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Application of a Pressure Electrostatic Generator to the Transmutation of Light Elements by Protons

TOM LAURITSEN, C. C. LAURITSEN AND W. A. FOWLER
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

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The design and performance of a pressure electrostatic generator capable of operating at 1.7 Mv in a cylindrical tank of over-all length 13′ 6″ and diameter 8′ at a pressure of 80 lb. per square inch is discussed. Studies of the gamma-radiation produced in the transmutation of F^{19}, N^{15} and C^{13} by protons are also reported.

INTRODUCTION

THE discovery of resonance processes in the transmutations of the light nuclei has necessitated the use in transmutation experiments of ion beams homogeneous in energy to a few kilovolts with total energies of several million volts. Herb[1] and his collaborators at the University of Wisconsin have demonstrated that the pressure electrostatic generator is capable of delivering over a microampere of analyzed ions with energies up to 2.6 Mev and homogeneous to one-half of one percent in energy, and have recently demonstrated that ions with energies up to 4.5 Mev, or even higher, can be secured without increasing the dimensions of the generator. The fact that these beams can be focused to a diameter of several millimeters even at relatively large distances from the generator has been shown to be a great advantage in regard to the accessibility of auxiliary apparatus, the freedom from extraneous radiation, and the possibility of high precision in employing point sources. During the past several years we have constructed and operated a pressure electrostatic generator similar in principle to the Wisconsin generator but differing in several details which merit some discussion at this time. Numerous electrostatic generators have been constructed and operated during this period. A short historical review of the development of the pressure electrostatic generator is included in a recent publication describing the generator of the Westinghouse Research Laboratories.[2]

GENERAL DESIGN OF THE GENERATOR. THE HIGH POTENTIAL ELECTRODE AND PRESSURE VESSEL

The generator constructed in this laboratory differs from the Wisconsin generator in being vertical rather than horizontal. This choice of arrangement was dictated by two considerations; first, the high vacuum ion tube can be built completely self-supporting and free from vibrations of the moving generator apparatus, and second, a convenient laboratory arrangement has been found to be one in which the generator equipment is located on a floor above an observation room into which the target tube of the generator projects.

An essential difference in the design of the present generator is the use of a re-entrant system in which the charging belts are contained on either side of the accelerating tube in a four-cornered porcelain structure which supports the corona hoops and the hemispherical high potential electrode. The entire structure is enclosed within a cylindrical air pressure tank with standard belled ends as shown in Fig. 1.

The equipotentials in this type of generator should be somewhat pear-shaped with the top roughly hemispherical about the high potential terminal, the extension at the bottom being governed by a voltage distribution system to be described later. From the best estimates available, it was decided that a tube length, belt length and support member length of about 8 feet should be sufficient for 2 Mv at 5 or 6 atmospheres 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

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[1] Herb, Parkinson and Kerst, Rev. Sci. Inst. **6**, 261 (1935); Phys. Rev. **51**, 75 (1937); Parkinson, Herb, Bernet and McKibben, *ibid.* **53**, 642 (1938); Herb, Turner, Hudson and Warren, *ibid.* **58**, 580 (1940).

[2] Wells, Haxby, Stephens and Shoupp, Phys. Rev. **58**, 162 (1940).

