High Current Ion Sources for Nuclear Investigations

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Since the capillary ion source described by Tuve, Dahl and Van Atta was a decided advance over previous types, it seemed desirable to investigate its possibilities further. The essential modification in the present design lies in the elimination of the auxiliary electrode for drawing ions out of the arc. This simplifies construction and greatly reduces the difficulties usually experienced in focusing ion beams. Currents as high as 4.2 milliamperes have been converged into a beam 12 mm wide with a focusing voltage of 10 kv. Possible explanations are presented for the observed dependence of the total ion current on arc current density, condition of the walls, and design of the outlet. Relative ease of starting and stability of the arc are discussed for various designs of tubes. When the arc was operated in hydrogen, the mass spectrograph showed a preponderance of diatomic and triatomic ions with proton fractions ranging from 5 to 20 percent of the total ion current. Ions other than those of hydrogen were not present in fractions exceeding 1 percent of the total. Evidence is presented for the breaking up of the heavy ions into protons and neutral particles on collision at high speed with gas molecules. Upper and lower limits are given for the efficiencies of these processes.

INTRODUCTION

RECENT developments in nuclear physics have served to emphasize the demand for high current sources of protons, deuterons, and helium ions. Further tests on the type of pure proton source described by Lamar and Luhr[1] have confirmed the conclusion reached by them that extreme cleanness of the various metal parts is necessary for the production of pure proton beams in this type of source. In their results there remained also much to be desired in the direction of increased ion current for a given gas transport. The capillary type ion source described by Tuve and his collaborators[2] gave ion currents, for a given gas transport, far in excess of those reported for the type of source mentioned above, though the proton purity was less. The present investigation was undertaken, therefore, in an effort to evaluate the various factors involved in the operation of the capillary discharge and to see in what directions one might hope for improvements. This paper is a presentation of the results of experiments carried on in this laboratory during the past year and reported first at the Washington meeting of the Physical Society. It is believed that our work, together with that of Dr. Tuve and his collaborators, constitutes a reasonably complete picture of the capillary type ion source.

[1] Lamar and Luhr, Phys. Rev. **44**, 947 (1933); Phys. Rev. **46**, 87 (1934).

[2] Tuve, Dahl and Van Atta, Phys. Rev. **48**, 315 (1935); Tuve, Dahl and Hafstad, Phys. Rev. **48**, 241 (1935).

APPARATUS AND EXPERIMENTAL PROCEDURE

A number of discharge tubes were tested, differing in detail one from another, but each having the same essential elements. A typical one is shown in Fig. 1. The metal envelope which enclosed the discharge was made in three pieces; a central stainless steel block, and two stainless steel tubes press fitted and soft soldered into the block. The discharge space consisted of two cylindrical enclosures (in every case 3.18 centimeters inside diameter) connected by a smaller hole or capillary. There was, in the side of the capillary, a tapered outlet through which ions, electrons, and neutral gas molecules might escape from the discharge. One of the enclosures contained an anode and the other an oxide-coated filament cathode. The stems for cathode and anode were supported by ground glass to metal joints on the ends of the steel tubes. These joints were made vacuum tight by means of picein w applied externally. The connection between the outlet side of the discharge tube and the miniature high voltage tube shown in the figure was also accomplished by means of picein wax. Hydrogen was introduced into the discharge tube and was pumped out of the high voltage tube with a pumping system having a net speed for air of 14 liters per second.

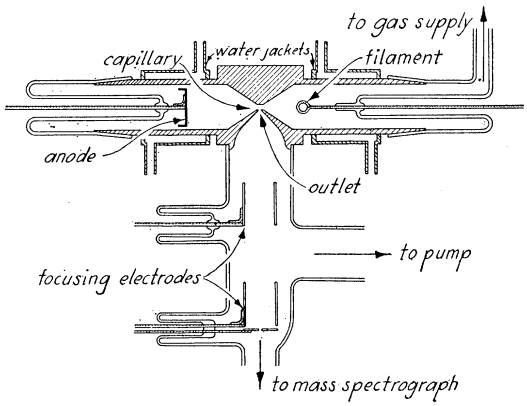

FIG. 1. Diagram of experimental tube.

