected for unfiltered radiation. Experiments with filters revealed that a filter of 1 mm. Pb.would make a monochromatic equivalent value in the neighborhood of 800 kv., or only slightly lower than that given for filtered radium radiation (1 mv.). With a filtration of 1 mm. Pb. and 6 mm. Fe., the output was 4.0 r per minute, or about eight time the efficiency obtained with the X-ray tube in the Kellogg Laboratory running at 1 m.v. peak alternating current. If one assumes a cubic law for the efficiency of production of filtered radiation, this value is quite reasonable.

Since an output of 15 r per minute is quite adequate for therapeutic purposes, the conclusion is that, once the machine is made to run consistently, with a minimum of maintenance, it is quite feasible as an X-ray source operating between 1 and 2 m.v. Subsequent to the development of this machine, Trump and Van de Graaff[14] have published a description of a more compact unit operating at

1.25 m.v. and 1 ma. with an output of 250 r/minute per milliampere of target current at 50 cm. with 2 mm. of Pb. and 5 mm. of Cu. filtration.

3b. Ion Tube

In order to operate the tube as a positive ion accelerator, it was necessary to make some changes in the ion source voltages. Again, many combinations of voltages were tried to secure focussing and the critical ones were finally made adjustable from outside the tank.

In the first place, to make the ions, an accelerating voltage of about 1000 volts was applied between the filament and filament holder. The ions made in the gas by the electron current are drawn out by the probe at -3000 volts and are focussed by variation of the voltage on the first shield, which is connected to the first ring below the terminal. This voltage, about -10,000 volts, can be varied by means of a needle corona gap, and is the principal adjustment. The potential on the next accelerator (D in Figure 5) is also variable, from about -10,000 to -30,000 volts. The remainder of the accelerators are controlled together by the main corona gap system, and have little effect on the focussing. In normal operation, the electron current in the ion source is between 50 and 200 milliamperes and the ion current to the probe of the order of 1 milliampere. The currents to the shields are low in comparison to the general flow down the corona gaps.

A great deal of difficulty was caused by the distortion of the beam by asymmetry in the tube. It was thought that this effect might be corrected by lining up the tube more accurately, but it was soon evident that mechanical lining up was not sufficiently good. Tests were then made with various tube sections shorted out and the motion of the ~~spot~~ beam noted. The worse offending section was then corrected and, by this empirical process, the ~~spot~~ beam brought to the center of the target. For some reason, possibly because of stray charges on the interior of the porcelain, the position of the ~~spot~~ beam still is rather uncertain, changing as much as a centimeter in position from day to day, or with changes in voltage. In order to use the spot, it was necessary to put a sylphon in the target tube and move the collimating system to suit the spot.

The action of the focussing is not very clear: it seems that the voltage on the first shield is the important one, but its control is subject to the setting of the second shield. As the voltage on the second shield is increased the first becomes more critical, finally reaching a point of instability; at low voltages on the second, the focal spot is enlarged. Best operation is at a needle spacing of about 2 cm.(four needles) on the second shield and 1 to 1.5 cm. on the first.

If the charging current is low, the spot suffers an aberration not unlike astigmatism: it pulsates between a figure of a line perpendicular to the filament, through a circle, to a line parallel to the filament with a frequency which increases as the charging current is increased. When the charging current is sufficient, a uniformly illuminated circular disc about 8 mm. in diameter appears. If the belt flaps, or if the tube voltage is unsteady, the spot may "blow up", pulsating from a small to a large disc, or may move around on the target with approximately the period of the disturbance.

The requirements on tube vacuum for a good ion beam are rather stringent. It is impossible to work with a pressure of higher than 10^{-5} mm. of Hg. and for best operation, a "sticky vacuum", better than 10^{-6} mm. is necessary. These readings are, of course, taken near the pumping system and do not necessarily reflect the conditions in the tube; particularly near the top end, where the gas is let in, the pressure may be quite a bit higher, as high perhaps as 10^{-4} or 10^{-3}mm.

The total current down the tube is measured by a microammeter between the target tube and ground, but is not very accurately known because no precautions were taken to guard from secondary electrons. Actually, it is something of the order of 1 to 10 microamperes, but the meter can be made to read any value between by putting 22 to 90 volts in series. The actual current in the spot is measured by the arrangement in Figure 8 where the negative slit, itself shielded from direct bombardment, prevents electrons from leaving the target and electrons starting higher up in the target tube from reaching the target. The total current indicated here is of the order of 5 microamperes. The current in the proton spot, magnetically separated, is about a third of a microampere, and in the mass two spot - singly charged H_2 molecules - about three times as great. The remainder of the current is apparently in the background of heavy ions or protons which have suffered collisions and have less than the maximum energy. As the hydrogen pressure in the ion source is increased, the ratio of mass ~~two~~ one to mass ~~one~~ two increases, as would be ? expected.