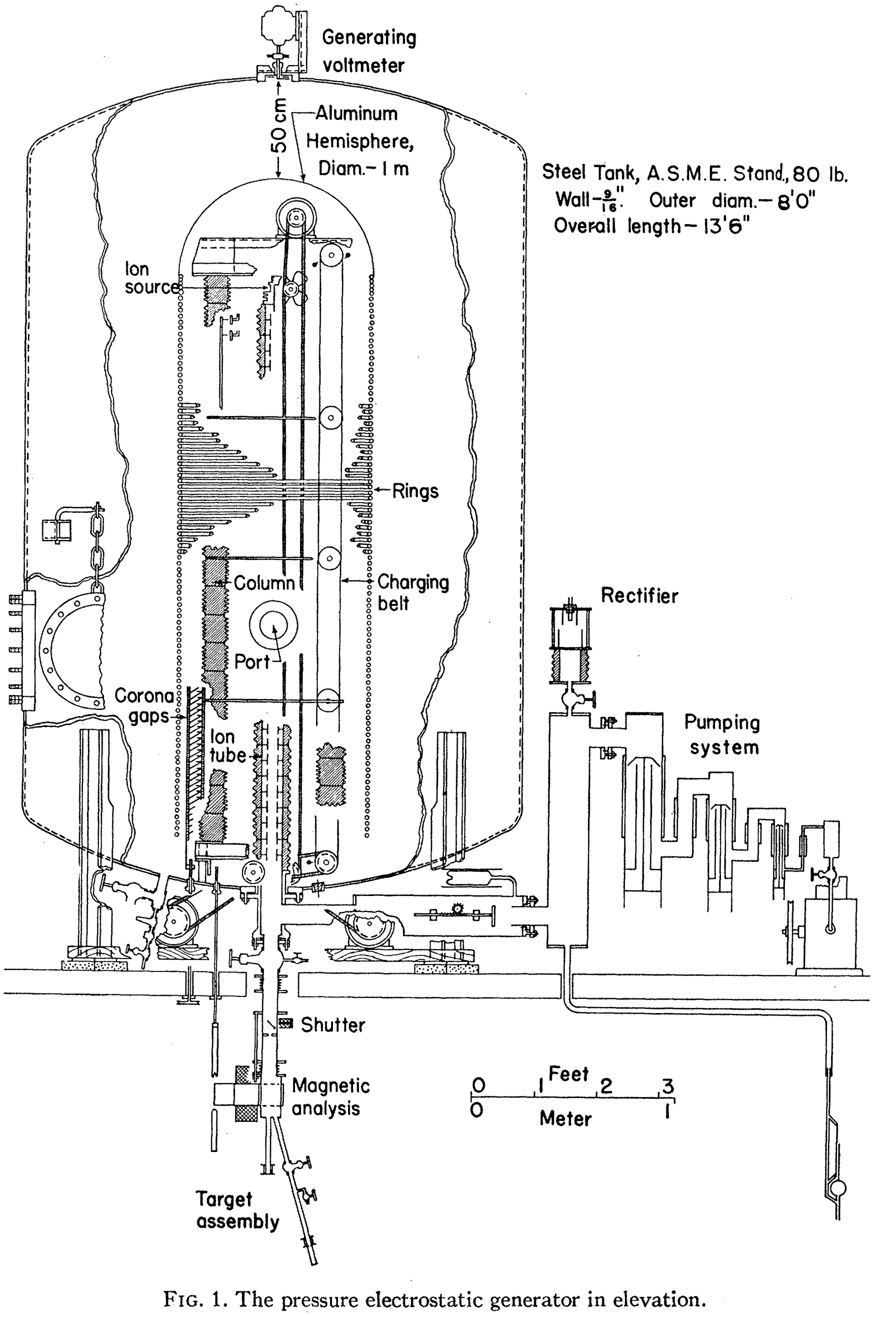

FIG. 1. The pressure electrostatic generator in elevation.

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 radius of 26.6 cm should be sufficient for 2 Mv at a pressure of 5 atmospheres. However, in view of the fact that one rarely gets within 50 percent 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. Subsequent alterations have reduced this distance to approximately 50 cm. From experiments with grounded walls arranged around a smaller generator constructed in open air, 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 a 1 : 2 ratio of inner to outer diameters concentric cylinders have a field strength at the inner cylinder equal to 72 percent of the field strength at the inner sphere of concentric spheres of the same radii. However, it must be noted that hoops spaced by roughly their diameters make up the "cylindrical" surface in the actual generator, and that the field is thus higher. A high potential terminal somewhat more than hemispherical, supported on a cylindrical column of smaller radius is to be recommended. The hemispherical terminal was spun from aluminum sheet and was turned over a steel hoop of $\frac{5}{8}$-inch section diameter at the periphery. Such a terminal can be lifted easily out of place by one operator when work on the upper end of the generator is necessary. Electrostatic forces can also raise it so it must be held firmly to the generator structure. For convenience in construction, the tank[3] was made cylindrical, rather than pear-shaped, with standard dimensions of 8 feet diameter, 10 feet shell length and 13 feet, 6 inches over-all length, with an 18-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.

Supporting and Insulating Columns. Corona Hoops and Gaps

In the original construction all parts of the apparatus were supported on a square tower constructed of 2-inch $\times \frac{1}{2}$-inch strips of Bakelite. A laminated Bakelite with a paper base and resinoid binder was employed. At voltages near 1.0 to 1.2 Mv considerable sparking was observed along these Bakelite members and subsequent examination showed that sparking and burning had occurred inside the material between the laminations. The Bakelite columns have been replaced with columns consisting of 20 porcelain stand-off insulators connected end to end with $\frac{5}{8}$-inch steel studs. Horizontal steel supports at the quarter heights have been found to give sufficient mechanical stability.

Corona rings made of $\frac{5}{8}$-inch aluminum tubing rest in the corrugations of the porcelain insulators. Light springs in the bottom of the corrugations make contact between the porcelain surface and the rings. The rings can be snapped from corrugation to corrugation with some ease for making accessible the interior of the apparatus.

To improve the stability a set of negative point-to-plane corona gaps, adjustable from outside the tank, which serve to distribute the potential along the ring system, have been installed. The tube and the supporting columns are subdivided by conductors in the grooves of the porcelain elements. Each conductor is connected to a corresponding ring and between adjacent rings are connected the corona gaps. The necessity of electrical connections between all conductors and the gap system cannot be overemphasized.