In the first tube tested the ends of the two enclosures, instead of being conical as shown in the figure, were flat and the capillary, instead of being concentric with the two cylindrical enclosures, was on the bottom. In other words, the lowest generating line of the capillary was a continuation of the lowest generating lines of the two cylindrical enclosures. This design was adopted in order to minimize the distance between the outlet and the first high voltage electrode thus giving the most favorable arrangement for the initial focusing of the ion beam. Since no difficulty was experienced in initial focusing, and since the lack of symmetry in the position of the capillary made the starting of the discharge difficult, that design was abandoned in favor of the one shown.

In order to start the discharge the metal walls are connected to the anode through a resistance of from 20 to 30 thousand ohms. A low current discharge then starts in the cathode enclosure, the walls of the enclosure acting as anode. Electrons from this discharge are shot through the capillary and precipitate a high current discharge to the anode through the capillary. A symmetrical field about the end of the capillary is most favorable for shooting electrons through the capillary and thus for starting the main discharge. The symmetrical field also tends toward greater stability of the arc for, if any transients tend to extinguish the arc, it immediately starts again. As regards convenience in tube design, it seems safe to say therefore that wide variations are permissible provided the walls at the ends of the capillary are geometrically symmetrical and, of course, provided cathode and anode are not too far removed from the ends of the capillary.

Various different filaments were tried but the one finally adopted consisted of a 20-mil molybdenum wire about 6 inches long wrapped with 8-mil nickel. The resulting "piano wire" was wound on a 3/32-inch mandrel to form a helix. The emitting surface was a mixture of barium and strontium oxides. The molybdenum served as a heating element and the nickel as a binder for the oxides.

Several 1/4-inch holes (not shown in the figure) were drilled through the stainless steel block for water cooling and water jackets were provided for each of the two stainless steel tubes.

A number of different capillaries were tried ranging in diameter from 1.5 to 4.0 mm and in length from 4 to 20 mm. The difficulty in starting a discharge increased with increasing length and with decreasing diameter of the capillary. In some instances the discharge started as soon as the e.m.f. was applied and in others it was necessary to apply a "leak tester" to the glass on the anode side. In most of the tests an e.m.f. of 230 volts was used simply for convenience although arcs have been maintained easily with an e.m.f. of 115 volts. The arc drop ranged from 60 to 140 volts. In general, the arc drop is least for the capillary having the greatest diameter and smallest length. For any one discharge tube the arc drop is a minimum at some one pressure and rises gradually as the pressure is changed on either side of the minimum.

Measurements of the number of ions leaving the discharge per second through the outlet were complicated by space charge near the outlet and by the emission of secondary electrons from the electrodes in the high voltage tube. Ten kilovolts, applied to the first electrode, were usually sufficient to overcome the space charge near the outlet and thus give saturation ion current. With this voltage most of the ions went through the first electrode and were collected by the second. The resulting secondary electrons, emitted by the second electrode, were prevented from contributing to the measured ion current by means of a small retarding potential (45 to 350 volts) maintained between the two high voltage electrodes.

The ion current was measured for each discharge tube as a function of the variables in the arc proper. These were the arc current, the gas pressure, the potential of the steel walls with respect to the anode, and the previous history of the tube. A slit (5 mm long and 1.5 mm wide) in the bottom of the second high voltage electrode allowed a small fraction of the ions to enter a mass spectrograph (not shown in the figure). It was possible, therefore, to determine the nature of the ions in a sample of the beam as a function of the variables mentioned above.

Results and Conclusions

The current of ions leaving the discharge through the outlet depends upon the number of ions produced per second in the discharge and upon the electric field in the vicinity of the outlet. These two variables and the variables on which they in turn depend will now be considered.

The number of ions produced per second depends upon the current density and potential drop in the capillary and upon the concentration and nature of the gas present. Experimentally it was found that, with the metal walls floating or connected to the anode through a high resistance, the ion current (leaving the discharge through the outlet) for constant arc current varied over fairly wide limits, in most cases by a factor of two. When an arc was first started, the ion current was always low and increased with continued operation. Since there was no accompanying change in the *relative* numbers of ions of different masses collected in the mass spectrograph or of arc drop, it was concluded that the increase in current resulted from an increase in the current density in the capillary rather than from any change in the nature of the gas or drop along the capillary. The following is a possible explanation of the change. There are two possible paths through which current can flow from anode to cathode: the capillary, and the metal walls. The fraction of the arc current which follows the metal path (and thus produces no ions) is greater or less, depending upon the number of secondary electrons emitted by the walls of the anode enclosure. Continued operation of the discharge tends to remove surface films from the walls, thus reducing the number of secondaries emitted and forcing the arc current to take the path through the capillary. If the walls are made negative with respect to the cathode, electrons from the cathode are prevented from reaching the walls and thus most of the arc current must go through the capillary. This procedure does not result in any great increase in ion current for a given power input since the current resulting from the emission of secondaries from the walls of the anode enclosure must be supplied by the metal wall circuit. Reductions in the fraction of the arc current taking the metal path can be accomplished by selecting, for tube construction, a metal which does not emit many secondaries and by reducing to a minimum the area of metal exposed to the discharge on the anode side of the capillary.