No attempt has been made as yet to investigate the homogeneity of the beam, but the character of the thin target curve, Figure 7, indicates that one may safely put an upper limit of 20,000 to 30,000 volts, or about two to three percent. It is quite probable that the homogeneity is better than this figure would indicate, because no allowance has been made in it for target thickness. When the machine is running properly, the magnetically deflected spot does not move perceptibly - a variation of one percent could easily be detected - and will remain in one place for hours with almost no attention.

Suggested improvements:

On the whole, the performance of the machine has been quite satisfactory. It has required a good deal of maintenance, particularly in the vacuum system, and in the electrical circuits associated with the ion source. Some difficulties with sparks puncturing condensers have occurred, but have been eliminated by electrically shielding them from the high voltage discharges. The low pumping speed at the top of the tube and the high pressure in the tank have made it necessary to have the seals very vacuum-tight, and some parts, particularly the filament lead-ins seem to develop leaks in operation, presumably due to heating of the ion source.

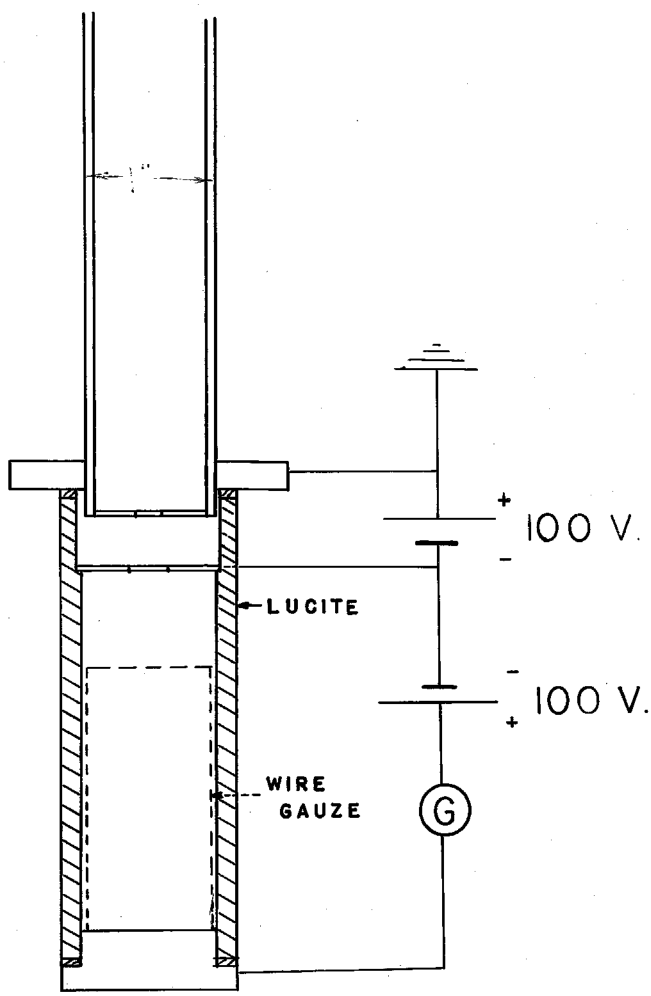

Fig. 8 Measuring System in Target Tube

It has appeared that the current necessary for operating the outfit with positive ions is quite small - of the order of 200 microamperes - and one could easily get along with one charging belt of 12 to 18" width. The space so saved might be used to advantage by making the tube larger in diameter, say 12". One might then obtain larger ion currents and have less vacuum trouble.

The importance of having the potential well distributed down the bakelite columns cannot be over emphasized: it might be worth while to substitute porcelain columns with corrugations to give a path length equal to that down the tube and tie them in to the distribution system.

In view of the difficulty of keeping the focal spot in one place on the target, it would be well to insert overlapping shields in the top four or five sections of the tube to prevent any charges on the porcelain from affecting the beam. According to Herb[8], some discharging takes place down the inside surfaces of the porcelain, and it might be well to corrugate these surfaces.

A few minor points that deserve attention are the following: All electrical connections in a vacuum must be made positively; two surfaces, even when pressed together with considerable force, may have quite high resistance. Set screws or soldered connections are strongly recommended. The parts of the vacuum system that might give trouble with leaks - the ion source, valves, target holders, etc. - should, if possible, be made so they can be enclosed in a bell-jar which can be evacuated for testing: reducing the outside pressure on a joint to a few centimeters is an excellent way of testing it. Valves placed in the system at such places as to isolate the parts are also very useful in localizing leaks.