The corona current constitutes the principal drain of the charge on the dome, and the large steady current flowing in the gaps minimizes the effect of small erratic discharges, and in this way helps to maintain a constant tube potential. The characteristics of the gap system are illustrated by the following data: When the tube is operating at 1 Mv, it is most convenient to use a tank pressure of 60 lb. per sq. in. and a gap separation of $\frac{3}{8}$ inch: under these conditions the current through the corona gap system is about 40 microamperes. To obtain a large corona current, the gap separation is kept as low as possible; of course, as the voltage is raised, the separation must be increased to prevent sparking. The corona current from a grounded needle, extending inward from a position on the wall of the tank just opposite the dome provides an additional current drain on the high potential end of the generator to improve still further the voltage stability. The length of the needle extending inside the tank wall may be varied during operation; it is normally about 1 inch. The

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[3] The tank was fabricated by the Pacific Iron and Steel Company of Los Angeles. The wall thickness is $\frac{9}{16}$ inch and the working pressure is 80 lb. per sq. in.

corona current from the needle is of the order of 40 microamperes.

As a result of modifications which it has undergone, the ring system is at present in poor condition; the rings are not uniform in size nor true in shape, and the surfaces of some have been marred. It is believed that the replacement of the rings, especially those near the high potential end of the generator will increase the maximum operating potential. The size and shape of the porcelain elements of the supporting columns are such that an equal spacing of the rings is inconvenient. Moreover, with the present spacing, and with the focusing electrodes connected to the ring system, it is impossible to load equally the several sections of the tube. It is believed that when these conditions are rectified, an appreciable increase in maximum operating potential will be realized.

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 in the system. A convenient arrangement was with two 24-inch belts symmetrically arranged about the center. 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, a saturation value of 2.7×10^{-9} coulomb per sq. cm is found, 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 were charged by means of a set of spray combs, consisting of a row of pins, spaced at $\frac{1}{4}$-inch intervals across the width of the belt, facing the metal roller on which the belt runs, and $\frac{1}{4}$ inch away. The combs were excited with 5000 to 20,000 volts d.c. which was brought in through an insulated lead-in bushing from a source outside the tank. In the original design, the rollers were covered with $\frac{1}{16}$-inch 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. A doubling system[4] was used at the upper roller to pick up the charge from the belt and spray the downgoing side with charge of the opposite sign.

The mechanical problem of running such a wide belt required some care. The eventual solution was a crowning of about $\frac{1}{2}$ degree for 2 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-inch brass tubing with steel end plugs which carried ball bearings running on a fixed shaft mounted on adjustable hangers. Careful balancing was 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 are driven by two one-horsepower motors outside the tank. The belt tension was 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.

(*Note added in proof.*—A Tilton woven endless belt has recently been installed and found to be very satisfactory especially in regard to smoothness in running.)

The maximum charging current obtained, measured with the terminal grounded, was 360 microamperes per belt, at atmospheric pressure, representing about 60 percent of the theoretical expectation. This current was obtained with 24-

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[4] Tuve, Hafstad, and Dahl, Phys Rev. **48**, 315 (1935).

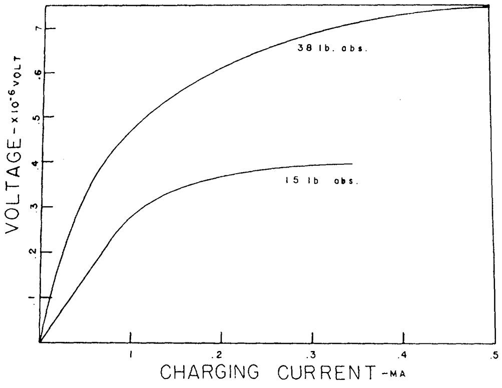

FIG. 2. Terminal voltage *vs.* charging current.

inch 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.

The charging current delivered by a belt varies to some extent with the dryness of the air. At humidities higher than 50 percent, 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 greatly on the surface resistivity of the belt. The fact that a canvas belt, having a very rough surface, gave 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 percent, 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 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. A similar difficulty had never been observed in operating the smaller generator in air. It was found that a wire stretched over the top of the roller in 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 was 280 microamperes per belt. The spray voltage required was, 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 pick-up combs several inches below the point of

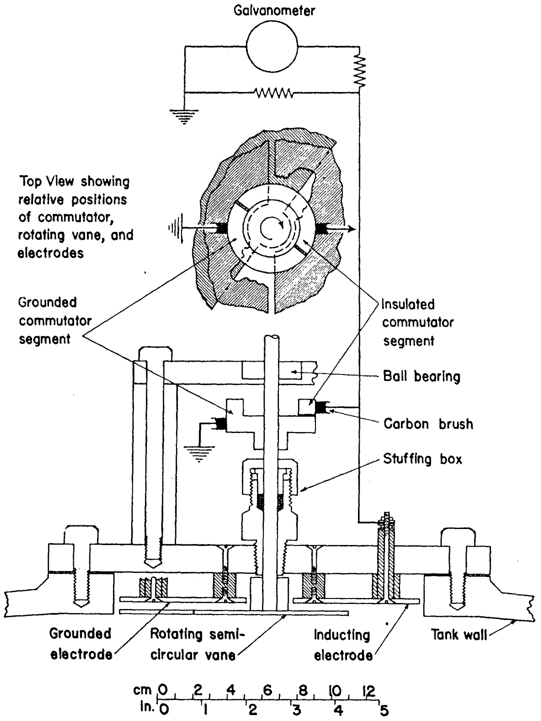

FIG. 3. The generating voltmeter. The grounded sector is driven by a $\frac{1}{8}$-hp induction motor not shown in the figure.

