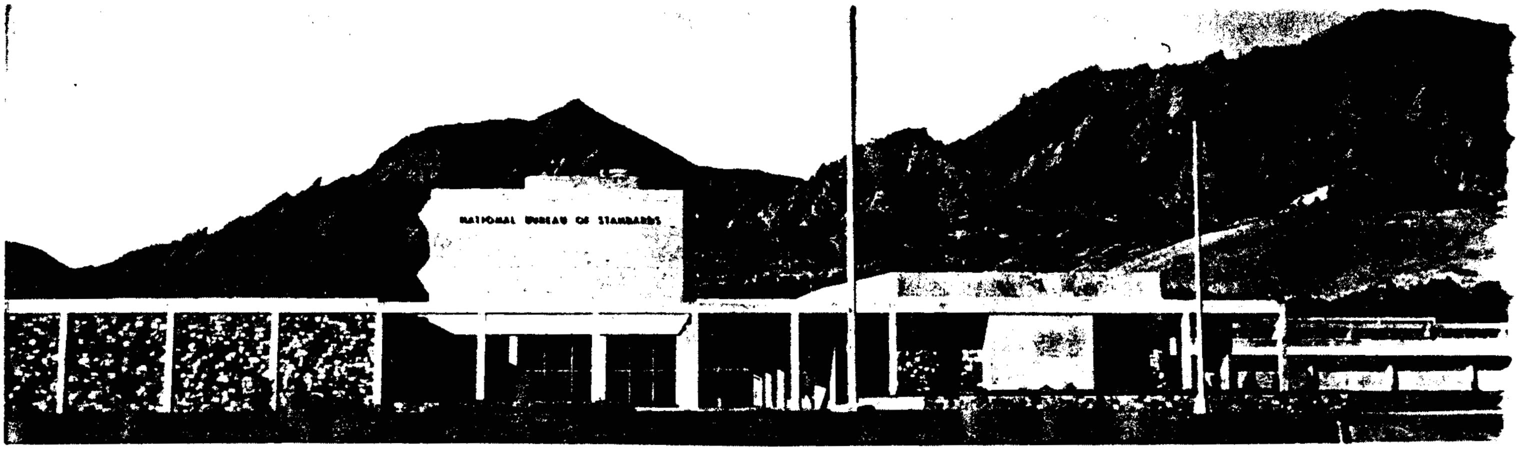

NBS REPORT

8452

THE BRUSH CATHODE PLASMA --A WELL-BEHAVED PLASMA

by

Karl-Birger Persson

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
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ABSTRACT

Results of probe, spectroscopic, and microwave studies are used to describe properties of a novel cold cathode discharge. The use of a brush cathode greatly exaggerates some of the usual cold cathode mechanisms, thus determining the interesting features of the plasma produced. The cathode fall is about an order of magnitude larger than for the corresponding normal cold cathode. The brush cathode generates a uniform electron beam in the energy range 1 to 10 kV and a corresponding negative glow with a longitudinal dimension (reaching distance of the beam) one to two orders of magnitude larger than for the normal cathode. The large dimensions of the negative glow and the fact that it is extremely well-behaved (no instabilities and no striations) make it ideal for a whole series of investigations in plasma physics and spectroscopy. The electron density in the helium plasma is in the range 10^{10} to 10^{14}cm^{-3}, the electron temperature in the range 0.05 to 0.10 eV. The negative glow is beam generated (essentially field free) and recombination dominated making it a practically uniform plasma ideal for the study of rate and transport coefficients. Preliminary measurements of the particle balance give a recombination rate of $5 \times 10^{-10} \text{cm}^3 \text{sec}^{-1}$ at 1100°K and an electron density of $3 \times 10^{12} \text{cm}^{-3}$ in excellent agreement with the collisional-radiative recombination theory developed by Bates, Kingston and McWhirter.[5] The recombination light emitted by the plasma is sufficiently strong to make spectroscopic methods very useful for measurements of the electron density and the electron temperature. Lines in the series $2s\,^3S - np\,^3P^0$ are observed up to the quantum level $n = 30$.

THE BRUSH CATHODE PLASMA - A WELL-BEHAVED PLASMA

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1. Introduction

The field of experimental plasma physics has need for a well-behaved plasma. A well-behaved plasma is a plasma where parameters such as electron density, electron temperature and significant collision frequencies can be varied in a controllable manner over more than an order of magnitude. The dimensions of the plasma should be large in comparison with mean free paths, wavelengths and other significant length parameters of the plasma so that the effects of sheaths and other boundary phenomena either can be neglected or else included in a rational manner. It is furthermore desirable that the plasma has no significant spatial fine structure and that it is sufficiently stable for study under steady state conditions. The only acceptable fluctuations should be those associated with thermal motion. It is generally very difficult to find a plasma that satisfies the criteria outlined above. This paper describes a beam generated plasma called the brush cathode plasma which resembles quite closely an ideal well-behaved plasma. It also is possible to label this plasma as a steady state afterglow plasma or negative glow.

2. The Beam Plasma

Most cross sections for the interaction between electrons and neutral, excited or ionized particles have maxima as function of the electron energy or velocity. Cross sections decrease rather rapidly with increasing energy for energies larger than those corresponding to these maxima. Maxima for elastic cross sections are generally located in the range of one to a few electron volts. Maxima for excitation cross sections (to excited electronic states) are in the range from a few electron volts to a few tens of electron volts. Maxima for ionization cross sections are in the range of a few tens of electron volts to a few hundreds of electron volts. Figure (1) shows the number of electron-ion pairs $s(V)$ that are generated per unit path length and per electron as function of the kinetic energy V of the electron expressed in electron volts.[1] Since $s(V)$ is defined as $n_{go}Q_i$ where n_{go} is the number density of the neutral gas at room temperature and at the pressure of 1 Torr while Q_i is the ionization cross section, it follows that the number S of electron-ion pairs generated per unit volume and per second in an electron beam with the current density J passing through a gas with the particle density n_g is

$$S = \frac{J n_g}{e n_{go}} s(V). \qquad (1)$$

The quantity $s^{-1}(V)$ has the dimension of length and represents the mean free path of the ionizing collisions at the electron energy V. It is important for the discussion in this paper to obtain a feeling for the distance L traveled by an electron beam in the energy range 1 to 10 kV before its energy is dissipated. The average energy loss per ionizing collision is βV_i where V_i is the ionization potential and β a numerical factor in the range 1 to 10 accounting for the fact that more than the ionization energy generally is dissipated in an ionizing collision. The reaching distance L of the electron beam can then be written as

$$L = \frac{1}{V_i} \int_0^V \frac{dV}{\beta\, s(V)} . \tag{2}$$

It is easily seen from Fig. (1) that the function s(V) for the range of interest can be approximated as

$$s(V) = \frac{C}{V} . \tag{3}$$

The constant C for helium as obtained from Fig. (1) is 430 at 1 Torr. Assuming that β is equal to 10, then $L = 5$ cm at 10^3 volts and 500 cm at 10^4 volts. Since it is likely that β is less than 10, the reaching distance L is sufficiently large so that the length of the associated plasma is significant. It is desirable that the current density in the electron beam be made uniform, filling a tube of radius R and with a beam energy such that the reaching distance L is large in comparison with the radius R. The high energy electrons in the beam generated pairs of electrons and ions that in the first order approximation can be assumed to be in thermal equilibrium with the parent gas. Furthermore, if it is assumed that the electrons and ions are lost either by ambipolar diffusion or by volume recombination, the particle balance equation for the plasma is

$$\frac{\partial n}{\partial t} = S + D_a \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial n}{\partial r} \right) - \alpha n^2 \qquad (4)$$

where n is the electron density, D_a the ambipolar diffusion coefficient and α the recombination coefficient. The dependence on the axial coordinate is neglected since it is assumed that the reaching distance L of the electron beam is large in comparison with the radius R of the tube. The source function S which is given by (1) can be considered independent of the coordinates provided the beam voltage is sufficiently large and constant with time. The steady state solution to (4) in the diffusion limit can then be written as

$$n = n_o \left(1 - \frac{r^2}{R^2} \right) \qquad (5)$$

provided

$$n_o = \frac{SR^2}{4D_a} = \frac{i\,s(V)}{4 \pi e D_a} = n_{oD} \qquad (6)$$

where i is the total beam current. The corresponding solution in the recombination limited case is

$$n_o = \sqrt{\frac{S}{\alpha}} = \frac{1}{R}\sqrt{\frac{i\,s(V)}{\Pi e \alpha}} = n_{o\alpha}. \qquad (7)$$

Assuming that the parent gas is helium with a pressure around 1 Torr, that the plasma is at room temperature, that the diameter of the discharge tube is in the range 5 to 10 cm and that the beam current is in the range 10^{-3} to 1 A, the electron density given by the limit formulas above is in the range 10^{10} to 10^{14} cm^{-3}. An evaluation of the electron density in the beam shows that it is several orders of magnitude less than the plasma density. Therefore, the properties of the beam generated plasma in the pressure range around 1 Torr is dominated by the cool electrons rather than by the beam electrons.

It is extremely difficult, if not impossible, to design an electron gun capable of delivering an electron beam in the energy range of 1 to 10 kV. operating at 1 Torr and with a cross section comparable with the reaching distance of the beam. The brush cathode solves this problem.

3. The Brush Cathode Discharge

The brush cathode is illustrated in Fig. (2). It consists of a collection of metal wires that are brazed end on to a common base plate. It is manufactured in such a manner that the wires form a reasonably well ordered close packed array. The wires do not touch each other and are electrically as well as mechanically connected only through the base plate. The free ends of the wires are etched electrolytically, producing a set of very sharp needle-like points that are located in essentially the same plane. The particular set of brushes used in the experiments described in this paper was made of 0.025 in. tungsten wires soldered to an invar base plate with Cu-Ag eutectic solder. The wires were 1 $\frac{3}{4}$ in. long and were spaced 1/16 in. apart.

This brush cathode has been used as a cold cathode and proved very successful in all cases that have been tried so far. It generates a high velocity electron beam in the pressure range around 1 Torr with a diameter equal to that of the cathode or tube envelope. Its effects are most spectacular in helium as is obvious from Fig. (1). The experiments and the measurements referred to in this paper are all done in this gas. The experience with the two discharge tubes shown in Figs. (3) and (4) is used to demonstrate the properties of the brush cathode discharge.

Tube A was made of high grade quartz to facilitate microwave and spectroscopic measurements while tube B was made of pyrex. The inside diameter of the cylindrical parts of both tubes was approximately 7.6 cm. The distance between the two main brushes in tube A was 26 cm while the length of the cylindrical part of tube B was 45 cm. The diameter of the sphere of tube B was 20 cm. The brush cathodes were made to fit the inside diameter of the tubes as well as possible without touching the tube envelope. The anode of tube A, located in the side arm, was also made in the shape of a brush electrode with the thought that it would make better contact with the plasma and avoid instabilities associated with the anode spots. Tube B was equipped with a ring anode fitting the inside of the cylindrical part of the tube envelope.