Let us consider now the electric field in the vicinity of the outlet and its effect upon the ion current. In general a metal surface in contact with an ionized gas and negative with respect to it is covered with a positive ion space-charge sheath.[3] The thickness of the sheath increases with increasing negative voltage and with decreasing ion density. In the capillary, then, the region of ionized gas in the center is surrounded by a space charge sheath separating this region from the walls. The thickness of the sheath depends upon the ion density in the capillary and upon the potential of the central region with respect to the walls. Consider now ions from the discharge which leave the capillary through the outlet in the side of the capillary. If the thickness of the sheath is large in comparison with the diameter of the outlet, the outlet introduces no distortion in the sheath. Thus ions drifting into the sheath from immediately over the outlet suffer accelerations normal to the sheath and leave the discharge through the outlet. As the sheath thickness decreases, a depression develops immediately over the outlet. Ions which then drift into the sheath are accelerated in a diverging field and thus not all of them get through the outlet. If the sheath is extremely thin it bends around the edges of the outlet thus allowing a part of the discharge itself to stick out through the outlet, the ions being removed from this part of the discharge by the field in the high voltage

[3] Langmuir and Mott-Smith, G. E. Rev. **37**, 449, 538, 616, 762, 810 (1924).

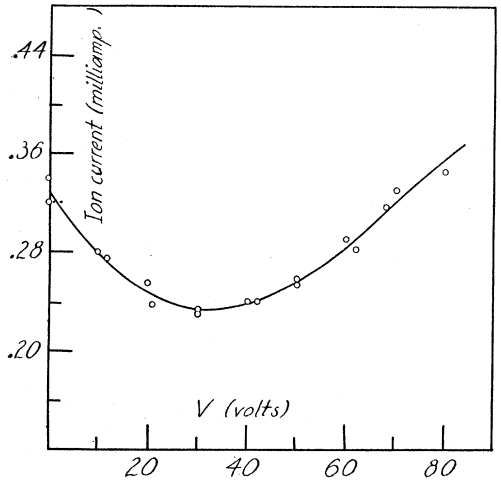

FIG. 2. Ion current *vs.* potential of the metal walls with respect to the cathode. Arc current 1 ampere, pressure 0.095 mm, capillary diameter 4 mm, and outlet diameter 0.83 mm.

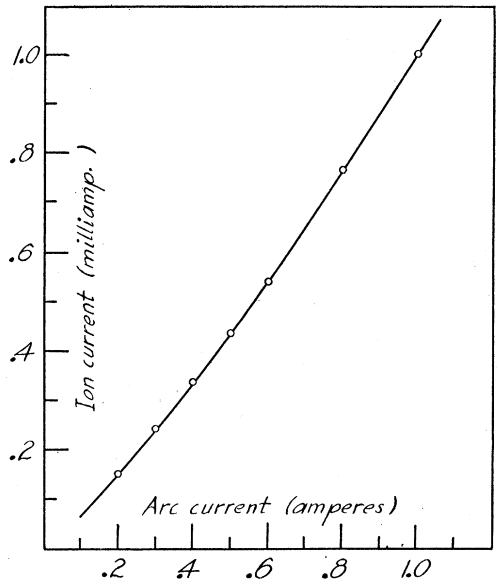

FIG. 3. Ion current *vs.* arc current with metal walls connected to anode through 20,000 ohms. Pressure 0.15 mm, capillary diameter 3.2 mm, and outlet diameter 1.2 mm.