tangency on the roller. With these modifications, the doubler operated quite consistently without outside control, as long as the current was over 100 microamperes.

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 Fig. 2. 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.

When the Bakelite supporting column was replaced by porcelain it was found necessary to reduce the belt width to 16 inches. One belt was removed entirely. Sparking down the remaining belt occurred for voltages near 1 Mv for charging currents exceeding 100 microamperes. The situation was greatly improved by the installation of three sets of guides, equally spaced along the belt. Each set consisted of four $\frac{3}{4}$-inch rods in a horizontal plane, two, separated by $\frac{1}{2}$ inch, serving to guide each side of the belt. They were connected to the nearest member of the ring system, and by their subdividing action tended to equalize the potential gradient along the belt and thus to eliminate high local fields. This arrangement was suggested to us by Dr. E. U. Condon of the Westinghouse Research Laboratories who had successfully employed this method. However, the charging belt was the seat of still another trouble: Its flapping produced voltage fluctuations. The guides could not be effective in preventing this without pressing firmly against the belt, and this was objectionable because of the excessive friction and injury to the belt which it entailed. Therefore each set of guides has been replaced by a single 4-inch roller, similar to the two upon which the belt runs, mounted between the two sides of the belt. They play the same role as the guides in distributing the potential along the belt, and in addition greatly improve the mechanical smoothness of the belt operation.[5]

Air for the tank is secured from the compressed air line of the Radiation Laboratory and is dried by passing over flaked calcium chloride. The air is also circulated over a pan containing potassium hydroxide on the floor of the tank.

VOLTAGE CONTROL AND MEASUREMENT

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 or of the corona needle in the side of the tank. For larger changes in voltage it is preferable to change the tank pressure. At high tank pressures the molecular beam can be used in the lower voltage region.

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

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[5] When the belt is damp, charge cannot be delivered past the first roller. However, this condition never prevails for a time longer than that necessary to pump up the tank to operating pressures and is thus not a serious inconvenience.

electrostatic voltmeter seemed the best because of its zero current drain and its proven reliability.[1] The design finally adopted is shown in Fig. 3: A grounded semicircular sector, driven by an induction motor, alternately covers and uncovers an insulated semicircular plate in the top of the tank facing the terminal hemisphere. The use of a synchronous motor was found to result in the rectification of stray alternating-current fields. The current from the stationary plate is rectified by means of a commutator and carbon brush and is measured by a galvanometer with high resistance in series to minimize currents from contact potentials and shunted to give a convenient sensitivity. To insure recharging of the stationary plate a second brush connects it to the tank on the off half-cycle.

The voltmeter has been calibrated from time to time usually by bombarding thick targets of CaF_2 with protons in the region of the 862-kv and 927-kv resonances. Even over extended periods of time the voltmeter calibration has been reproducible within 1 percent accuracy. A calibration run in which a thick lithium target was bombarded with the molecular beam and a thick calcium fluoride target with the atomic beam indicated that the values 880, 862 and 927 kv for the well-known resonances in these cases are internally consistent to better than 0.5 percent. Additional observations on the resonances on $F^{19}+H^1$ at 334 kv and 1363 kv, and in Li^7+H^1 at 440 kv checked the linearity of the voltmeter scale to 1 percent. The laboratory intercomparison standards first set up by Tuve[6] and collaborators and extended by Herb[7] have been of inestimable value in the work with this generator.

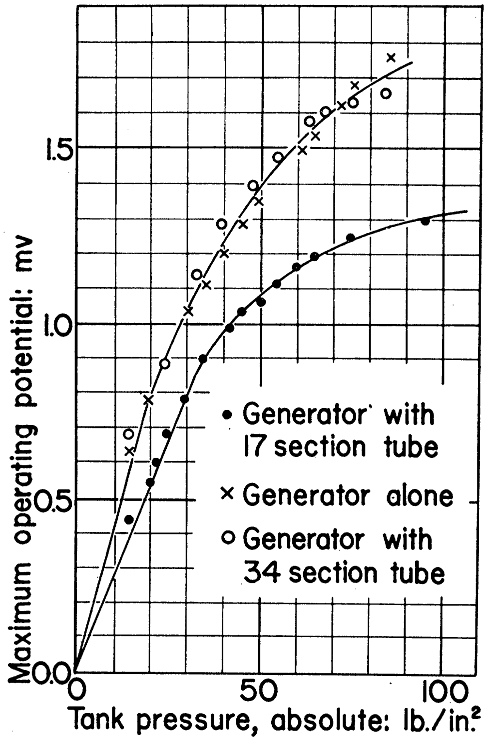

FIG. 4. Maximum operating voltage *vs.* tank pressure.