Figures (5) and (6) show the voltage-current characteristics of tube A with the helium pressure as a parameter. Perhaps the most outstanding feature of these characteristics is that they have positive slopes beyond a certain current. This is particularly obvious for the low pressures. The characteristics in Fig. (5) were taken when both brush electrodes in the ends of tube A were used as parallel cathodes. The curves in Fig. (6) were taken with one of the brushes used as the anode and the other as a cathode. The following phenomenological description of the discharge refers to observations done in helium at 1 Torr with both end brushes used as cathodes. The changes in the discharge with increasing current are illustrated in Fig. (3). The tube broke down at little less than 500 volts. The situation illustrated in Fig. (3, I) is developed at a current of a few mA. The brush cathode is partially filled with a plasma, A, that looks like a positive column plasma. It extends outside the points of the brush and the wires seem to be surrounded by what looks like a uniform plasma. Moving away from the cathode along the axis of the tube, one finds dark space B which is separated from the negative glow D by an exceedingly sharp and flat discontinuity C. The plasma D has all the characteristics associated with the negative glow in an ordinary discharge tube. The negative glow is separated from traces F of the positive column by a Faraday dark space E. That the striations F belong to the positive column was demonstrated in a tube sufficiently long so that the positive column was well developed. It was then found that the whole positive column consisted of almost stationary striations where each individual striation had an almost spherical shape. The main change in the plasma associated with additional increase in current was an expansion of the negative glow as illustrated in Fig. (3, II). All traces of positive column with the exception of what could be labelled anode spots disappeared. With further increase in the current, the two negative glows increased even more until they seemed to meet in the center of the tube. The points on the voltage-current characteristics where this occurred are labelled B in Figs. (5) and (6). With still further increase of the current, the negative glow became more intense and filled the tube while the anode spots disappeared. The disappearance of the anode spots was associated with the small wiggles labelled C on the voltage-current characteristics. The only observable change in the discharge associated with increase in the current beyond this point was a more intense negative glow giving the discharge the appearance illustrated in Fig. (3, III). The most unique and characteristic features of the discharge when it reached this stage were that the negative glow filled the tube, that the voltage-current characteristic was positive and that the maintaining voltage was larger than the breakdown voltage.

It was in this state that the plasma generated by the brush cathode could be labelled a well-behaved plasma. However, before the properties and benefits of this plasma are discussed in detail, it is necessary to demonstrate that the negative glow is maintained by an electron beam.

The behavior of the discharge in tube A as function of the current is in itself strong evidence for the presence of a high velocity electron beam. The presence and the crude properties of the beam are, however, best demonstrated in tube B as illustrated in Fig. (4). By increasing the current in this tube into the 10 to 30 mA range, it was found that the negative glow went through the ring anode and reached into the sphere all the way to the opposite wall. The visible plasma in the sphere had in this case, as is shown in Fig. (4), approximately the same cross section as the cylindrical enevelope. The fact that the column does not expand radially when it enters the sphere indicates that a beam is involved. Since the beam originates in the cathode region and goes through the anode at the relatively high pressure of 1 Torr, it follows that the beam is a high energy electron beam. This conclusion is confirmed by observing the behavior of the beam in a magnetic field. By introducing a magnetic field of the order 4 to 6 gauss, it is found that the beam bends like an electron beam with a radius of approximately 20 cm. This corresponds to an electron energy in the range of 600 to 1300 eV. The voltage drop across the tube,which later will be shown to be identical with the cathode fall, is 2000 volts. In view of these observations, it is logical to conclude that the beam starts in the cathode region with an energy closely corresponding to the cathode fall, is attenuated by ionization and other collisions and ends up in the sphere with an energy in the range 600 to 1300 eV. An additional observation that adds to this picture is that when the beam hits the far wall in the sphere, it heats this wall to a temperature substantially higher than that of the cylindrical part of the envelope which also is in contact with the plasma.

Such high energy electron beams could not have existed in the discharge without very high accelerating electric fields near the cathode. In order to investigate these fields, the cathode region was explored with a movable probe in an arrangement illustrated by Fig. (7). The movable probe was made of 0.015 in. tungsten wire completely enclosed in glass with the exception of the flat end surface which served as the probe area. It was movable along a line making an angle of 45 degress with the axis of the tube and located in such a fashion that the whole distance between the cathode and discontinuity as well as a fair fraction of the negative glow could be explored. These measurements were done on tube A at several pressures and currents. In every case the tube was filled with the negative glow, thereby ensuring a good and stable electric contact between the plasma and the anode. The first attempts to measure the potential distribution failed because the probe plasma impedance close to the cathode was extremely high. This problem was finally solved by measuring the potential with a very sensitive electrostatic voltmeter in series with a variable and accurate voltage supply.

These measurements gave the results shown in Fig. (8). The potential V_p of the probe was measured with respect to the anode. It was found during these measurements that the distance d from the cathode to the discontinuity as well as the cathode fall varied as a function of the current. The results of the measurements were therefore plotted in the normalized form V_p/V_c as function of x/d where x is the distance from the probe tip to the cathode. All data taken by the probe fitted reasonably well on a common curve of the form

$$\frac{V_p}{V_c} = - \left(1 - \frac{x}{1.08d}\right)^2 \tag{8}$$

giving rise to an electric field varying linearly with the coordinate x and with the corresponding space charge density independent of the coordinate. The product pd in Torr-ohm as obtained from these measurements is shown in Fig. (9). The cathode fall V_c was found to be practically identical with the voltage drop across the tube provided the negative glow was filling the tube to such a degree that all traces of the positive column and the anode spots had disappeared. The necessary information about V_c is therefore given by the voltage current characteristics in Figs. (5) and (6). The conclusion that the negative glow in the brush cathode plasma is a field free plasma is based on the observations that once the movable probe was within the negative glow its potential with respect to the anode was independent of its position. This conclusion is strengthened by the observation that on all tubes designed so far the appearance and behavior of the negative glow is independent of the location and size of the anode as long as the anode is in good electrical contact with the negative glow. In connection with these probe measurements, it is important to mention that no significant potential drop or field was observed in the neighborhood of or at the discontinuity.

The difficulties with the probe measurements together with the fact that it is almost impossible to design a probe sturcture that is capable of a true point measurement made it desireable to find out if these fields also could be measured in terms of the Stark shifts in the available optical line spectrum. A survey of the spectrum indicated that the transition $2^1P - 6^1D(4144\text{Å})$ would serve well for this purpose. The Stark shift measurements on this transition were in excellent agreement with the probe measurements and showed that the electric field was a linear function of the coordinate. These measurements will be reported elsewhere.

The probe measurements and the Stark shift measurements just discussed established beyond doubt the existence of the high potential drops and fields in the cathode region that are necessary for the generation of a uniform high energy electron beam at high pressures. For example, at a pressure of 1 Torr of helium and at a current of 70 mA, Fig. (6) shows that the cathode fall is 2000 volts. The corresponding distance d was approximately 1 cm. It follows then from formula (9) that the field at the cathode was of the order 3700 V/cm, a rather substantial field at this pressure. The probe measurements and the Stark shift measurements referred to in this paper are not taken under such circumstances that they provide a key to the cathode mechanism, since these measurements were done on tube A. This tube had a double cathode arrangement and the distance between the two cathodes was sufficiently short so that the electron beam from one cathode very likely interfered with the operation of the other. This interference is most likely the explanation for the difference between the voltage-current characteristics in Figs. (5) and (6).

4. The Negative Glow

The primary motivation for development of the brush cathodes was to generate well-behaved plasmas suitable for a series of investigations. It remains now to show that the plasma associated with the brush cathode is well-behaved.

A well-behaved plasma is obtained in tube A when the current through the tube and the voltage across it are larger than the values corresponding to the points C on the voltage-current characteristics. That the voltage-current characteristic is positive and the maintaining voltage is larger than the breakdown voltage when the tube is run in this manner account for the very high stability of the discharge. No oscillations or instabilities have been observed from very low frequencies up to 60 kGc/sec although a very sensitive spectrum analyzer was used as a detector. When the tube is run in the manner specified above, the space bounded by the two discontinuities and the tube envelope are completely filled with the plasma of interest. The following discussion concerns itself exclusively with the properties of this plasma.

The double cathode geometry with the intercathode distance small compared to the reaching distance of the beam is used to minimize non-uniformities associated with the attenuation of the electron beam in the high pressure gas. The source function S in Eq. (4) can then be assumed constant. The steady state normalized form of this equation is most suitably written as

$$\frac{1}{\xi}\frac{\partial}{\partial\xi}\left(\xi\frac{\partial\psi}{\partial\xi}\right) + \delta^2(1 - \gamma\psi^2) = 0 \qquad (9)$$

where

$$\xi = r/R, \qquad \psi = n/n_o$$

$$\delta = \frac{2R}{\Lambda}, \qquad \gamma = \frac{\alpha n_o^2}{S}, \qquad \Lambda^2 = \frac{4n_o D_a}{S} \qquad (10)$$

and where the boundary conditions now are $\xi = 0$, $\psi = 1$ in the center of the plasma and $\xi = 1$, $\psi = 0$ on the radial boundary. Two parameters, δ and γ appear in this equation. It is easily shown that, in view of the boundary conditions, the parameter δ can be expressed as a single valued function of the parameter γ. The solution of interest can therefore be written as $\psi(\xi,\gamma)$ and $\delta(\gamma)$. Since these solutions cannot be written in closed analytical forms, they were obtained numerically on NBS computers and are shown in Figs. (10) and (11). The parameter γ which expresses the influence of the volume recombination process, is in any realistic situation less than unity while the diffusion parameter δ is always larger than unity. That the recombination process has very little influence on the density profile unless γ is very close to unity is well illustrated in Fig. (10). The density profile is primarily determined by the diffusion process even if as much as 75% of the electrons and ions are lost by the recombination process.

The observations made on the plasma in tube A filled with helium fit qualitatively very well with the theoretical picture given above. At the pressure of 1 Torr, the major part of the volume is filled with a plasma that has the pink color so characteristic of the negative glow in helium. It has a uniform appearance and is separated from the tube walls and the discontinuities by a relatively dark green plasma. The thickness of the green boundary range is approximately 1 cm at 1 Torr and is observed to be approximately inversely proportional to the pressure. The pink color associated with the helium negative glow is known to be caused by a volume recombination process[2] that is a strong function of the electron temperature. Heating the electron gas in this plasma with either a microwave or an rf signal causes the pink glow to decrease in size and intensity as is expected according to the theoretical model presented above. The thickness of the green boundary range is approximately equal to Λ, the diffusion length. This diffusion regime is represented in Fig. (10) by the range in which the electron density decreases very fast. A crude comparison between these curves and the observations on the plasma indicate then that volume recombination is by far the dominant electron loss process in the plasma in its cold condition. By increasing the electron temperature sufficiently, it is possible to eliminate the pink glow completely. The volume bounded by the discontinuities and the tube wall is then completely filled by the dark green plasma which looks so uniform that even boundary ranges cannot be observed. The light observed in this state of the plasma is presumably entirely beam excited. With further increase of the heating power, one can actually observe a breakdown process. In the center of the tube appears a glow with the pink-yellow color that is observed in the positive column of an ordinary helium discharge.