III. Application of the Generator to the Study of the Fluorine-Proton Reactions

A. Introduction

The Fluorine-proton reactions have received a good deal of attention in the literature for several reasons. In the first place, since F^{19} is one of the three elements in the first row of the periodic table which have only one isotope each, the experimental conditions are particularly unambiguously defined. The relatively high yield from the reactions also aids the experimenter. The possibility of treating the intermediate nucleus, Ne^{20} as a system of five alpha particles tends to simplify the theoretical discussion - one might, for instance, expect rather general restrictions on spin and symmetry to hold which would prohibit certain modes of disintegration and reduce the number of possibilities. Despite these advantages, however, some features of these reactions are still not well understood, and it is the object of this work to obtain additional information on these unclear points.

The present state of the information on $(Ne^{20})^*$ can best be illustrated by the energy diagram in Figure 9. Here, on the left side, are plotted values of total energy of the atom in terms of mass units from 19.998 to 20.020, while, on the right, for convenience, the scale is raised by the mass of one alpha particle, 4.0039 mass units.* The combination $H^1 + F^{19}$, or 1.0081 + 19.0045, is plotted at the level 20.0127 (to show the penetration of the proton through the barrier of F^{19}, this barrier has been raised by the mass of one proton). The mass of Ne^{20} is plotted at 19.9988, or just 12.84 Mev. below $(Ne^{20})^*$, $O^{16} + He^4$, with a barrier representing the escape of an alpha particle from the Ne^{20} nucleus is 20.0039 (16.000 + 4.0039). The ground state of O^{16} (16.000 m.u.) is represented on the right (with 4.0039 m.u. shift in zero) while the barrier representing the escape of an alpha particle from O^{16} - i.e. the combination $C^{12} + He^4$ (12.0040 + 4.0039) starts at 16.0079.

* The masses used are Bethe's - reference 15.

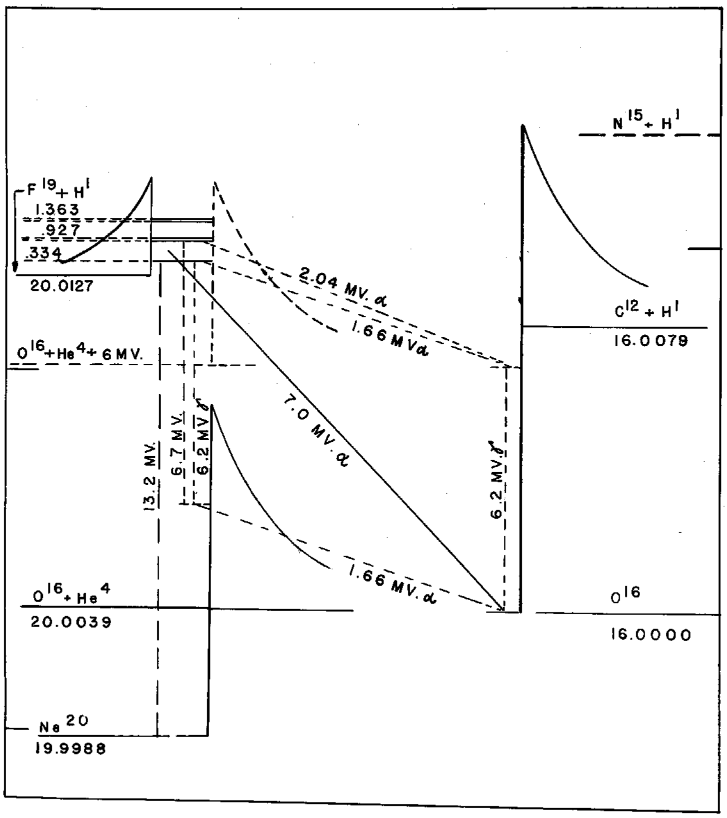

Fig. 9 Energy Diagram of the F-p Reactions

By the barriers are to be understood that any system lying below the line 20.0039 on the left, or below 16,0078 on the right, is energetically prohibited from disintegration with ejection of an alpha particle. It follows from the relatively high binding energy of the proton in the nucleus and from the high mass of the deuteron that their ejection from the O^{16} is impossible. For example, $N^{15} + H^1$ is 15.0049 + 1.0081 = 16.0130, or some 4 Mev. more energy than is available.

It has been found by experiment that the reaction gives 5.90 cm. (7.0 Mev.) alpha particles[16], with a yield which increases approximately exponentially with bombarding energy, and a single 6.0 Mev. gamma ray line[17]. The gamma ray yield has been shown to exhibit very sharp resonance at bombarding energies of 0.334, 0.479, 0.660, 0.862, 0.927, 1.335, 1.363 Mev.[7,18] A yield curve, made by Bernet, Herb and Parkinson,[18] is reproduced in Figure 10.