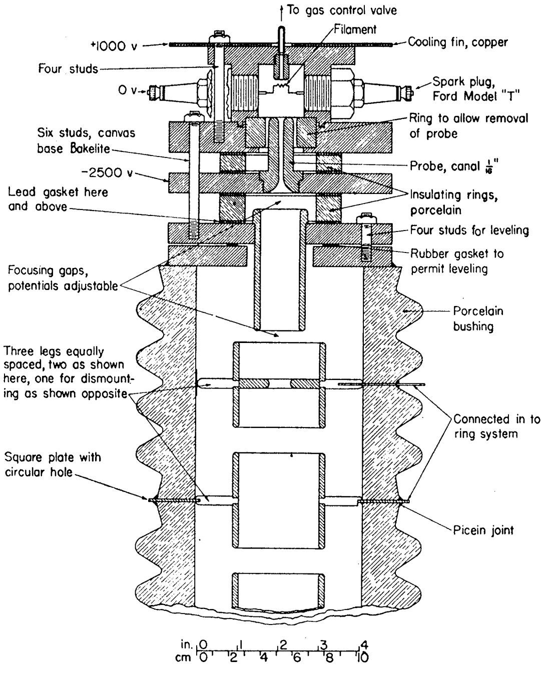

FIG. 5. The ion source and first tube sections.

ACCELERATING TUBE

In the selection of the type of tube to be used, an appeal was again made to previous experience. The use of the short ion path tube in this laboratory has shown its advantages of less critical focusing 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 of distributing the potential in the tube would tend to offset these

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[6] Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 504 (1936).

[7] Bernet, Herb and Parkinson, Phys. Rev. **54**, 398 (1938).

advantages however: An 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 focusing 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 focusing sleeves were made 2 inches in diameter, $5\frac{5}{8}$ inches long, and spaced $\frac{3}{8}$ inch apart in 6-inch 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 inches 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. With the $5\frac{5}{8}$-inch focusing electrodes the tube consisted of seventeen accelerating sections. The maximum operating voltage was found to be 1.3 Mv and after numerous attempts in redistributing the voltage had failed to raise this maximum it was decided that the potential was limited by breakdown inside the tube. Examination of the focusing electrodes showed their surfaces at the ends to be pitted, thus confirming this view. To remedy this situation the cylindrical focusing electrodes have been replaced by another set in which the size of the gaps was increased from $\frac{3}{8}$ inch to $\frac{5}{8}$ inch, and their number doubled. The maximum operating voltage has been increased from 1.3 to at least 1.7 Mv; the results of the tests of the operating voltage are shown in Fig. 4. The dimensions of the new electrodes differ from the old only in that the length is 2 inches. This alteration introduced no difficulties in focusing. From our experience the maximum operating voltage is 75 kv per section with 50 kv per section a safe limit.

The ion source (Fig. 5) used was copied from the type formerly used at this laboratory on other tubes.[8] In it the electrons emitted from the hot filament are drawn by a potential of 1000 volts through a region at a pressure of the order of 10^{-3} mm of Hg of the gas to be ionized, and the ions so formed drawn out by a probe at a negative potential of 2500 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 focusing, two small accelerations are provided, controllable from outside the tank by means of adjustable needle gaps. To bridge between the $\frac{1}{16}$-inch diameter of the canal and the 2-inch diameter of the sleeves in the tube, the first focusing sleeve was made 1 inch in diameter and is connected to the first ring below the terminal. The second accelerating shield is connected to the second ring. The remainder of the gaps are connected to corresponding corona gap sections.

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 ion source is cooled by a small fan. The filament, a seven-turn helix of 0.013-inch tungsten, is heated by means of a low voltage transformer, and its temperature, controlled from outside by means of a rheostat, determines the current at any given gas pressure. Gas is supplied from a small tank at high pressure and controlled from outside by a rubber disk valve. All controls are brought down by $\frac{3}{4}$-inch hard rubber 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.

The tube is exhausted by three oil diffusion pumps in series, with a Cenco Hypervac as forepump. The oil pumps have successive diameters of 3, 5 and 8 inches. Valves placed at strategic places in the pumping line and target assembly make it easy to isolate and find leaks in the vacuum system. Brass, wedge-disk, gate valves with nonrising stems have been found to be convenient for this purpose.

THE PRODUCTION OF X-RADIATION

As has been indicated, some time was spent in investigating the possibilities of the installation

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[8] Crane, Lauritsen and Soltan, Phys. Rev. 45, 507 (1934).