The phenomenological description of the behavior of the plasma under the influence of pressure and temperature variations also fits the theoretical model suggested in this paper. However, better evidence is required in terms of more exact measurements of the electron temperature and the electron density. These two parameters are measured with Langmuir probes, microwave techniques and spectroscopic observations.

Two 1 cm long Langmuir probes made of platinum wire, with the diameters 0.010 and 0.001 in. were inserted in the center of the plasma just under the anode. The probe characteristics were measured with the anode as reference electrode. Considerable difficulties in obtaining reproducible characteristics were experienced in the beginning. The characteristics exhibited time dependent hysteresis effects. By running the discharge for considerable times and simultaneously bombarding the probe with the electrons available in the plasma, the hysteresis effects were eliminated and the characteristics became very reproducible.

Figure (12) shows a semi-logarithmic plot of the electron branch of the characteristic for the large probe taken at a discharge current of 150 mA and at 1 Torr pressure. The curve is normalized with respect to a point well up on the electron branch. In the ideal case for a Maxwellian velocity distribution, the semi-logarithmic plot should yield a straight line. All characteristics taken with the larger probe exhibit curvature of the kind shown in the figure. This kind of curvature is expected when the voltage drop caused by the probe current through the plasma is a significant fraction of the plasma potential. The electron branch of the probe characteristic then must be written as

$$\frac{i}{i_o} = e^{-\frac{e}{kT}\left[V - \frac{i}{i_o}(i_o R_p)\right]} \tag{11}$$

where R_p is the resistance in the plasma between the probe and the anode. If this mechanism really is responsible for the observed curvature, the voltage drop $i_o R_p$ can be evaluated from the curvature and through a simple correction true probe characteristic can be obtained. The corrected curve is the broken line in Fig. (12). The electron temperature obtained from the corrected probe curve is 1009^oK. The corresponding temperature from the uncorrected curve is in the neighborhood of 1200^oK showing that the correction is rather substantial.

Merely the presence of the curvature in the semi-logarithmic probe characteristic is not a sufficient excuse for the introduction of this correction process. Experience with the smaller probe gives strong support to the contention that the voltage drop in the plasma is the cause of the curvature. A second reason is that the corrected temperature agrees within experimental error with the electron temperature obtained from spectroscopic measurements. The third reason is that the plasma resistance obtained from the probe characteristic agrees within reason with the corresponding resistance evaluated from the plasma parameters.

The experience from the measurements with the large probe indicated that is surface was too large to give the electron saturation current and thereby the electron density. The conclusion was that the saturation current was comparable with or larger than the anode current (150 mA), corresponding to an electron density comparable to or larger than $2 \times 10^{10}\,\mathrm{cm}^{-3}$. The smaller probe was inserted with the hope that it would give a reasonable saturation current. The smaller probe gave consistently 200 to 300 degrees higher electron temperature than the larger probe. Also, the corresponding characteristics deviated more from the ideal probe curve than the characteristics obtained with the large probe. Something akin to a saturation effect was seen but it was decided that it was probably due to other effects. That the voltage drop in the plasma due to the probe current itself gives rise to such a saturation effect is easily seen from formula (11). This effect is more evident for a small probe than for a large probe since the resistance R_p is larger for the small probe. Another effect that brings in an artificial saturation is the heating of the electrons in the vicinity of the probe. This effect is also more prominent for a small probe than for a large probe. The data obtained with the small probe were not sufficiently accurate and reproducible to disentangle these two mechanisms and therefore were rejected. The kind of difficulties with the probe measurements observed in this experiment are not general. They are peculiar to the kinds of plasma generated in the brush cathode tube where the electron density is high and the electron temperature is low.

The unusual properties of the brush cathode plasma make it particularly interesting to find out whether spectroscopic methods used[3] as diagnostic tools on certain hydrogen plasmas can also be used for measurements of the electron density and the electron temperature in the helium brush cathode plasma. Preliminary studies of the optical emission spectrum from the helium brush cathode plasma revealed that the series $2\,s\,^3S - np\,^3P^0$ was quite suitable for this purpose. Under some conditions, it is possible to observe lines in this series up to the quantum level $n = 30$. The melting of this series and the associated continuum is shown in Fig. (13). The variation of intensity in the continuum as well as that of the higher lines in the series as function of the wavelength can be used for measuring the electron temperature. Figure (14) shows the appropriate semi-logarithmic plots derived from the measurements at a discharge current of 150 mA and at a pressure of 1 Torr. The two lines have approximately the same slopes giving a temperature of 1095°K. This is a little more than 100 degrees higher than the corrected temperature obtained with the larger Langmuir probe. This agreement is excellent since the probe can be expected to cool the plasma surrounding it. The Inglis-Teller theory[4] relates the melting of the lines to the electron density within a factor of two. The melting is defined in this theory as the point where the width of a line is equal to the separation between two neighboring lines. The quantum number for melting in the case mentioned above is 25 and corresponds to an electron density of approximately $3 \times 10^{12}\ \mathrm{cm}^{-3}$ according to the Inglis-Teller theory. That this is approximately the correct electron density was confirmed with the help of a microwave interferometer using 8 mm waves.

The low electron temperature and the high electron density as measured with the probes, the microwave interferometer and the spectrometer agree with each other and with the crude theoretical model suggested here. The low electron temperature is consisten with the concept of a field free plasma. The energy of the electrons in the beam is apparently sufficiently high so that the beam does not interact with the various wave mechanisms in the plasma. The only energy that is delivered to the plasma is probably the energy associated with an electron that is freed in the ionization process. The low electron temperature gives a very low diffusion loss rate allowing the design of discharge tubes where the volume recombination loss process is by far the dominant loss process under steady state conditions as is the case with the tubes discussed in this paper. The evidence presented above is further enhanced by considering the particle balance and the energy balance.

From the observations that have been discussed so far, it is evident that in the first order approximation, the energy of the electron beam is equal to the voltage drop across the tube and that the beam current is equal to the discharge current. This circumstance allows the calculation of the rate of production S of electron-ion pairs per unit volume. At the discharge current 150 mA and the pressure 1 Torr, it is seen from the characteristic in Fig. (5) that the voltage drop across the tube is 2340 volts. The curve for helium in Fig. (1) gives a reciprocal ionization mean free path s(V) of 0.21 cm^{-1}. From the discharge current and the cross section of the tube, one finds that the current density in the beam is 3.3×10^{-3} A cm^{-2}. Introducing these data into formula (1), we obtain a rate of production S of $4.4 \times 10^{15} \mathrm{sec}^{-1} \mathrm{cm}^{-3}$. Since the electron density is measured to be $3 \times 10^{12} \mathrm{cm}^{-3}$, one obtains from Eq. (7), the value 5×10^{-1} $\mathrm{cm}^{3} \mathrm{sec}^{-1}$ for the recombination coefficient. This is almost identical with the value predicted by the collisional-radiative recombination theory developed by Bates, Kingston and McWhirter.[5] The collisional-radiative recombination theory mentioned above applies to the atomic hydrogen ion plasma. The authors of the theory have made similar calculations for the alkali ion plasma and found that the result was rather insensitive to the species of singly charged ion. The theory therefore most likely applies to the helium plasma. The agreement between measurements presented in this paper and the collisional-radiative theory is better than anticipated in view of the rather crude approximations that have been used in deriving the source function S and should be taken with some reservation until confirmed by more extensive measurements of the recombination coefficient as function of the electron density and the electron temperature.

Assuming that the ions are in thermal equilibrium with the parent gas and that the cool plasma electrons experience only elastic collisions, it is easily shown from the moment theory that the energy balance can be formulated as

$$\frac{T_o - T_g}{T_e} = \frac{M}{3m} \frac{S}{n(\nu_{ei} + \nu_{eg})} \cdot \frac{\Delta V}{V_e} \qquad (12)$$

where ν_{ei} is the collisional frequency for the interaction between the electrons and ions referred to an average electron, ν_{eg} the corresponding frequency for the interaction between the electrons and the neutral gas atoms, where T_g is the temperature of the parent gas, T_e the electron temperature and $V_e = kT_e/e$ and ΔV is the average energy in electron volts of the low energy electrons that are generated in the ionization process by the high energy electron beam. The electron temperature is so low and the electron density so high that the electron-ion collision frequency is more important than the electron-neutral collision frequency. Using Allis's formula[6] for the conductivity in a fully ionized plasma, the collision frequency ν_{ei} for this particular plasma is found to be the order of $2 \times 10^9 \text{sec}^{-1}$. Using the measured electron density and the calculated rate of production S, the factor in front of $\Delta V/V_e$ of Eq. (12) is of the order 10^{-3}. Since the electron temperature expressed in electron volts in this case is of the order 0.1 volt, it follows that ΔV must be of the order of 10 volts to give 10% difference between the temperatures of electron gas and the parent gas. This is probably a high value since the energy ΔV we are concerned with here is the energy that is fed into the cool electron gas. It is very likely that the corresponding value for ΔV is only a fraction of the ionization energy. The electrons with energies in the range of the excitation and ionization energies would most probably dissipate the major part of their energy in inelastic collisions. The calculations above indicate therefore that there cannot be a large temperature difference between the electron gas and the parent gas in a beam generated plasma, as is confirmed by the observations. Most of the energy in the brush cathode tube is dissipated in the cathode region and, in particular, in the cathode. The cathode and the cathode region are unfortunately in good thermal contact with the gas,probably accounting for the relatively high temperature that was observed.

The existence of the very sharp discontinuity in front of the cathode has already been mentioned in the discussion of the brush cathode plasma from a phenomenological point of view. The probe measurements have indicated no potential or field discontinuity in that neighborhood. A possible explanation for the discontinuity may be obtained in terms of the non-linear diffusion or flow theory that the author has discussed in an earlier paper.[7] A rather striking observation supports this contention. It has been mentioned that the recombination dominated plasma is separated from the tube walls by a boundary range with quite different color and with a thickness corresponding to the diffusion length. The discontinuity is separated from the recombination dominated plasma in identically the same fashion. The thickness of the boundary layer in front of the discontinuity is the same as that in front of the tube walls and responds in the same manner to variations in the pressure and temperature. The discontinuity behaves therefore as a boundary to the recombination dominated plasma. It was shown[7] that the influence of the inertia of the ions on the diffusive flow gives rise to a non-linearity which demands that the drift velocity is equal to the random thermal velocity (Mach number = 1) on a boundary that can be considered as an infinite sink (the tube walls). It was also shown that if the drift velocity for some physical reasons must increase beyond the random thermal velocity, it can do so only if it is accompanied by a more or less discontinuous change in the drift velocity and the density when the Mach number is equal to unity. The situation in front of the cathode is such that the ion drift velocity will necessarily exceed the random thermal drift velocity before the ions reach the cathode. The observed discontinuity is then most likely located at the point where the ion flow has reached the Mach number unity.

