Asymmetry of Collector Currents

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The two unsymmetrical components of current to a collector in mercury vapor were separarely measured from the anode and the cathode directions. A collector taking current from both directions would receive the approximate sum of these unsymmetrical components. Sets of readings at different positions in an arc type of discharge show that both random electron currents and random positive ion currents are greater to the cathode face of the collector than to the anode face except in a region near the cathode where exactly the reverse is true. Determinations of space potentials and electron energies were not greatly affected by the asymmetry of the currents but determinations of electron concentrations were and the results indicate a region of maximum concentration from which positive ions and electrons may diffuse or drift in both directions. From a consideration of the rate of absorption of the primary beam a value of the mean free path is obtained and the region of maximum ionization appears at approximately this distance from the cathode.

INTRODUCTION

IN several recent papers[1, 2] on the subject of measurements with collector electrodes the assumption has been stated or implied that the energy distribution of the electrons or ions is essentially isotropic. This ideal state may be approximated under certain conditions as, for example, in a uniform positive column which is shielded from the primary electrons emitted by the filament but, in general, the nature of current flow in a gas demands an essential asymmetry which may differ considerably in different regions of a discharge and which may appreciably affect collector measurements. Especially in discharges between a hot cathode and an anode not far removed, as in some recent experiments, the asymmetry may be considerable. Such a lack of symmetry may be due in part to a beam of primary electrons from the cathode, a drift of one or more groups of electons or positive ions in an electric field or diffusion of one or more groups of electrons or positive ions in the direction of a decreasing concentration gradient. The following measurements with a suitable collector give information regarding these factors.

In the present experiment, in order to study the differences between the random and drift currents in the two main directions of a discharge tube, a double collector with two plane faces separated by mica insulation was used. These two faces were kept at the same relative potential and the experimental tube was so arranged that the relative distances of the anode, cathode and collector could be continuously varied. Langmuir has used a single plane collector[3] backed with mica insulation and has found that when turned toward the cathode the current-voltage characteristic showed a marked rise due to reception of the primary beam. He also noted that when faced toward the axis of the tube the primary beam was lacking but the other groups of carriers appeared as before. An advantage of the double collector is that approximately simultaneous sets of readings for the two faces may be taken at any one collector position thus minimizing the effect of variations in the discharge.

APPARATUS

The collector which was used for most of the current determinations consisted of two plane circular faces of nickel, each having an area of 9.6 mm^2 and a thickness of 0.15 mm. These were fixed at the end of a small bore glass tube. The mica insulation between the two faces extended beyond them in a circular ring 1 mm in width. This double probe or collector was suspended so as to be raised or lowered by a winch operating through a ground glass joint, the faces moving along the axis of the tube. Electrical connection was made to these faces by a double spiral of baked-enamel wire. The arc was maintained between an oxide coated filament[4] and the surface of a mercury column of adjustable height in a tube of 32 mm diameter. The whole was connected in the usual manner

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[1] Sloane and Emeleus, Phys. Rev. **44**, 333 (1933).

[2] Druyvesteyn, Zeits. f. Physik **64**, 781 (1930).

[3] Langmuir, Phys. Rev. **26**, 592 (1925).

[4] Courtesy of Westinghouse Electric Company.

to a condensation pump and McLeod gauge and the customary electrical circuits were employed. Both collector faces were connected to the same source of variable potential, and it was so arranged that the current to either face might be measured. Varying the potential on one face while the other was kept constant did not appreciably affect currents to the other and gave results of no importance other than that the insulation between the faces could thereby be tested. As the hot filament kept the temperature of the tube somewhat higher than the temperature of the mercury surface the vapor pressure was that due to the temperature of the mercury. This temperature though not directly measured was kept uniformly close to 45°C as indicated by a thermometer inside a small insulating jacket surrounding the mercury column. The discharge was run over considerable intervals of time in order to get steady conditions and it was found possible to check results satisfactorily by repetition. The edge corrections for the collector electrode faces were omitted because they appeared to be very small and, in considering the differences between the currents to the separate faces, they would presumably cancel.

Current-Voltage Curves and Their Interpretation

Typical current-voltage characteristic curves for the two faces, which we may call the cathode face (*C.F.*) and the anode face (*A.F.*) are shown in Fig. 1 and their sum is shown by the dotted curve. These measurements were made at a distance of 10 mm from the cathode and the curves are members of a series taken at different positions with the anode 45 mm from the filament, with 10 milliamperes flowing through the arc and with fifty volts on the anode. The collector potentials were measured with respect to the center of the cathode. It is interesting to note the large difference between the potentials for which the currents to the two faces are zero. These so-called floating potentials, which an insulated collector would assume and at which it would receive zero current, are 21 volts and 47 volts for the cathode and anode faces, respectively, and 38.5 volts for a collector receiving the sum of the two currents. Differing from each other by 26 volts, only that potential indicated by the anode face is anywhere near the neighborhood of space potential. These differences decreased with increasing distance from the cathode.