From the close agreement of the energy excess (Q value) of 7.95 Mev.[16] (5/4 x 7.0 + 15/16 x 0.85) with the mass difference of 8.14 Mev. it is obvious that the long range, non-resonant alpha particles are the result of disintegrations which leave O^{16} in its ground state, or nearly so. From the absence of any indications of either a 13 Mev. or a 7 Mev. gamma ray, one must conclude that the transition to the ground state of Ne^{20} is forbidden and that the observed gamma ray must be accompanied by a short range alpha particle and represent again a reaction leaving O^{16} in its ground state, either by emission of the gamma ray first and a drop to an excited state of $(Ne^{20})^*$ and subsequent ejection of a short range alpha particle, or by ejection of the alpha particle first leaving $(O^{16})^*$ in a state excited by 6 Mev. which subsequently decays with emission of the gamma ray. There is, of course, the possibility that the mass of Ne^{20} or of F^{19} could be incorrect and that there are two successive 6 Mev. gamma ray emissions to normal Ne^{20}, but this is very unlikely.

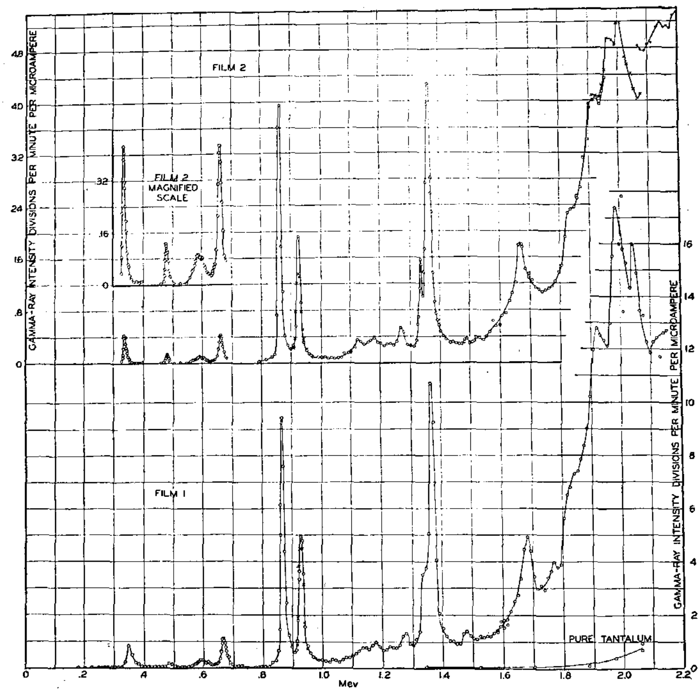

FIG. 2. Gamma-ray intensity *vs.* energy of bombarding ions.

Fig. 10 Gamma-ray Yield from F^{19} - H^{1} (ref.18)

At the time when the present investigation was undertaken, the short range alpha particles had not yet been found.[16] Because of their short range, they presented considerable difficulty, both because of the necessity of having an extremely thin window in the side of the target tube and because the protons scattered from the beam by the target would have nearly the same range as the alpha particles would be expected to have. At the higher resonances, the problem would be still more difficult, because there the proton range would actually exceed that of the alpha particles.

Lacking confirmation of the above proposed course of the reaction through the alpha particles, one might be able to establish it by measuring the gamma ray energy as a function of bombarding energy. If the gamma ray energy does not shift, it must represent a drop from a level in O^{16}, since otherwise it would take up the excess energy of the proton. Even if the double drop to the ground state of Ne^{20} occurs, one compdnent of the gamma ray would shift a detectable amount. Of course, if the gamma ray energy does shift, one might still have an alpha particle coming from the $(Ne^{20})^{**}$ level, although one would then have some difficulty in explaining the high intensity of the gamma ray.

The fact that the character of the reaction at the resonance is quite different from that in the continuum would suggest the possibility of differences between the behaviour at various resonance levels. The extreme irregularity of the yield curve would seem to lend weight to this supposition, since, for identical states, one should expect a monotonic dependence of the yield at various levels on bombarding energy. In particular, one might suspect the two components of the doublet at 0.862 and 0.927 Mev. of being quite different.

With the discovery of the alpha particles by McLean and Becker[19] the problem was somewhat simplified: there can now be no doubt that the reaction is as indicated. There remains, however, the question as to whether the alpha particles or the gamma rays come off first and whether the reaction is the same at the higher resonances where the emission of the alpha particles cannot be confirmed. It was to settle these points that the investigation to be reported was undertaken.

B. Experiment :

The experimental arrangement used is shown in Figure 11. The protons coming down the tube are collimated by a series of slits, and separated from the rest of the beam by magnetic deflection. On a level with the center of the cloud chamber, they strike a target of CaF_2, on a copper backing. The resultant radiation passes through the lead slit system and ejects positive and negative electron pairs from the lead foil in the chamber. The electron paths are bent in a known magnetic field and their tracks photographed stereoscopically. From the curvature of the tracks measured in reprojection, the energies are deduced by the relation:

$$E = .51\left\{1+\left(\frac{H\rho}{1700}\right)^2\right\}^{1/2} + .3 \quad \text{Mev.}$$

Where H is the magnetic field in gauss, ρ is the sum of the radii of curvature of the two components of the pair, and the energy is expressed in Mev. The .3 Mev. is added to take into account the energy loss of the electrons in the lead foil.