The discussion of the brush cathode plasma will be terminated with a few words about the reasons why it does not exhibit any spatial find structures (striations) and why the plasmas that are generated by electromagnetic fields generally will be plagued by these structures. This is best shown with the help of the equation

$$D_a \nabla^2 n + S = \alpha n^2 \tag{13}$$

which expresses particle balance in the steady state plasma. To the author's knowledge, there has never been generated by electromagnetic fields in the laboratory a plasma where the recombination is the dominant loss mechanism. The recombination term can therefore be neglected for these cases. Furthermore, the source term in the electromagnetically generated plasma is proportional to the electron density and is generally written as $S = \nu_i n$ where ν_i is the ionization frequency referred to in an average plasma electron. This leads to the following particle balance equation

$$D_a \nabla^2 n + \nu_i n = 0. \tag{14}$$

This is, however, an eigenvalue equation which has a simple solution only if

$$\nu_i = \frac{D_a}{\Lambda_o^2} \tag{15}$$

where Λ_o is the diffusion length for the container corresponding to the lowest eigenvalue. Both ν_i and D_a are generally strong functions of the electron temperature or the electric field. The implication is then that the simple solution is obtained only for a unique electron temperature, electric field and electron density. If these parameters differ from these unique values, it follows that the solution to Eq. (14) must be written as a sum of the fundamental mode and a whole series of higher modes. This is the situation in which the plasma exhibits spatial fine structure. Consider now the beam generated plasma to which Eq. (13) applies. The source term is in this case for all practical purposes independent of the plasma electron density. The beam electron density is several orders of magnitude less than the plasma electron density and the source function S can be considered as constant. Equation (13) even in the absence of the recombination term is no longer an eigenvalue equation. It gives a solution where the electron density decreases monotonically from the center of the plasma to the boundary with the profile determined uniquely by the parameters of the equation. The solution exhibits no spatial fine structure.

5. Summary and Conclusions

A new gas discharge cathode, the brush cathode, has been developed and shows considerable promise for a whole series of applications and investigations. The design of the cathode is such that some of the secondary emission effects that are invoked in the operation of the common cold discharge cathodes are de-emphasized, resulting in much higher cathode fall than is ordinarily observed. The high cathode fall results in the generation of a uniform electron beam with a diameter determined by the dimension of the cathode or the discharge tube, with a beam energy corresponding to the cathode fall and with a beam current approximately equal to the discharge current. The upper limit of the diameter of the beam, if it is to be thought of as a uniform beam, is determined by the self-magnetic field and this limit can be neglected in most laboratory experiments. The reaching distance of the electron beam determines the longitudinal extension of the negative glow. The energy of the beam is sufficiently large so that it has a considerable reaching distance in helium even at rather high pressures. The longitudinal extension of the negative glow is from one to two orders of magnitude larger than ordinarily is observed. This large size makes the negative glow associated with the brush cathode a very useful laboratory medium.

The properties of the brush cathode give a unique character to the discharge and the associated plasma. The discharge can be made to have a positive voltage-current characteristic with a maintaining voltage that is several times larger than the breakdown voltage. This is reminiscent of the characteristic obtained in the abnormal glow region for ordinary cold cathodes. This characteristic behaves in a similar manner with increasing current until it goes over to an arc characteristic due to the formation of an arc spot on the cathode surface. The design of the brush cathode prevents the formation of the arc spot. The positive voltage-current characteristic and the high maintaining voltage of the brush cathode discharge probably accounts for the lack of instabilities and oscillations. The voltage-current characteristic can be made flat over a very large current range making these tubes suitable as voltage stabilizers. The stabilized voltage can be made larger or smaller than the breakdown voltage depending on the pressure, the design of the tube and how it is operated.

The very large negative glow and the high energy electron beam are the most interesting features of the brush cathode plasma. The negative glow is beam maintained and recombination dominated. It has high electron densities, low electron temperatures and lacks spatial fine structure. It is suitable for a whole series of investigations. Perhaps the most obvious investigations are studies of rate and transport coefficients as function of the electron density, electron temperature, the pressure and nature of the parent gas. Diffusion and recombination coefficients have in the past generally been obtained from measurements on decaying plasmas with initial conditions essentially unknown, a situation that generates considerable uncertainties with regard to identification of processes. These processes can be studied in a brush cathode plasma under steady state conditions and be uniquely identified. Several kinds of diagnostic tools and methods can be applied simultaneously and the measurements can almost be termed precision measurements. The negative glow of the brush cathode plasma also gives a better initial condition for the decay measurements than those used in the past. It is particularly important for decay experiments that the initial electron temperature is as close as possible to the temperature during the decay and that the initial density profile is well known. The negative glow is also very suitable for measurements of the electrical conductivity and the heat conductivity as a function of the electron density and the electron temperature.

The negative glow of the brush cathode discharge can be made sufficiently large and uniform so that it indeed becomes possible to study the behavior of different wave mechanisms in the presence and absence of a uniform steady magnetic field and under steady state conditions. The negative glow can be made large enough to be considered essentially infinite.

The negative glow is far from thermal equilibrium. The electrons in the plasma are generated by extremely energetic electrons in the beam. The cool electrons are lost by recombination. Only the quantum levels that are close to the continuum are populated in a Saha-equilibrium with the free electrons. The populations in the lower quantum level can therefore be expected to deviate from this equilibrium and perhaps show population inversions. This is a condition that is necessary for laser operation. The important aspect of this plasma is, however, that such population inversions do not depend on wall mechanisms. If the population inversions can be found or generated in the brush cathode plasma, one can then generate laser beams with very large cross sections.

The presence of the high energy electron beam raises considerable hope for the possibilities of converting part of its energy into useful coherent or incoherent electromagnetic radiation in the very high frequency range. Coherent radiation would be obtained by designing the plasma such that the beam couples strongly to one of the plasma wave mechanisms. Incoherent radiation would be obtained from scattering of the electron beam against the ions and the neutral particles. The latter situation seems to be particularlu promising in the presence of a longitudinal magnetic field. The upper limit for the current that can be carried by the brush cathode has not yet been found. The present cathodes have been operated up to 0.5 A with a cathode fall in the range 3000 to 5000 volts and have shown no tendency to deviate from the behavior that is described in this paper. It is obvious from the facts that have already been mentioned that the negative glow associated with the brush cathode lends itself particularly well to a whole series of spectroscopic investigations.

6. Acknowledgments

The investigation presented in this paper would not have been successful without the cooperation of a number of people here at the National Bureau of Standards Boulder Laboratories. F. B. Haller was particularly valuable for his help in the design and manufacture of the brush cathodes, the tubes and in the general investigation. The spectroscopic measurements were made by Drs. R. L. Barger and A. L. Schmeltekopf, while H. Wassink was of considerable assistance in the microwave measurements.

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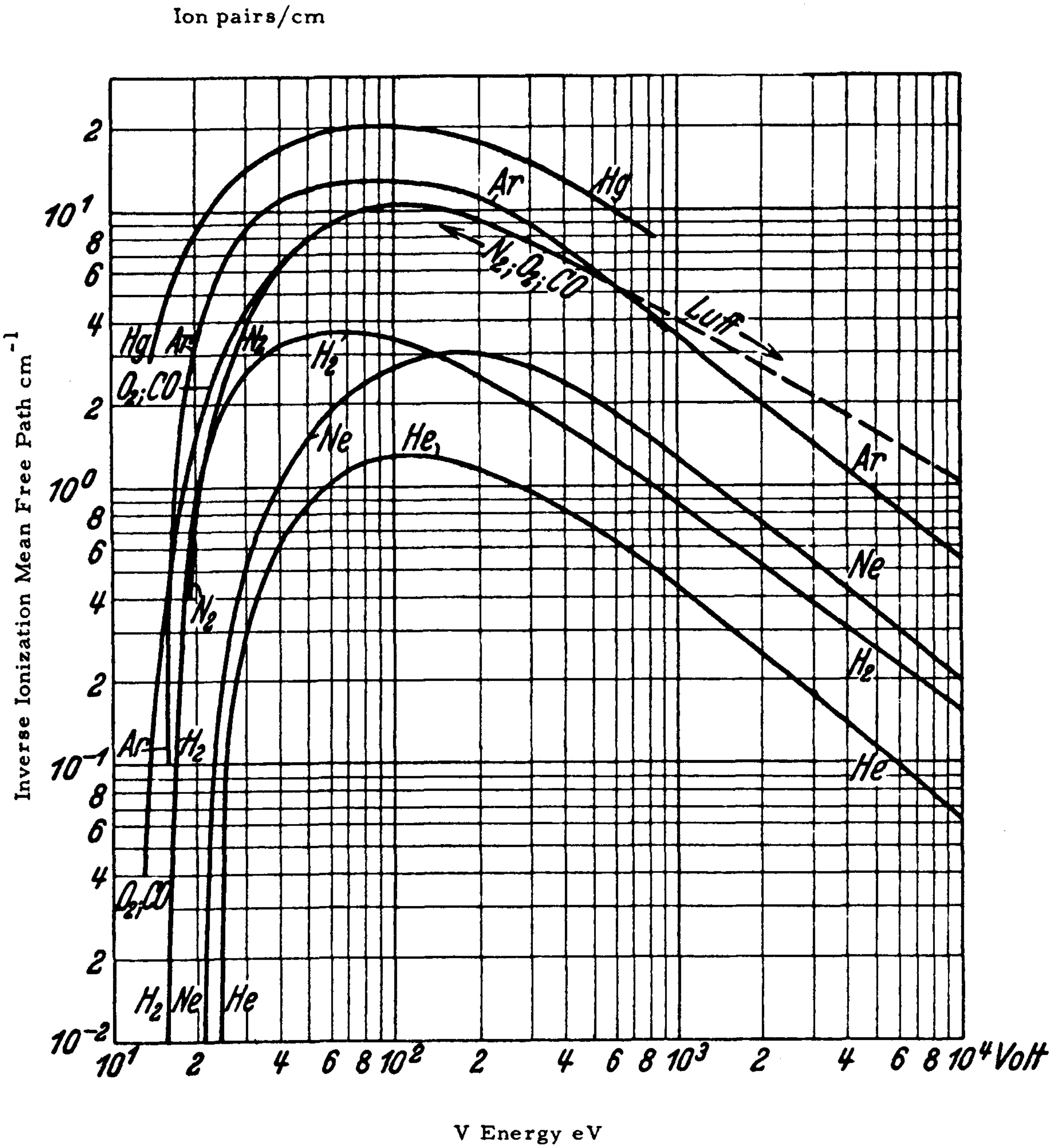