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, focusing depends only on the relative voltages on the lenses, and not at all on the mass of the ions, except for relativistic effects, the main lens system of the tube is suitable either for electrons or positive ions.

It was found that the voltages on the first and second gaps (17-section tube) should be reversed for best operation and that, unless these voltages were fixed by a power supply, electron bombardment could change them and the focal spot would pulsate. Good focusing was obtained by accelerating the electrons to 200-volt energy with the probe, then to 600 volts with the first gap, and then decelerating them back to 200 volts with the second gap. The second gap voltage was found to be quite critical for focusing.

The remainder of the gaps were at the voltage naturally taken up by the corresponding tube sections and did not greatly affect the focusing. With electrons, once the voltages were set, the focusing 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 focusing without much trouble with tube vacuum. Satisfactory operation was 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 some fraction of the beam was lost. Actually, on some occasions, as much as 300 microamperes of electrons hit the 2-inch target, mostly within a 5-mm 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 1.3 Mv.

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 1.3 Mv and 100 microamperes, was 17 roentgens per minute at 60 cm with 1 mm Cu and 0.5 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 Mev). With a filtration of 1 mm Pb and 6 mm Fe, the output was 4.0 r per minute, or about eight times the efficiency obtained with the x-ray tube in the Kellogg Laboratory running at 1 Mv 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 roentgens 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 Mv. Subsequent to the development of this machine, Trump and Van de Graaff[9] have published a description of a more compact unit operating at 1.25 Mv and 1 ma with an output of 250 roentgens per minute per milliampere of target current at 50 cm with 2 mm of Pb and 5 mm of Cu filtration.

The Production of Ions

The ion source has been previously described in this discussion. The ions made in the gas by the electron current are drawn out by the probe at -2500 volts and are focused 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 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 focusing. 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.

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[9] J. G. Trump and R. J. Van de Graaff, Phys. Rev. **55**, 677 (1939).

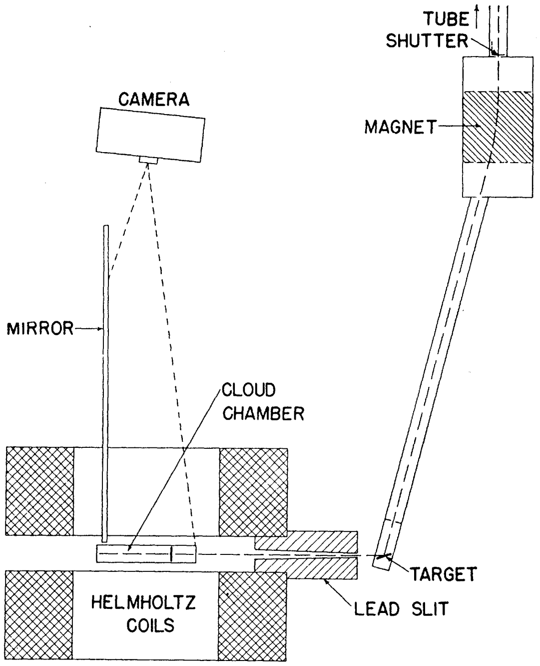

FIG. 6. Cloud chamber and target assembly.

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 beam noted. The worst offending section was then corrected and, by this empirical process, the 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 beam still is rather uncertain, changing a few millimeters in position from day to day, or with changes in voltage. In order to use the beam, it was necessary to put a sylphon in the target tube and move the entrance slit of the magnetic analyzer to suit the spot. A second sylphon made it possible to adjust the relative positions of entrance and exit slits. The beam was deflected through 15° in the magnetic analyzer. The mass 2, 3, and 4 beams of $\frac{1}{4}$-inch diameter are just separable with the analyzer in which the effective diameter of the analyzing field is 4 inches and the exit slit is 3 inches below the lower edge of the field. Holes of $\frac{1}{4}$-inch diameter drilled in 1-inch disks of $\frac{1}{16}$-inch thick fused quartz are used as slits. Lucite windows in the target tube make it possible to view the fluorescence of the quartz under bombardment and thus to locate the position of the beam.

The requirements on tube vacuum for a good ion beam are rather stringent. It is impossible to work with a residual pressure of more 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 indicate the exact conditions in the tube; particularly near the top end, where the gas is let in, the pressure may be as high as 10^{-4} or 10^{-3} mm of Hg.

We have secured total unanalyzed currents up to 10 microamperes, mass one beams of hydrogen up to 1.5 microamperes, and mass two beams up to 2.5 microamperes. As the hydrogen pressure in the ion source is increased, the ratio of mass one to mass two beams increases.