It was considered advisable to separate the proton component from the rest of the beam, both because the analysis acts as a voltage check - when discharges occur, the spot goes off the target - and to avoid contaminating the target with carbon. Thick targets were used because the two high resonances are so strong that any difference in their character would show up very easily: thin targets would be a little better but are more difficult to keep in good condition.

At the high resonances the intensity was so great that the resultant electrons and positrons became confused in the chamber. Particularly because of the large number of single electrons, produced by Compton processes in the wall of the chamber and the surrounding material, pairs were difficult to find and rather uncertain because of the possibility of coincidence of single electrons with single positrons coming from unsymmetrical pairs. To decrease the relative number of

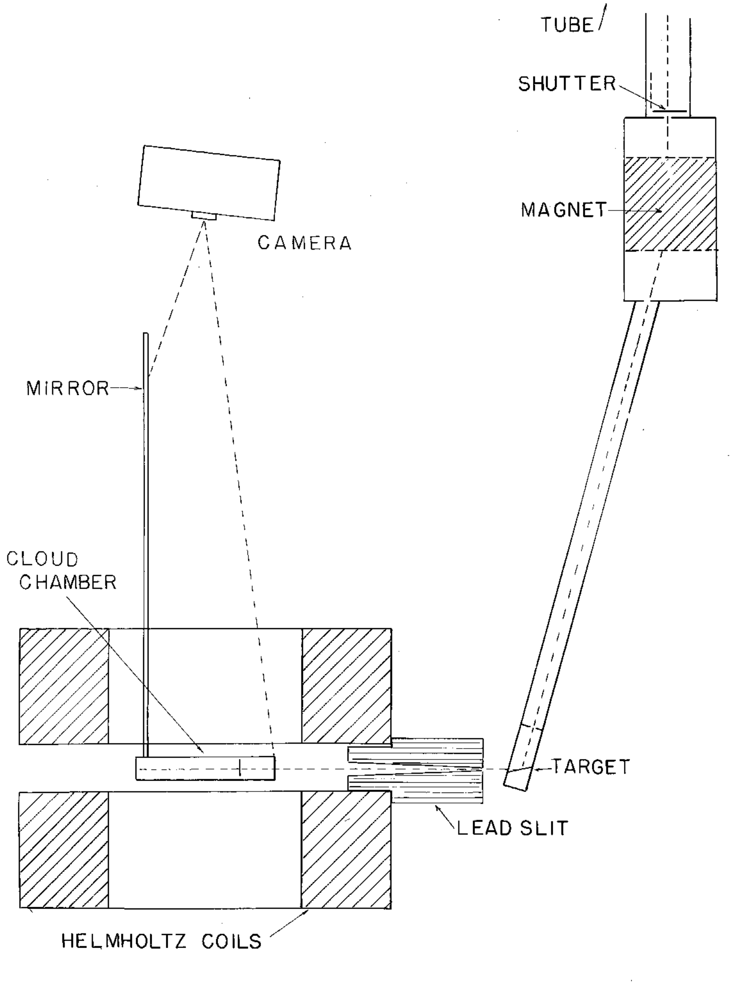

Fig. 11. Experimental Arrangement

Compton electrons, a thin window was put in the chamber wall and an effort made to collimate the gamma ray beam to prevent scattering in the surrounding material. Since then a larger fraction of the electrons come from the lead foil in the chamber, ~~and~~ the confusion is considerably diminished. Lead is used as the foil because the probability of pair formation increases as the square of the atomic number and represents, at 6 m.v. in Pb., about one half of the total absorption. The piece used here was .010" thick, so that electrons originating on the target side lost .3 Mev. each.

In order to avoid "old" tracks - tracks formed by ions left over from some time before the expansion which have suffered such diffusion as to be valueless - the proton beam is cut off by an automatically operated shutter until after the expansion has taken place, only slightly before the camera is tripped. By this means, one obtains a high percentage of clear sharp tracks.

The chamber was operated by motor-driven switches, on a 15 second cycle, so that about 250 pictures per hour could be taken. At the highest intensity, about five to ten percent of the pictures contained acceptable pairs, while at the lower intensities less than one percent were useful.

Curvatures were measured by matching with celluloid cards, ruled with circular arcs at .5 cm. intervals. Only those pairs were taken which could be confirmed as coming from the lead foil and which pointed toward the target. Ordinarily, it was possible to eliminate coincidental pairs if the two components originated more than 2 mm. apart in the lead. It is estimated that less than one percent of the pairs can be spurious.