Fig. 1 The inverse ionization mean free path as function of the electron energy

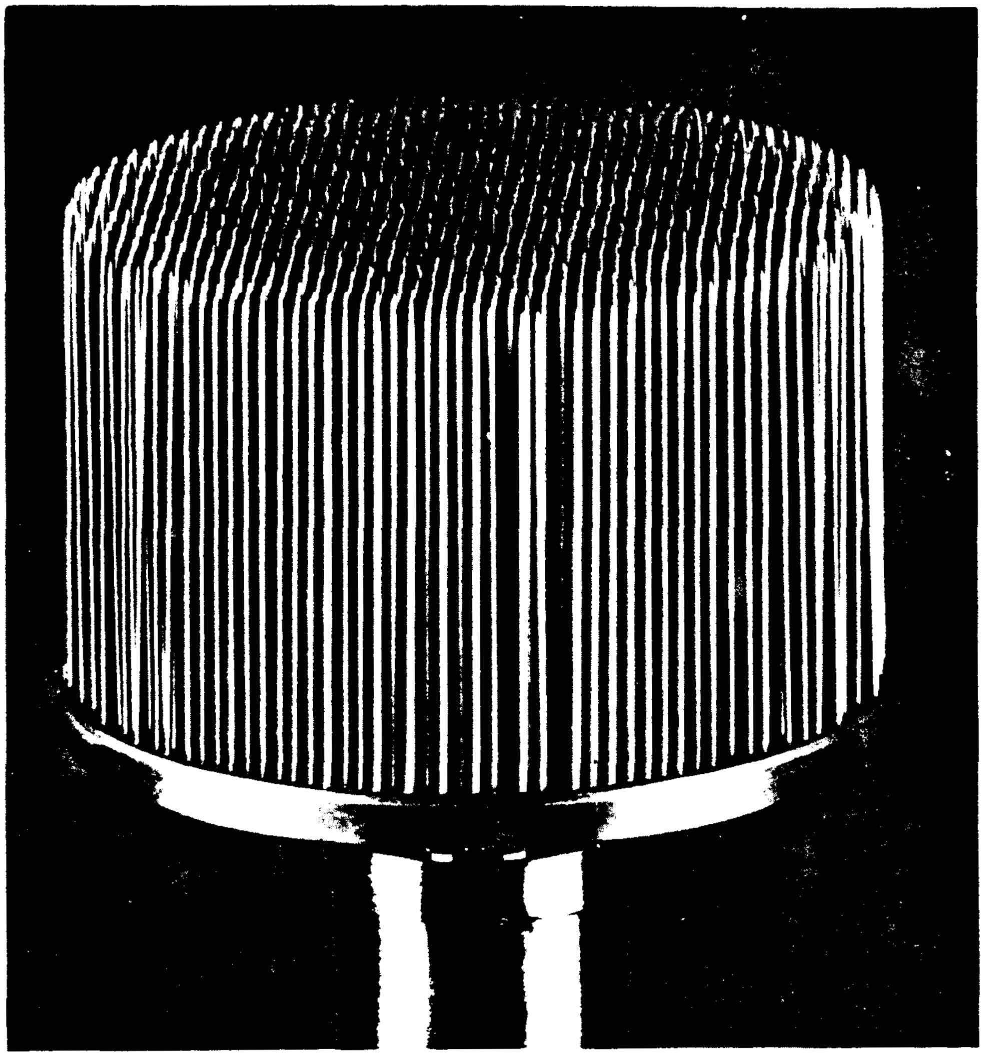

Fig. 2 The brush cathode

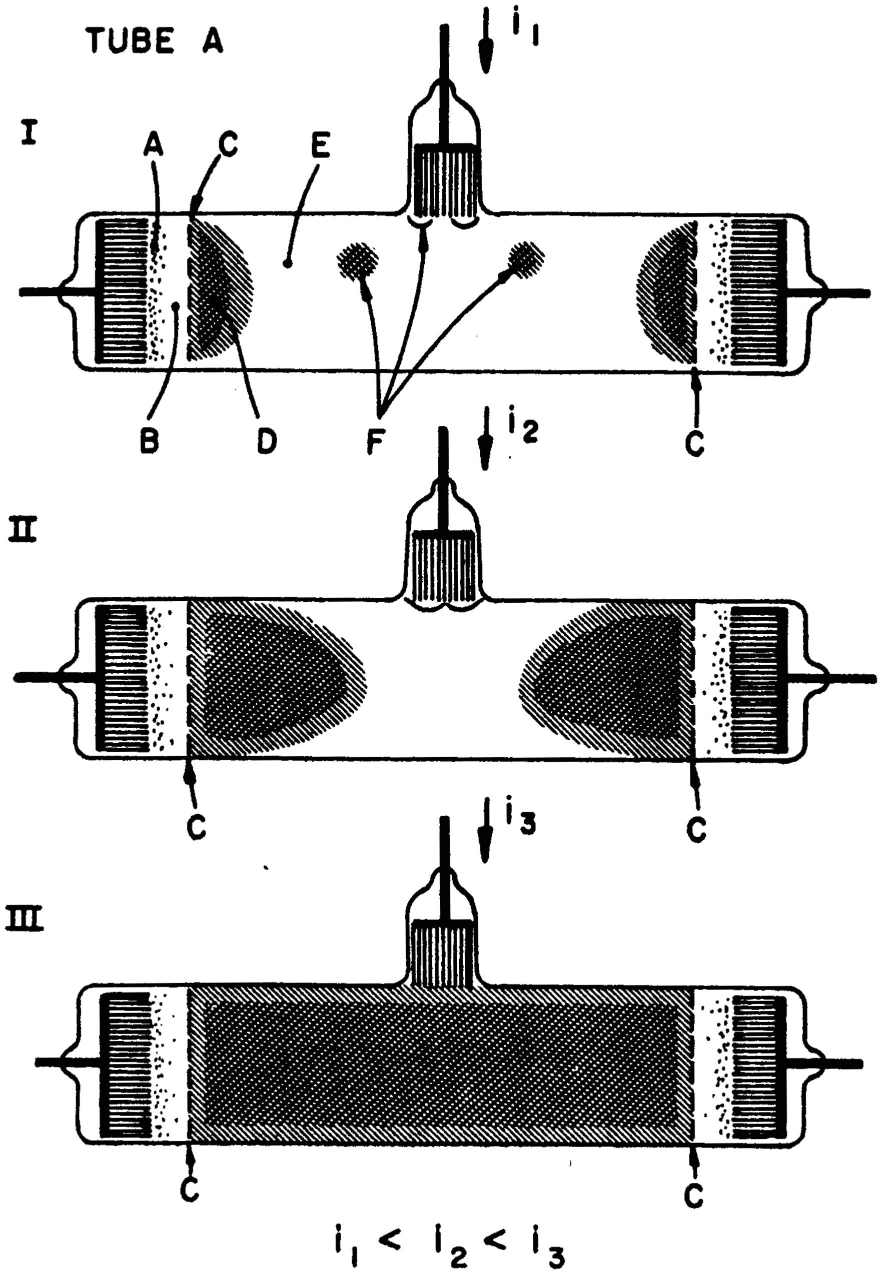

Fig. 3 The double brush cathode discharge tube. Tube A

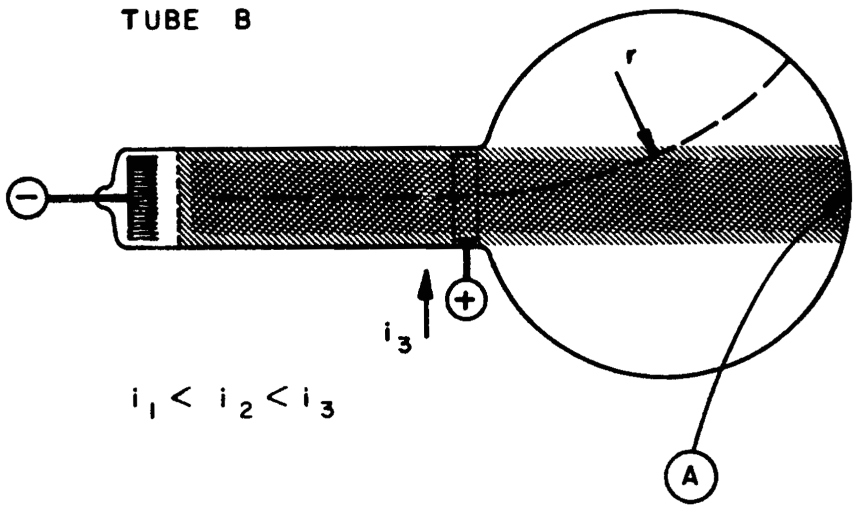

Fig. 4 The single brush cathode discharge tube. Tube B

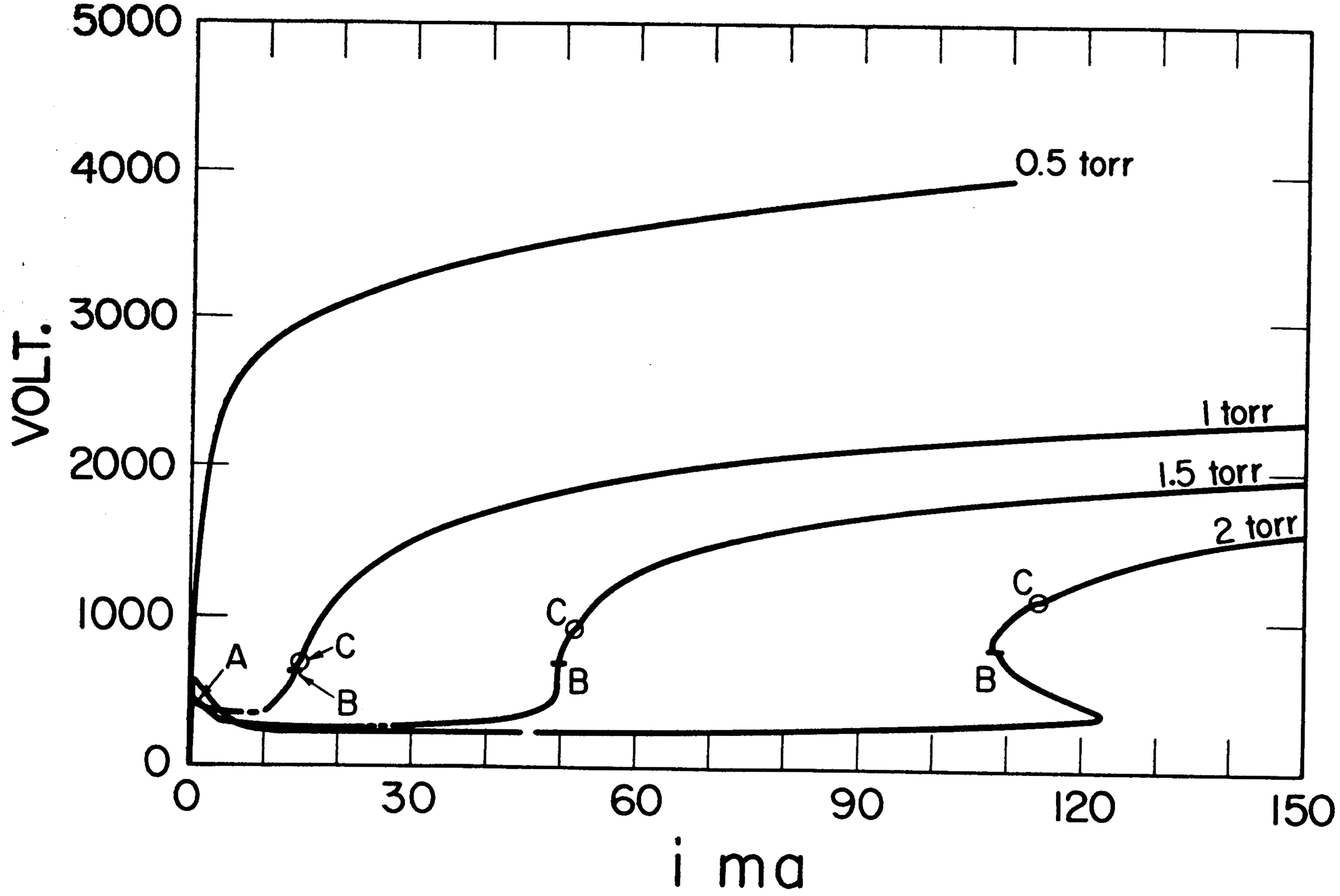

Fig. 5 The voltage-current characteristics for tube A in double cathode operation