Disintegration of F^{19} by protons

A complete discussion of the disintegration of F^{19} by protons is included in the next article of this issue of *The Physical Review*. We propose to discuss here only the measurements of the energy of the radiation produced in the reaction

$$\begin{aligned} &F^{19}+H^1\rightarrow{}^{\gamma}Ne^{20}\rightarrow{}^{\gamma}O^{16}+He^4\\ &{}^{\gamma}O^{16}\rightarrow O^{16}+h\nu, \end{aligned} \tag{1}$$

where the superscript, γ, refers to those states of Ne^{20} or O^{16} involved in the production of the 6.2-Mev gamma-radiation. The gamma-radiation has been shown to exhibit resonance at proton bombarding energies of 0.334, 0.479, 0.589, 0.660, 0.862, 0.927, 1.335 and 1.363 Mev.[7] The emission of short range alpha-particles has been definitely established at the first five resonances[10] and unpublished work in this laboratory indicates that it also occurs at the remaining three. The energy release[10] in the reaction has been determined to be 1.74 Mev and since the energy release of the reaction involving long range alpha-emission is 7.95 Mev[11] the predicted gamma-ray energy is 6.21 Mev with an uncertainty of approximately 0.2 Mev. A necessary consequence of the process envisaged in reaction (1) is that the

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[10] McLean, Becker, Fowler and Lauritsen, Phys. Rev. **55**, 796 (1939); W. E. Burcham and C. L. Smith, Nature **143**, 795 (1939); W. E. Burcham and S. Devons, Proc. Roy. Soc. **173**, 555 (1939).

[11] Burcham and Smith, Proc. Roy. Soc. **168**, 176 (1938).

alpha-particle energy but not the gamma-ray energy should vary with the resonance energy of the protons. That the alpha-particle energy does vary in the predicted manner has been demonstrated at Cambridge at certain of the lower resonances and confirmed and extended to higher resonances in this laboratory. This section is a discussion of cloud-chamber measurements of the gamma-ray energy at various resonances and is a more detailed discussion of results previously reported.[12] Results similar to those reported here have also been secured at Cambridge[13] with coincidence and spectrograph methods.

The cloud-chamber method of determining gamma-ray energies from the energy of secondary pairs has been discussed in detail in previous reports from this laboratory. The exact experimental arrangement used in these experiments is shown in Fig. 6. The gamma-ray beam was collimated with lead slits and a thin aluminum window was set in the wall of the cloud chamber nearest to the target. A 10-mil Pb lamina was used as secondary emitter. The loss of energy of a fast electron in traversing such a lamina is approximately 0.3 Mev. In order to reduce as far as possible the error caused by fluctuations in the magnetic field, the coil current was read during nearly every expansion by means of a null potentiometer and held constant to $\frac{1}{2}$ percent. The absolute value of the field was checked against an accurate standard solenoid by means of a search coil and a Grassot fluxmeter several times during the course of the experiment and is considered to be accurate to better than 1 percent. The remaining error due to spread in measurement of the tracks was brought to the same order of magnitude as the magnetic field uncertainty by counting enough pairs.

TABLE I. *Results of gamma-ray energy measurements.*

PROTON ENERGY (KEV)	TARGET	RESONANCES INVOLVED (KEV)	NO. OF PAIRS	MEAN ENERGY (MEV)
425	Thick	334	33	6.17±0.10
950	Thick	All≤927	93	6.30±0.06
950	Semi-thick	862,927	29	6.13±0.09
1400	Semi-thick	1335, 1363	49	6.03±0.09
All pairs			204	6.19±0.04

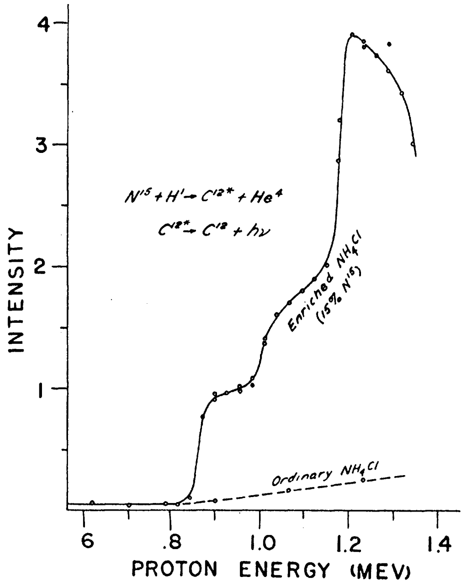

FIG. 7. Excitation curve for gamma-radiation from $N^{15}+H^1$.

The results for various bombarding energies and various targets are shown in Table I. The resonances involved in each experiment are indicated in the third column, the number of pairs measured in the fourth column, and their mean total energy in the fifth. The estimated uncertainty is the mean deviation from the mean divided by the square root of the number of pairs measured. These results indicate that within the statistical uncertainty of approximately 0.1 Mev there is no dependence of gamma-ray energy on the resonance energy of the protons. It is to be pointed out however that these results contain no information on the nature of the radiation produced by protons in the region of bombarding energies from 1.1 to 1.3 Mev. The mean of all the measurements is 6.19±0.04 Mev which, upon including a possible systematic error of 1 percent and rounding off, can be taken as 6.2±0.1 Mev. The deviation from the mean was approximately 0.6 Mev so that no structure in the gamma-ray line involving smaller separations than this would be revealed by these experiments. Recent experiments in this laboratory on the short range alpha-particles reveal no structure in the radiating state of O^{16} to even smaller limits.