In order to reduce as far as possible the error due to fluctuations in the magnetic field, the coil current was read during nearly every expansion by means of a null potentiometer and held constant to within 1/2%. The absolute value of the field was checked against an accurate standard solenoid by means of a search coil and a Grassot flux meter several times during the course of the experiment and is considered to be accurate to better than 1 %.

The remaining error due to the spread in measurement of the tracks was brought to the same order of magnitude as the magnetic field uncertainty by taking enough pairs and choosing an appropriate magnetic field value. The uncertainty of fitting a given track is largest for extremely high and extremely low curvatures, so a field value was used which gave an average radius of about 8 cm. for one component of a 6 Mev. pair. As a check, and to eliminate a tendency to discriminate against higher energies, a series of pictures at a somewhat higher field were also taken. The error in measuring a single 8 cm. track of about 5 cm. length (the minimum length used) is estimated to be five to ten percent, so that fifty to one hundred pairs should establish a mean to a precision of about one percent. The principal cause of this uncertainty is scattering: some of the tracks suddenly change direction at some point and tend to disturb the measurement of the curvature. This error is not quite a symmetrical one, as the scattering away from the direction of curvature is easier to detect than one which is toward it, tending to shift the mean slightly toward the low side. The tendency to assign too much curvature to tracks which are nearly straight is another factor causing some displacement toward the low side; for this reason, symmetrical pairs, in which both members have reasonable curvature are given slightly more weight in computing the average.

C. Results

The pairs obtained at 1 m.v. bombarding energy are plotted in Figure 12, and those at 0.334 Mev. (obtained by using the molecular spot at .850 Mev.) are plotted in Figure 13. The pairs are grouped in non-overlapping intervals of 2 cm. radius of curvature, or about .5 Mev. The mean value of the principal line, computed directly from the measured radii, is 6.33 Mev. $\pm$ .1 Mev. for the resonances up to 1 Mev. (mainly the two at 0.862 and 0.927 Mev. and 6.2 $\pm$ .2 Mev. at the 0.334 resonance). A shift of 0.600 Mev. would be more than three times the probable error, so it is reasonably certain that no shift occurs.