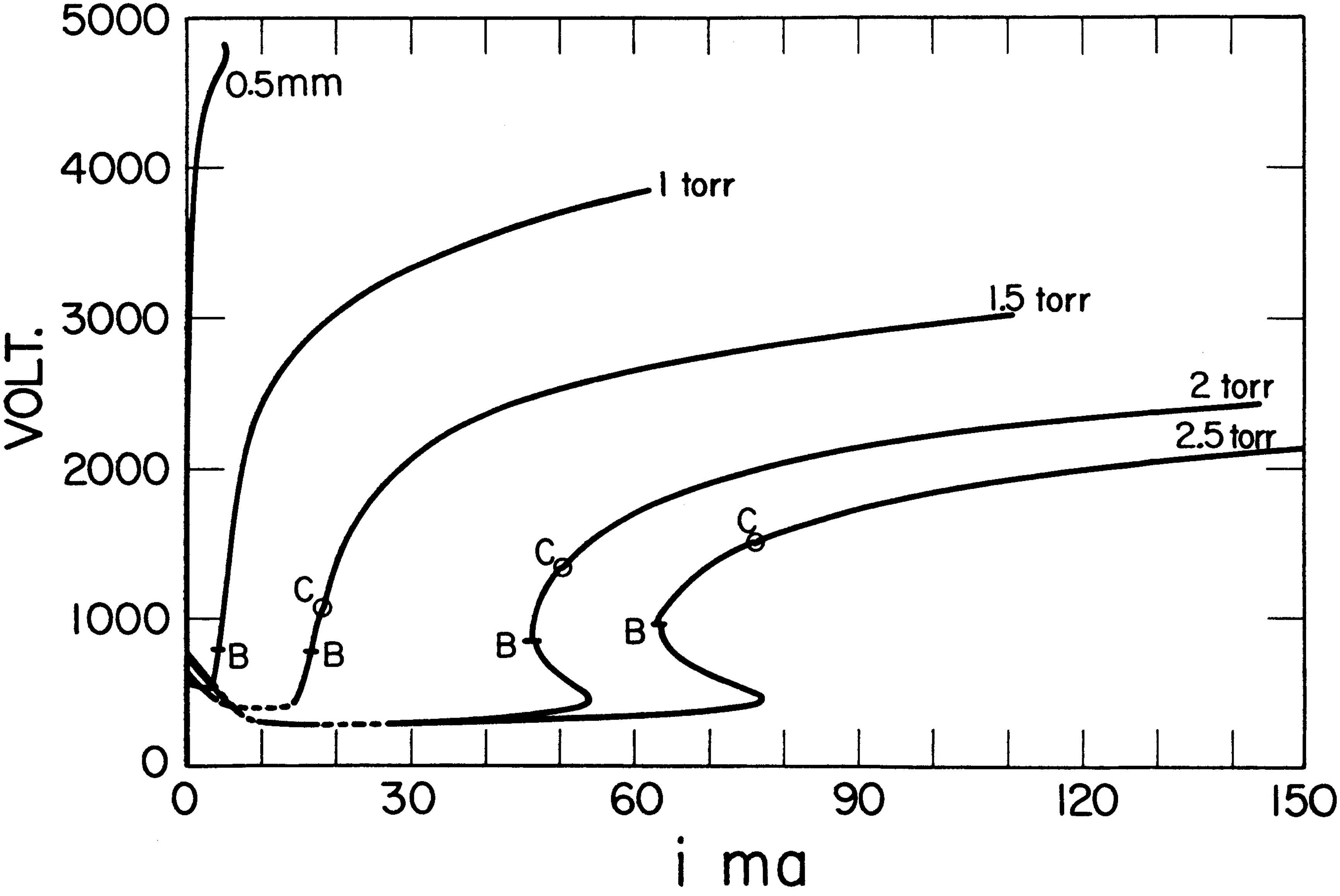

Fig. 6 The voltage-current characteristics for tube A in single cathode operation

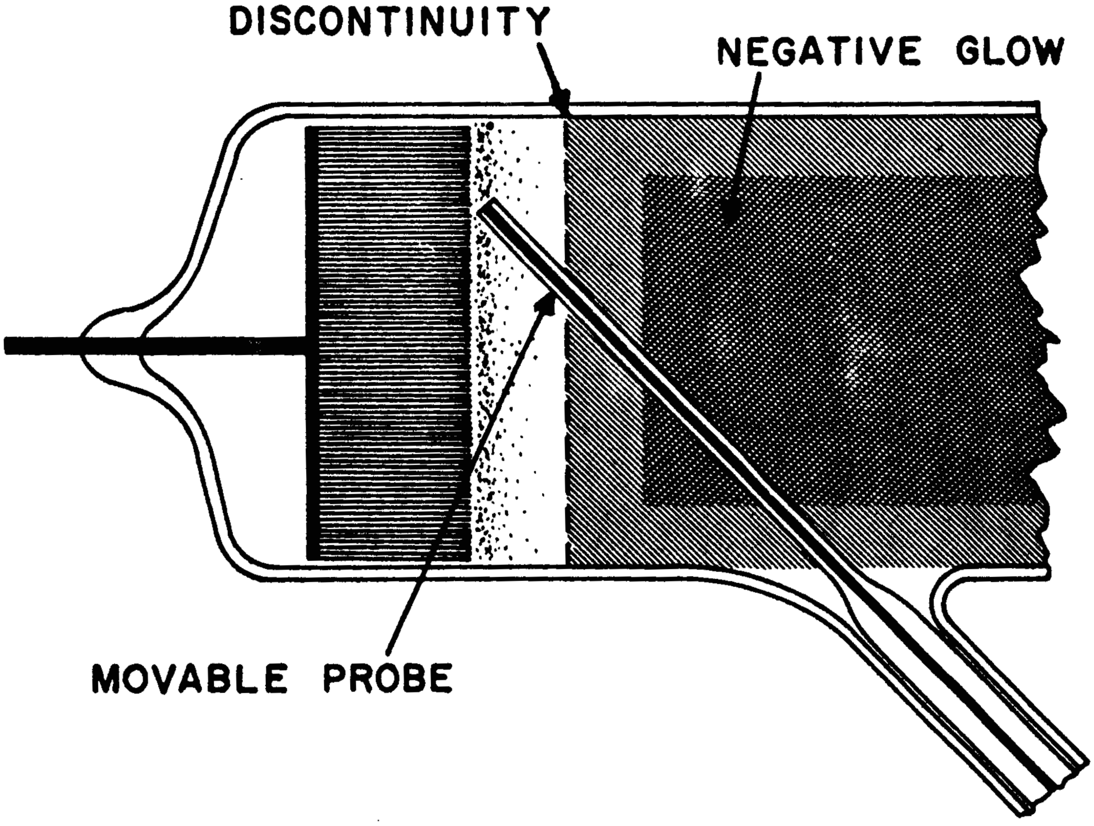

Fig. 7 The movable probe for investigation of the potential distribution in the Holm dark space