tube. The fraction of the area of the outlet available for this "sticking out" of the discharge increases, therefore, with decreasing sheath thickness and thus, in this region, the ion current increases with decreasing sheath thickness for constant ion density. The correctness of this picture is indicated by the results presented in Fig. 2. In this figure the ion current is plotted as a function of the negative potential of the metal walls with the cathode as a fixed reference, other measurable variables remaining constant. As one would expect from the above picture, for high negative voltages, as the negative voltage and thus the sheath thickness increase, the ion current increases. In the intermediate region the ion current is low. As the sheath thickness decreases after having passed the minimum, the ion current again increases indicating a "sticking out" of part of the discharge through the outlet. It was not possible to extend this curve in either direction in search of a leveling off, since further increase in negative voltage put the arc out, and since any decrease made the walls positive with respect to the cathode, thus allowing electrons to reach the walls and complicating the interpretation of the curve. Maximum ion currents are obtained, therefore, either from a number of extremely small outlets or from one large one.

Fig. 3 is a plot of ion current leaving the discharge with arc current as the independent variable. If the effective area of outlet were constant, one might expect an approximate proportionality between ion current and arc current. But since the sheath thickness decreases with increasing ion density and thus with increasing arc current, the effective area of outlet is not constant. Since, in this case, the outlet was relatively large (1.18 mm in diameter) it is believed that the sheath was small by comparison and thus the effect of changing sheath thickness on outlet area was small, and thus the lack of any great curvature is taken as good evidence for a proportional dependence of ion current on arc current for constant outlet area.

A number of tests were made to determine the dependence of ion current and arc stability on gas pressure. Over the range from 0.035 to 1.0 mm no marked dependence of ion current on gas pressure was observed although it increased slightly with increasing pressure. In pure hydrogen, however, for pressures below 0.06 mm the arc shows a marked tendency to go out. A pressure of 0.1 mm is suggested, therefore, as a sufficiently high pressure to insure reliable operation. As far as the operation of the arc is concerned, it can be made stable at low pressures by introducing traces of impurities into the hydrogen although this is undesirable since under

these conditions an appreciable fraction of the ions are those of the impurity.

The design of capillary arc shown in Fig. 1 presents a different focusing problem from that usually encountered since there is no auxiliary electrode for drawing the ions out of the arc. In this problem there are two limiting cases: one in which the outlet diameter is large in comparison with the sheath thickness so that a part of the discharge actually sticks out through the outlet, and the other in which the outlet is small so that the ions are shot out by the potential drop in the sheath. In either case there is very little net space charge in the immediate vicinity of the outlet, for in the first case electrons drifting out of the discharge with the ions tend to neutralize space charge, and in the second not only does the smallness of the outlet reduce the number of ions but the sheath drop furnishes them with an initial velocity. Studies of focusing were greatly simplified by the fact that slight traces of gas in the high voltage tube rendered the beam sufficiently luminous to be clearly visible in a darkened room. With low voltage on the first high voltage electrode, the beam appeared to come from a rather large area indicating considerable spreading of the ions after leaving the outlet. As the voltage was increased, not only did this area decrease, but the ions continued to converge in their flight down the tube. With an ion current of 4.2 ma and a voltage of 10 kv the beam reached a minimum width of 12 mm at a distance of about one centimeter below the first high voltage electrode. Since this beam width was sufficiently small to allow the ions to pass through the first high voltage electrode, and since the work of Dr. Tuve and his collaborators[2] on further focusing was already so complete, these studies were not continued. It should be added, however, that the apparent beam edge was always extremely sharp. That this corresponded with the physical facts was shown by the sharp drop observed in the current collected by the first electrode when the beam appeared just to clear its edges. There are, therefore, certain advantages to be gained by allowing the ions to leave the discharge with negligible velocities and impart all of the energy in a region of relatively high vacuum. Under these conditions, one is not faced with the problem of refocusing an initial beam, heterogeneous in energy and direction, which comes from a region in which gas scattering is possible.

Studies of total ion current were, of course, complicated by the passage of part of the arc current through the metal and by the dependence of the effective area of the outlet on sheath thickness, as discussed above. The indications were, however, that the ion density, and thus the ion current for constant effective area of outlet, were approximately proportional to the current density in the capillary. With a 3.2-mm capillary and a 1.2-mm outlet, the ion current for a 1.92 ampere arc was 4.2 ma. Thus one may expect about 16 ma per square centimeter effective area of outlet for a current density of 1.0 ampere per square centimeter in the capillary. In the 3.2-mm capillary, the current density for a 1.0-ampere arc is about 12.5 amperes per square centimeter. Currents as high as 5 amperes have been passed through such a capillary, giving a current density of 62.5 amperes per square centimeter and thus an ion current density of 1000 ma per square centimeter. For the sake of comparison, the source described in the first reference gave 8 ma per square centimeter for a 1.0-ampere arc.