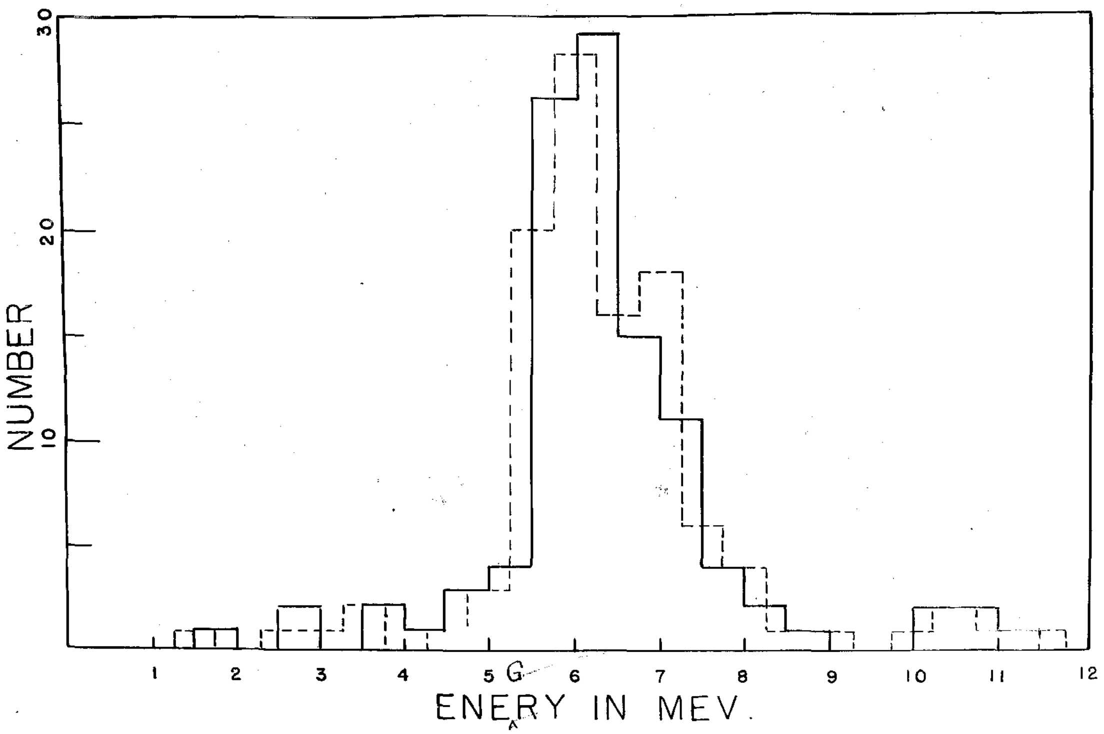

Fig. 12 Pairs at 1 Mev. Bombarding Energy

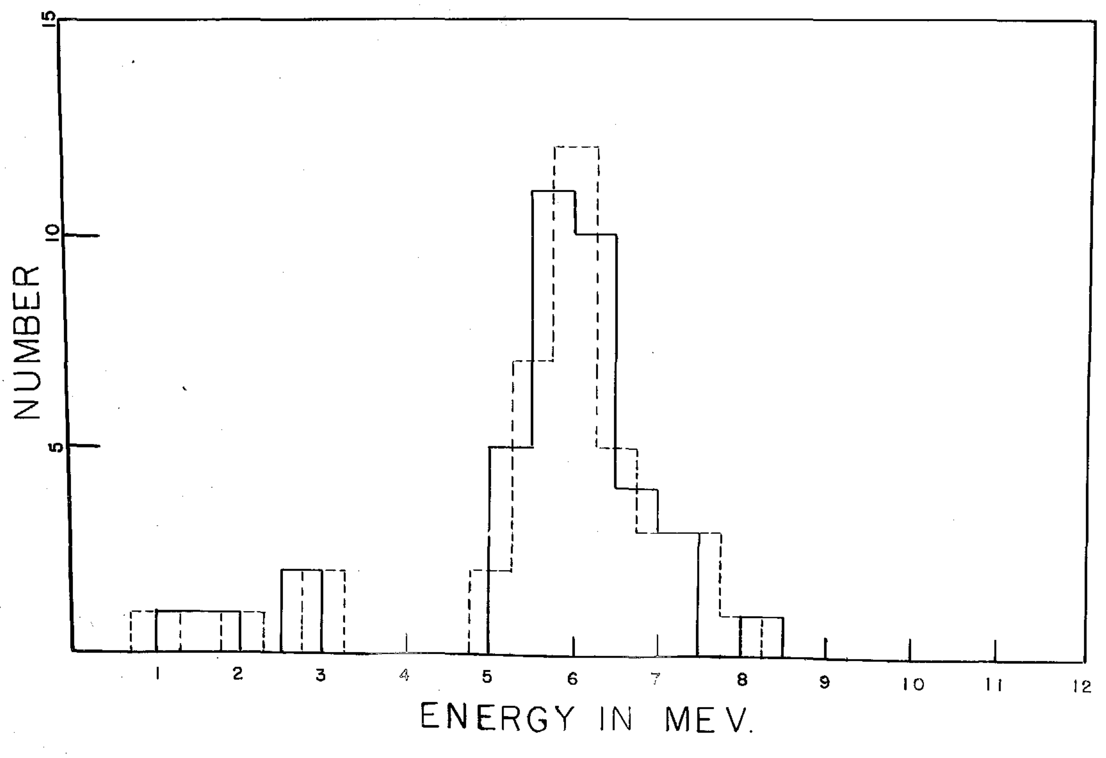

Fig. 13 Pairs at 0.334 Mev. Bombarding Energy

There is some evidence for a line at 10.5 Mev. appearing at the high bombarding energy, but it is certainly less than 5% of the main line and could conceivably be due to contamination by boron or lithium. It is possible that one of the small resonances allows a drop to a 3 Mev. state in $(Ne^{20})^{**}$ with the emission of a 10.5 Mev. line and then a further drop to the ground state, giving a 3 Mev. line, but the evidence is not very good. In such a case, one would not expect to find many of the low energy pairs because of the low cross-section for pair formation at that energy, A series of pictures should be taken at each resonance, using thin targets, to trace this radiation, but the low intensity makes such a process rather tedious.

It seems quite clear, however, that the 0.862 and 0.927 Mev. resonances do not differ markedly from the lower ones, and that the gamma ray does not take up the excess bombarding energy. The fact that the line is somewhat broader at the high resonances might indicate the appearance of a 7 Mev. line in one of the resonances and requires some further investigation.

Theoretical Discussion

The character thus established for the Fluorine-proton reactions has rather interesting theoretical implications which can best be understood by reference to the dispersion formula[20], governing the probability of various nuclear processes. The expression given by the theory for the cross-section for the process giving rise to the product Q from the entry of a proton into the nucleus is:

$$\sigma^{p}_{Q} = \pi \lambda^2 K \frac{\Gamma_Q \Gamma_p}{(E-E_0)^2 + \frac{1}{4}(\Gamma_p + \Gamma_Q)^2}$$