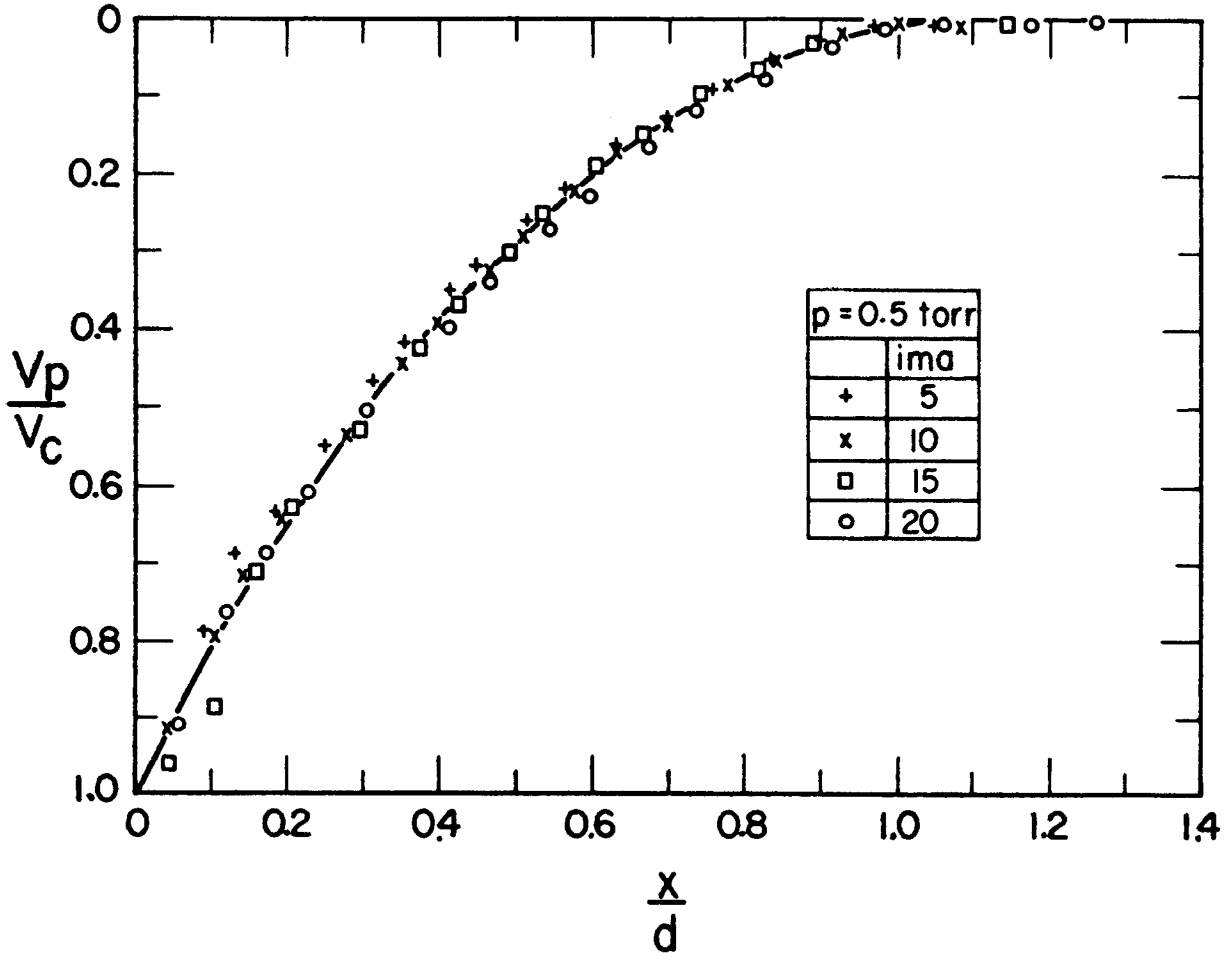

Fig. 8 The potential distribution in front of the brush cathode

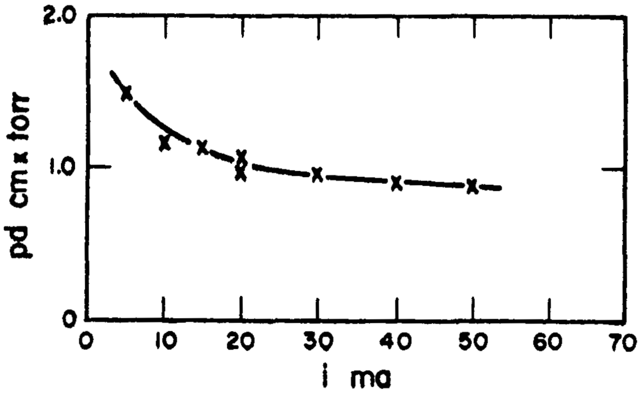

Fig. 9 The product pd for the dark space in front of the brush cathode as function of the discharge current