In Fig. 4 a fairly typical mass spectrograph curve is presented merely to show the positions and shapes of the various peaks. Although a number of complete curves were taken, in the interest of speed only the heights of the various peaks were recorded in most of the tests. In most of the tests taken with the mass spectrograph, the two high voltage electrodes and the mass spectrograph were 1160 volts negative with respect to the steel walls of the discharge tube. As can be seen, the diatomic and triatomic ions are in the majority, the relative magnitudes of the two peaks depending on the pressure, while the primary proton peaks are disappointingly low. With pure hydrogen, the fraction of the ion current carried by primary protons ranged from 5 to 20 percent, and was usually about 10 percent. No marked dependence, of primary proton percentage on the arc variables, was observed over the ranges of currents and pressures used although there was some slight indication of an increase with measured pressure. There was some evidence that the addition of helium to the hydrogen tended to increase the proton per-

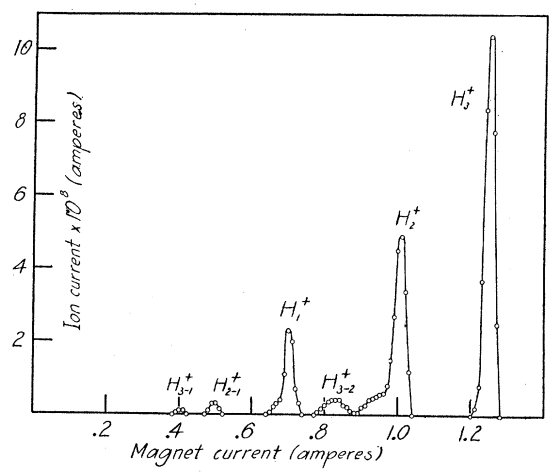

FIG. 4. Typical mass spectrograph curve. Pressure 0.13 mm.

centage, but the evidence was not conclusive and since the effect, if present at all, was small, only a few tests were made.

It was hoped that the mechanism employed by Lamar and Luhr[1] for producing protons might be of use in this type of ion source. Briefly, if both ions and neutral particles have a low accommodation coefficient, and if the walls are maintained highly negative, ions striking the walls rebound as neutrals retaining a large fraction of the energy gained in the negative potential drop. This energy going into the gas tends to increase its temperature. If the neutral particles also have a low accommodation coefficient large temperature differences are possible between gas and walls. With the gas at a high temperature, the hydrogen exists in the atomic rather than the molecular state and the ions are therefore protons. Tests on the capillary type source and further tests on the type described in the reference above confirmed the conclusion that extremely clean surfaces are required for the existence of low accommodation coefficients. This surface cleanness, although possible, requires care in technique which is hardly practical in a high voltage installation.

Some hope for increased proton percentages is offered by the fact that heavy ions at high speeds break up, on collision with gas molecules, into protons and neutral particles. That this occurs is indicated by the presence of peaks in Fig. 4 at 0.4 and 0.5 ampere magnet current. If these are protons, they appear with one-half and one-third energy as would be expected if they were formed by the break-up of H_2^+ and H_3^+, respectively. This conclusion is further substantiated by the fact that the relative heights of these two peaks vary in the same way as the relative heights of the H_2^+ and H_3^+ peaks. The peak at 0.8 ampere results from the break-up of H_3^+ ions to form H_2. It is possible, on knowing the relative heights of the various peaks, the pressure in the discharge tube, and the various dimensions of the apparatus, to get some idea of the efficiency of these break-up mechanisms, the only uncertainty being the angular distribution of the protons after break-up. A lower limit to the efficiency of break-up can be set by assuming no angular scattering. With this assumption, every heavy ion, which would have entered the spectrograph had it not been broken up, produces a proton which does enter the spectrograph. Knowing, then, the number of protons per heavy ion, the length of path in the discharge tube at constant potential, and the pressure in the discharge tube, one can calculate from these data the average number of collisions per centimeter path at normal pressure and temperature which result in break-up. This calculation gives, as a lower limit, for the H_2^+ five and for the H_3^+ two collisions per centimeter path at one millimeter pressure and room temperature resulting in break-up. As an extreme upper limit, one might assume that on break-up the protons are scattered equally in all directions. Knowing the solid angle subtended by the slit system of the spectrograph at any point along the path of the ion beam, one is able to perform the necessary integrations and solve for the efficiency necessary to account for the observed number of protons. This assumption leads to about 250 times as many collisions per centimeter path as the former one. A more reasonable assumption is that the protons are scattered as though they had collided as elastic spheres with spheres of equal mass. Since the resulting distribution gives four times as many protons scattered in the forward direction as the equal angular distribution, the ratio between upper and lower limits is now reduced to about 60. For 1160-volt ions, therefore, the number of collisions per centimeter path at normal pressure and temperature resulting in break-up lies some-