where Γ_Q is a measure of the probability of the ejection of the particle Q, and $\lambda^2 \Gamma_p$ is a measure of the probability of entry of the proton into the nucleus. E is the total kinetic energy of the particles in the nucleus, and E_0 is the energy of a stationary state of the motion of these particles. K is a factor depending upon the angular momenta. If the energy brought in by the proton is just sufficient to raise the total energy to a value corresponding to a stationary state of the configuration in which the particle Q has a large part of the energy, the decay of that state, or the probability of the particle's actually leaving the nucleus, is expressed by the formula. Because of the term $E-E_0$ in the denominator, the cross-section exhibits resonance. The "damping factor", $(\Gamma_p + \Gamma_Q)^2$, is a measure of how precisely the energy of the system must correspond to E_0 before it has an appreciable probability of decaying. The greater the resonance width, the shorter the lifetime of the state, for, by the uncertainty principle:

$$\Delta E \, \Delta t \sim \hbar \qquad\qquad \Delta E = \Gamma_Q + \Gamma_p$$

Large width and short lifetime do not necessarily imply high probability of disintegration, since the cross section depends on these factors in such a way that it is a maximum for $\Gamma_p = \Gamma_Q$, and so is limited by the smaller factor.

The Γ factors may be broken up into two parts: A "P" factor expressing the probability that the particle can penetrate the barrier once it is excited to a state where it has enough energy to exist outside the nucleus, and a "G" factor, expressing the probability that the particle in question can be formed with that energy. The P-factor has a relatively slow increase with energy:

$$P = e^{-\int_R^{r_E} \{2M\,[E - V(\rho)]\}^{1/2} \frac{d\rho}{\hbar}} \qquad (21)$$

while little is known about the G-factor's dependence on energy. According to the conception of a many-body model, on which the whole of this treatment is based, the probability of formation of alpha particles, protons, and neutrons is about the same, while that of the deuteron or any other particular association is much less, because of the high mass energy which would have to be furnished for binding. The probability of finding the nucleus in such a condition that it could emit radiation (dipole, quadrupole, etc.) decreases with increasing complexity of the radiation and is in all cases small. (G of order of 1 Mev. for alpha particles in light nuclei, and 0.1 volts for gamma radiation). The value of G may be considerably modified by selection rules which slow up the process and thus give the system time to define its energy.

In the case of the F-p reactions, it is clear that the $(Ne^{20})^*$ may exist in two quite separate states: one giving long range alpha particles with a yield which may be said to have a resonance width of the order of 1 Mev., and one giving short range alpha particles which have very sharp resonances - of the order of 5 kv. wide. Now the fact that the width in the first case is so great is an indication that the disintegration takes place in a very short time, for by the uncertainty relation, if ΔE is of the order of 10^6 volts, Δt is of the order of 6×10^{-22} sec, or about the time that a 1 Mev. proton would take to go across the nucleus, about 10^{-13}cm.[22] The fact that the disintegration occurs so rapidly may be taken to indicate that no exclusion rules apply. Since the alpha particle and normal O^{16} have spin 0, and F^{19} almost certainly has spin 1/2, the conclusion is that the proton with spin 1/2 is captured with its spin opposing that of the F^{19}, i.e. into a singlet state of $(Ne^{20})^*$, in this case.[23]

If the proton is captured into a triplet state, i.e. with its spin added to that of the F^{19}, one would expect the very general requirement of spin conservation to preclude the direct emission of a high energy alpha particle leaving O^{16} in its normal state. Instead, the nucleus would have to remain together until the excess spin could be converted into angular momentum by the very loose coupling between spin and angular momentum, which would slow the reaction down by a factor of 10^4,[23] or would have to disintegrate with the emission of a short range alpha particle, leaving $(O^{16})^*$ in a triplet state, which would later rearrange itself and decay by gamma ray emission to normal O^{16}. It is probable that both modes of disintegration occur; that at resonance both the long and the short range alpha particles appear, with the short range having the higher intensity.[9] The fact that the alpha particle comes off before the gamma ray is consistent with high yield, as the gamma ray width is very small and would hardly be able to compete with the long range alpha particles, even from the triplet state.

Attempts to calculate the cross-section for alpha particle emission from the triplet state as a function of bombarding energy have been made, assuming that the dependence on energy is largely determined by the P-factors, with only a slow variation of the G's. The function so obtained can be made to have a flat maximum around 1 Mev., but the ratios of the yields so obtained is not consistent with those given by experiment,[18] and it does not seem that the theory is very satisfactory in this application. While some statements can be made as to the character of the yield curves, they are necessarily of a statistical nature, applying only over very broad energy intervals. One thing, however, seems reasonably certain: the great variation shown in the experimental curve indicates that the processes giving the various resonances can hardly be identical. One would suspect differences of spin, parity or angular momentum to enter, and change the yields. It is, in view of this fact, a little surprising that the gamma ray shows no more change than it does. Certainly more work, both experimental and theoretical, is indicated on this problem.

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