At the higher bombarding energies (950 and 1400 kv) there is some evidence for a line at 10.5 Mev but it is certainly less than 5 percent of the

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[12] Lauritsen, Fowler and Lauritsen, Phys. Rev. **56**, 858 (1939).

[13] Dee, Curran and Strothers, Nature **143**, 759 (1939).

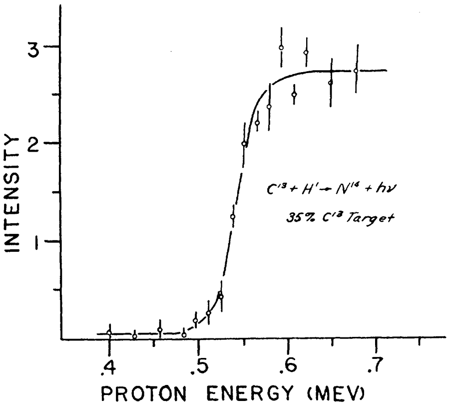

FIG. 8. Excitation curve for gamma-radiation from $C^{13}+H^1$.

main line and could conceivably be due to calcium or to boron contamination. However, it is possible that one or more of the higher resonances allows a weak radiative transition 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. In such a case one would not expect to find many low energy pairs because of the low cross section for pair formation at that energy. The few low energy pairs observed can be attributed to radiation degraded by scattering in material surrounding the cloud chamber.

Disintegration of N^{15} by protons[14]

The production of gamma-radiation by the bombardment of N^{15} by protons up to 1.4 Mev in energy has been studied using targets of ammonium chloride containing 14.8 percent N^{15} supplied to us by Professor H. C. Urey and Dr. Harry Thode of Columbia University. The excitation curve for a thick target is shown in Fig. 7 and indicates resonance (half-width $\lesssim 20$ Kev) in the gamma-ray production at proton energies of 0.88, 1.03 and 1.20 Mev. The yields above resonance were found to be 0.4, 0.3 and 1.2×10^{-7} quanta per proton, respectively. The yield from ordinary ammonium chloride targets was small compared to the yield from the enriched targets. Cloud-chamber investigations of the electron and pair secondaries produced in thin lead and carbon laminae by the gamma-radiation indicate that it consists mainly of a line at 4.4±0.2 Mev. This line is to be attributed to the reaction $N^{15}(p, \alpha)C^{12*}$, an excited state in C^{12} at this energy being well known.

Disintegration of C^{13} by protons[15]

The gamma-radiation showing resonance at 560 kv in the bombardment of carbon by protons has been attributed[16] to the reaction $C^{13}(p, \gamma)N^{14}$ for which $Q = 8.2$ Mev because the observed energy of the radiation (7.4 Mev) was greater than the available energy in the reaction $C^{12}(p, \gamma)N^{13}$ for which $Q = 2.6$ Mev. We have confirmed this conclusion by bombarding a carbon target containing approximately 35 percent C^{13} prepared for us by Dr. C. H. Townes and Professor W. R. Smythe of the California Institute. The excitation curve is shown in Fig. 8. Under the conditions of the experiment the radiation from $C^{12}(p, \gamma)N^{13}$ at 420 kv was not detectable. With an ordinary carbon target the same would have been true of the $C^{13}(p, \gamma)N^{14}$ radiation.[6] Cloud-chamber investigations of the secondary electrons and pairs produced in thin lead and carbon laminae by the gamma-radiation indicate that it consists of three lines at 2.8±0.4, 5.4±0.3 and 8.1±0.2 Mev of approximately equal intensity. These results substantiate the analysis made by Rose[17] of the absorption curves measured by Dee and his collaborators. It is to be concluded that the excited state of N^{14} at 8.1 Mev radiates to the ground state directly or through an intermediate state at 2.8 or 5.4 Mev with equal probability.

(*Note added in proof.*—The recent results of Bonner, Becker, Streib and Rubin as communicated at the Pasadena Meeting of the American Physical Society in December, 1940, indicate that the intermediate state in N^{14} is at 5.4 Mev.)

In conclusion we wish to thank Mr. J. F. Streib who collaborated in recent improvements on the generator and who kindly prepared many of the figures accompanying the text.

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[14] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **58**, 192 (1940).

[15] C. C. Lauritsen and W. A. Fowler, Phys. Rev. **58**, 193 (1940).

[16] Dee, Curran and Petržílka, Nature **141**, 642 (1938).

[17] M. E. Rose, Phys. Rev. **53**, 844 (1938).