where between 5 and 300 for H_2^+ ions and between 2 and 120 for H_3^+ ions. These tests were not repeated for other voltages. However, the absence of marked broadening of the primary proton peak for high pressures, and negative voltages of the capillary walls as high as 180 volts, indicated that the efficiency of break-up must be extremely small for voltages less than 180.

The possibility of using the break-up mechanism for producing protons depends, of course, upon the relative importance of scattering in removing ions from the beam as it passes through the gas. In order to test this an additional electrode was introduced 4.0 centimeters below the outlet to the tube. It consisted of a cylinder 1.0 centimeter in diameter and 4.0 centimeters long with a plate extending from the upper edge of the cylinder radially to the glass walls of the discharge tube thus sealing this region from the region of high vacuum. Previous tests, without the additional electrode, having shown little change in total ion current with pressure, it was assumed that, with the additional electrode any decrease in ion current with increasing pressure resulted from scattering in the region between outlet and additional electrode. The measurements indicated an approximate exponential dependence of ion current on pressure as would be expected from loss due to scattering. The loss for a gas path equivalent to 1 mm at 1 mm pressure was 3/4 of the current in the beam. With this gas path the fraction of primary protons increased to 30 percent. These were definitely primary protons from the discharge since they possessed the full energy and their high percentage merely showed preferential scattering of the heavier ions. In all of the tests with the additional electrode, the maximum current was realized with a potential of about 3 kv on the electrode, showing for lower voltages an underfocusing and for higher an overfocusing of the ion beam.

Since the angular distribution of the protons after formation from the break-up of heavier ions is not known it is not possible at the present stage to give an accurate estimate of the ultimate limit to the total proton current. However, a few remarks as to the directions in which to proceed in designing a "break-up" region seem to be in order. The design of such a region presents two problems: that of breaking up the ions and of focusing the resulting protons. The first of these problems is relatively simple. One needs, simply, to give the ions an energy of 1 kv or more and to have sufficient gas present to insure the desired number of break-up collisions. In order to focus the protons the field in the break-up region should be strongly converging so that scattered ions may be drawn back into the ion beam. The region should be wide in comparison with its length so as to provide the field with ample opportunity to act on the ions before they reach a wall and are lost. In the source described by Tuve and his collaborators[2] some of the lines of force from the auxiliary electrode pass through a constriction, separating this electrode from the discharge, and up into the capillary. This arrangement provides a converging field in a region of reasonable gas pressure, but the voltage drop in this leakage field is necessarily low since high voltages here extinguish the arc. Since the efficiency for break-up with low voltages is small, few protons are produced in this region. It seems more advisable, therefore, to get the ions completely out of the discharge, possibly by one of the mechanisms outlined above, and then provide them with the necessary energy in the region of gas. The outlet to the break-up region should be a hole in a diaphragm rather than a long tube since the angle spread of the beam leaving this region is probably large. A discussion of the relative merits and demerits of diaphragms as compared with tubes is given in the second reference. Although the "break-up" mechanism for forming protons has with it the undesirable feature of gas scattering which makes focusing difficult, it does not make focusing impossible and seems to offer the most promising means of obtaining high proton yields.

In conclusion, the authors wish to express their indebtedness to Mr. Walter Kallenbach, head of the Physics Shop, whose advice in design and whose cooperation in execution made possible the testing of a large number of tubes. We wish also to thank Dr. C. M. Van Atta for his excellent suggestions and advice during the preparation of the manuscript.