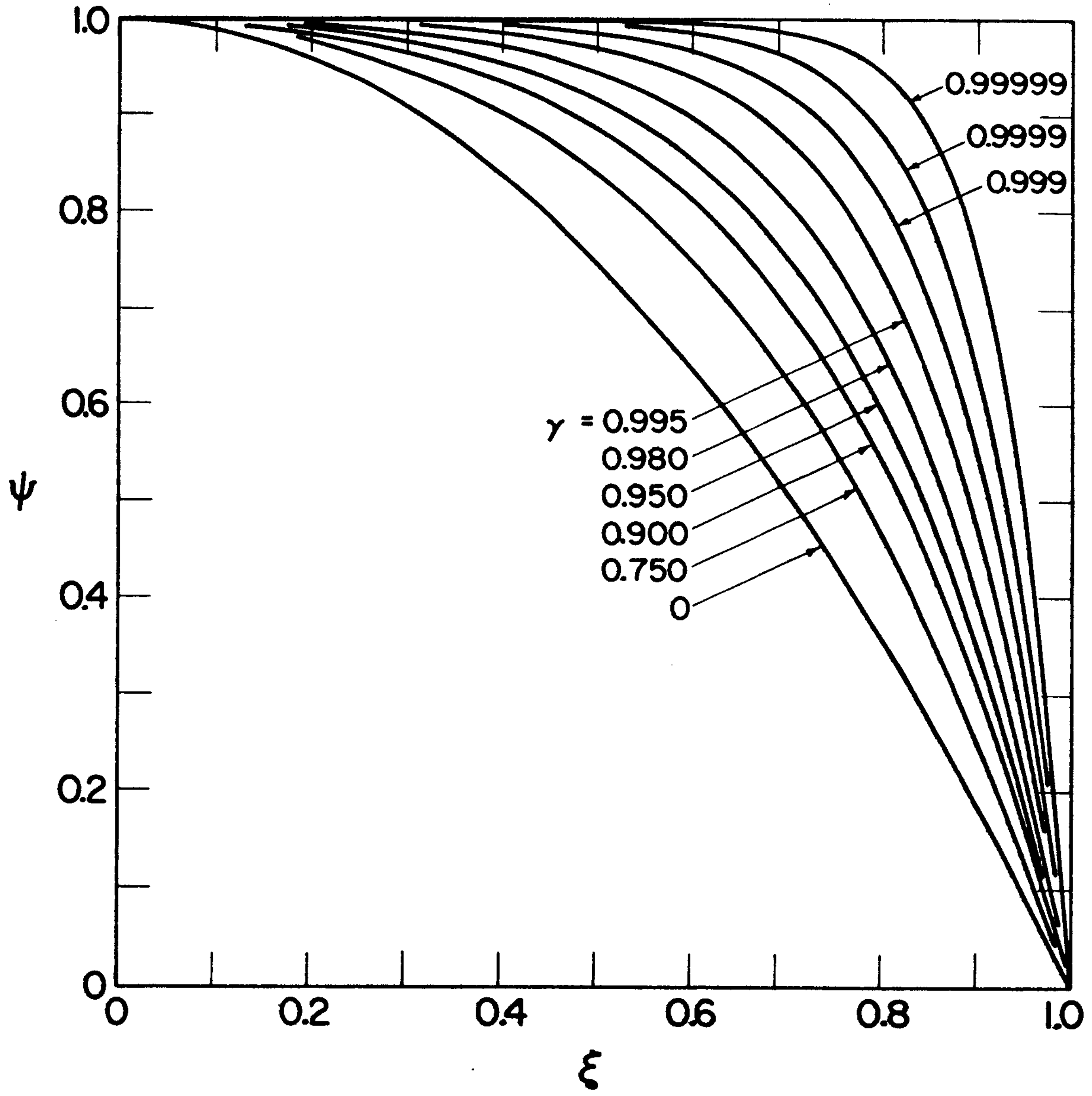

Fig. 10 The normalized electron density distribution

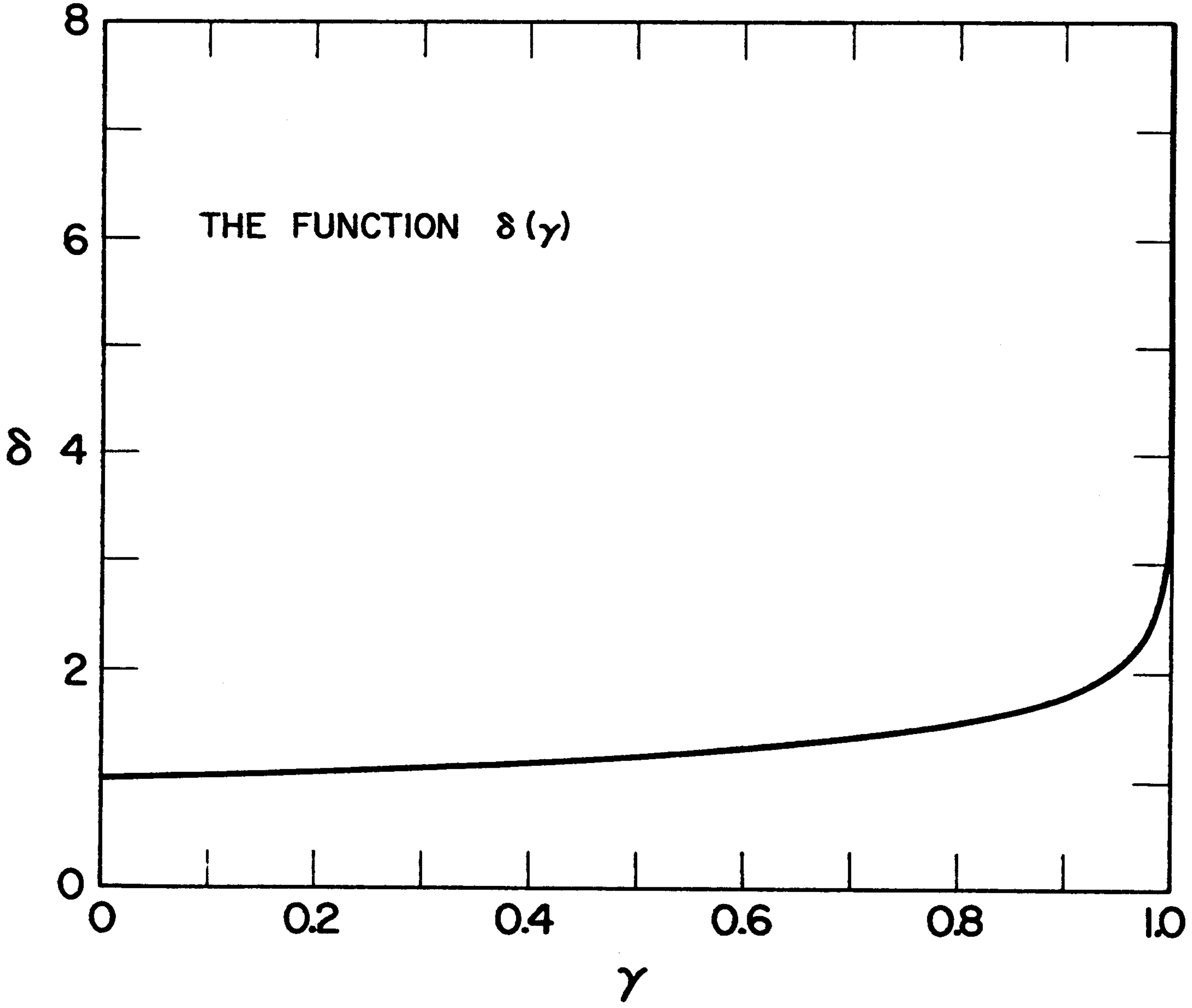

Fig. 11 The diffusion parameter δ as function of the recombination parameter γ

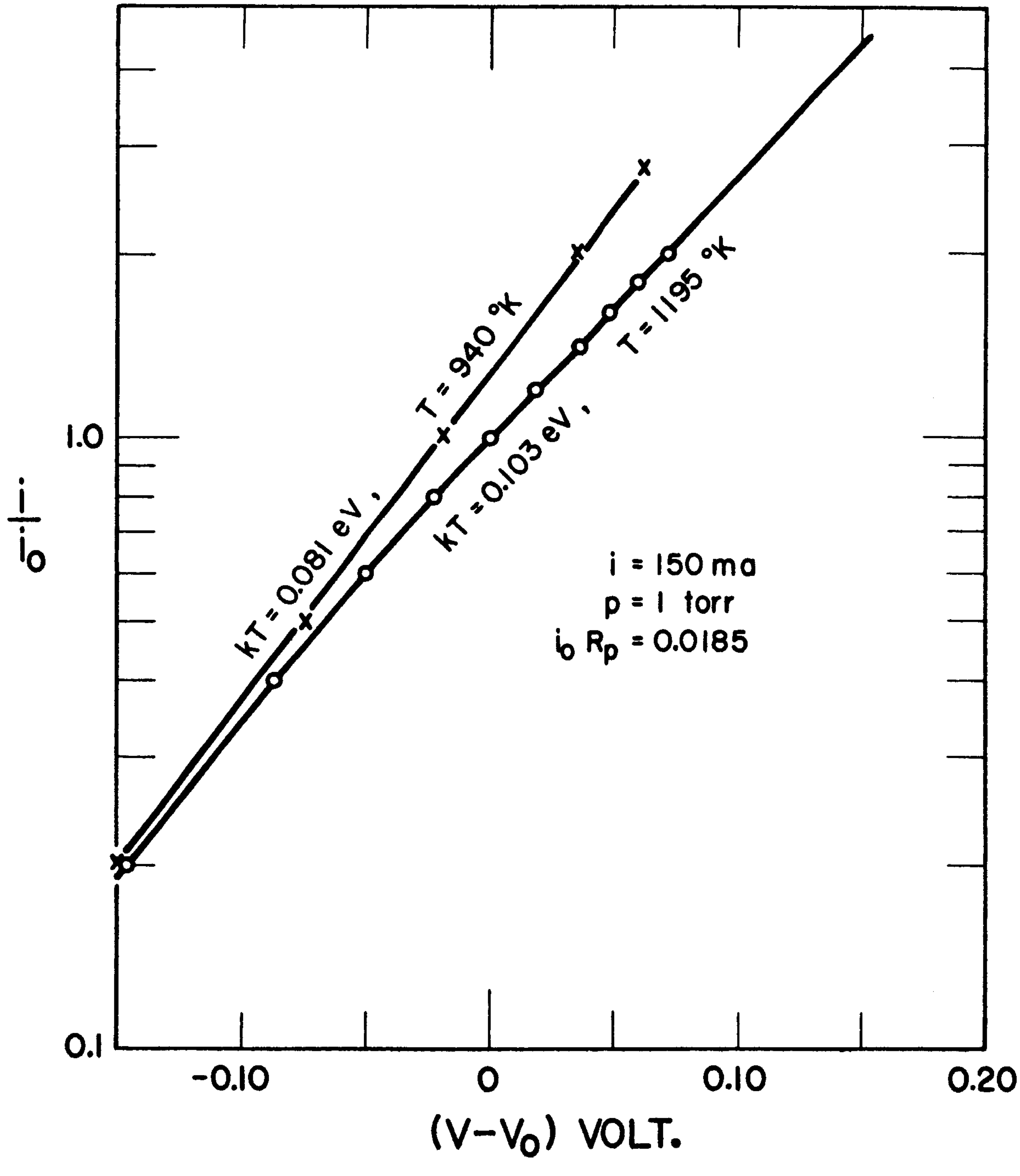

Fig. 12 The normalized probe curve

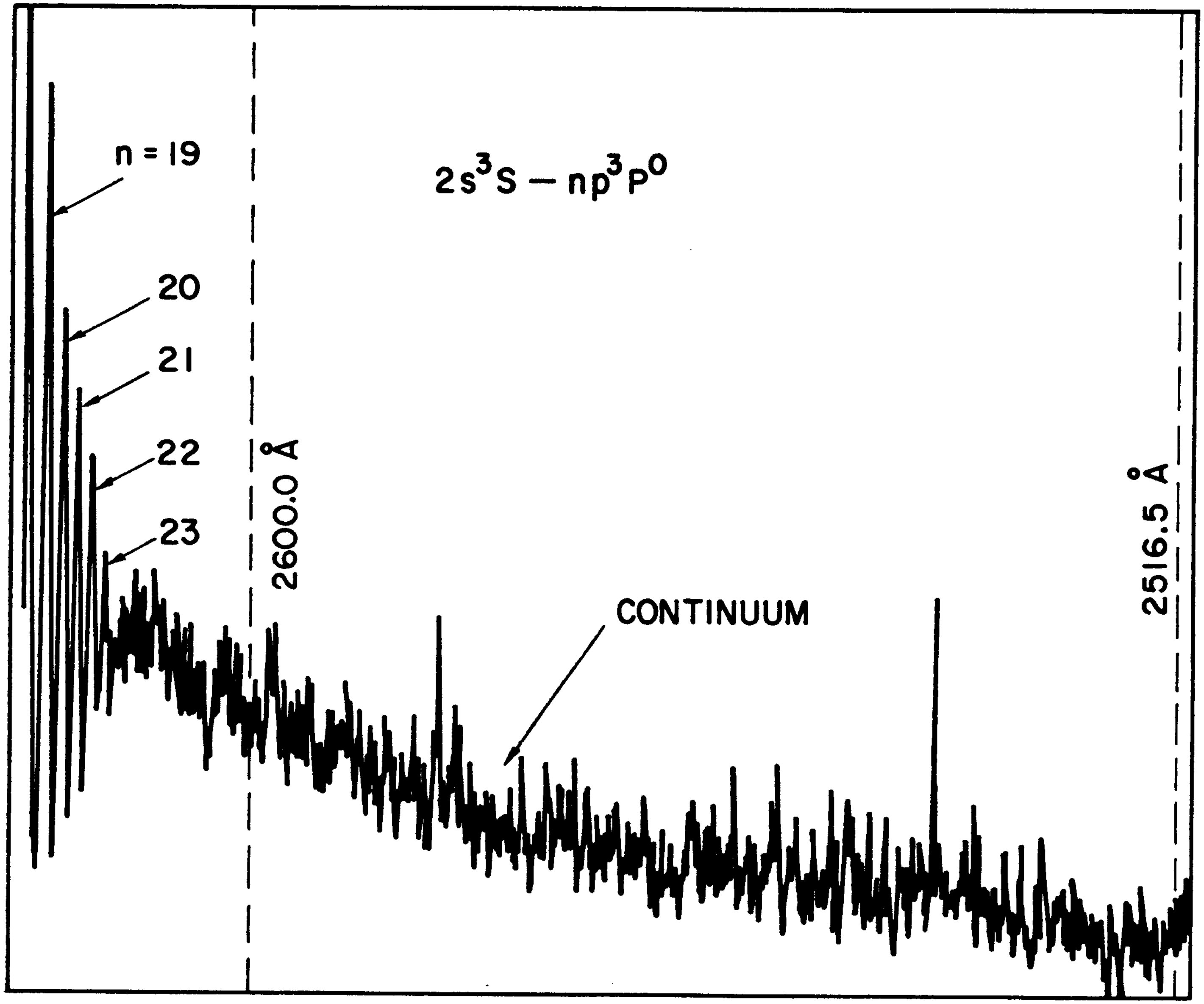

Fig. 13 The melting of the series $2s^3S - np^3P^0$

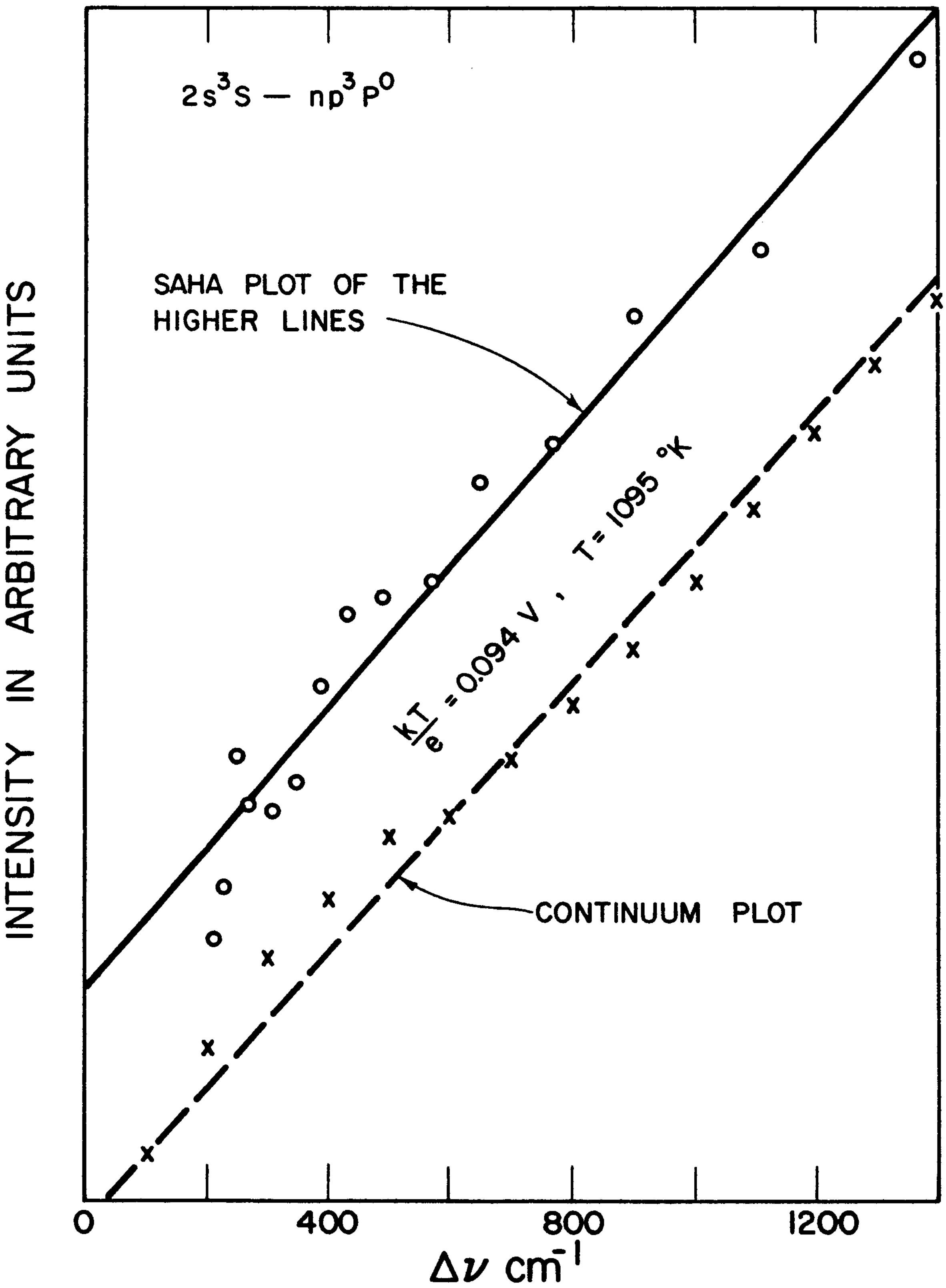

Fig. 14 The semi-logarithmic plots of the intensities of the series 2s^3 - np^{3}P^0 and the corresponding continuum