The marked rise of the current-voltage characteristic for the cathode face of the collector at a little above zero potential as seen in Fig. 1 indicates reception of the primary electrons from the filament. These electrons having been accelerated through the cathode fall region have sufficient energy to penetrate the sheath about the collector when the latter is in the neighborhood of fifty volts negative to space. That these primary electrons have a distribution of velocities has been noted by previous observers[5] and although the present curves show them being received over a considerable voltage range, they nevertheless represent a very definite and distinct group. The values of the current due to this group must be subtracted as corrections from current readings at higher voltages in order to obtain true current values due to scattered electron groups of lower energies. An approximate value for this correction may be obtained by taking the difference in ordinates between the prolonged adjacent branches of the curve for a mean value of the primary current. All electron current values must of course be corrected for the positive ion current and, as in the present experiment the positive ion current

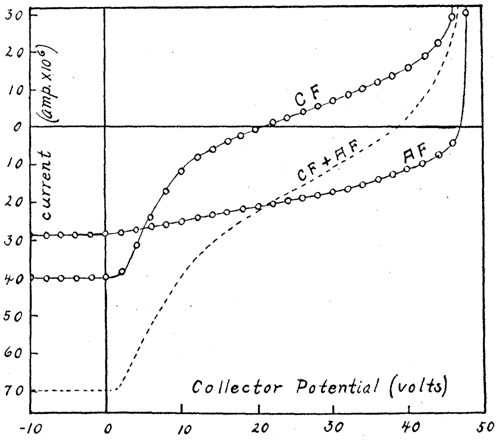

FIG. 1. Current-voltage characteristics for the two collector faces at 10 mm distance from the cathode.

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[5] Langmuir and Jones, Phys. Rev. **31**, 389 (1928).

was quite constant for each curve, the electron currents could most easily be determined by simply taking the ordinate above this level.

Current-voltage characteristic curves corrected for the primary electron beam and plotted semi-logarithmically are shown in Figs. 2, 3 and 4 for three different positions in the discharge. These curves uniformly exhibit two distinct parts below space potential, the two parts having totally different slopes yet each being essentially rectilinear between the transition portions and each therefore representing an entirely different electron group.

There is little evidence for the existence of a large number of different Maxwellian electron groups and the present curves may be taken to represent two general groups of scattered electrons, one a comparatively small group scattered about a relatively high mean energy value, and the other a comparatively large group scattered about a relatively low mean energy value. The former group which is fed by the primary beam and which is in process of scattering we may call the secondary group and the latter group in which the scattering process has been largely completed we may call the slow group.

The first part of the curve in Fig. 3 showing currents to the cathode face (*C.F.*) of the collector represents secondary electrons scattered about a mean energy value of 33 volts with a concentration of 3.8×10^7 per cc, while the second portion of the curve represents the slow group of electrons scattered about a mean energy value of 1.9 volts with a concentration of 1.1×10^{10} per cc. Similarly the curve for currents to the anode face (*A.F.*) shows the secondary electrons scattered about a mean energy value of 35 volts with a concentration of 2.6×10^7 per cc and the slow group scattered about a mean energy value of 1.9 volts with a concentration of 0.9×10^{10} per cc. These energies are readily determined from the slopes of the straight

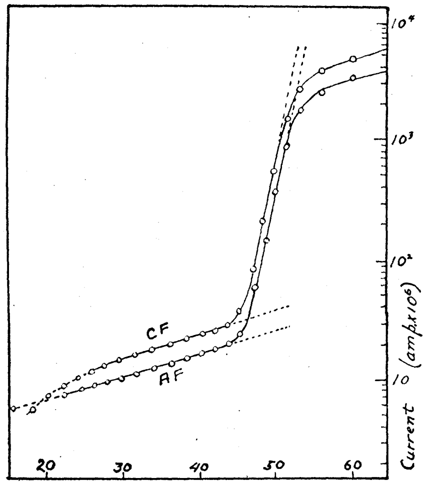

FIG. 3. Semi-logarithmic characteristics at 10 mm distance from the cathode.

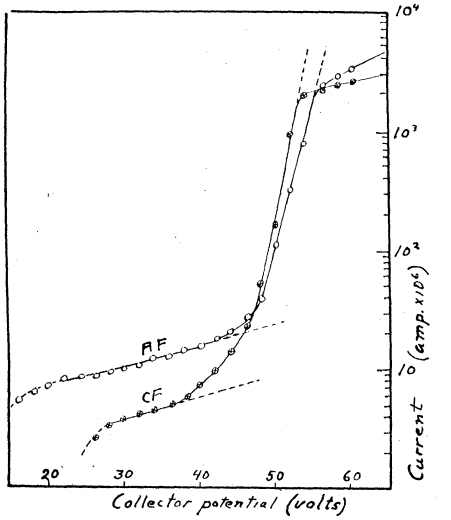

FIG. 2. Semi-logarithmic characteristics at 2.5 mm distance from the cathode.

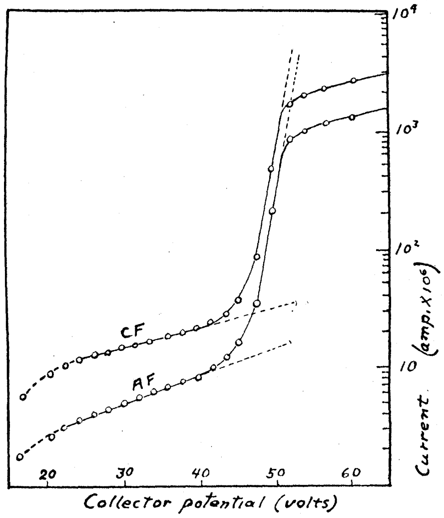

FIG. 4. Semi-logarithmic characteristics at 35 mm distance from the cathode.

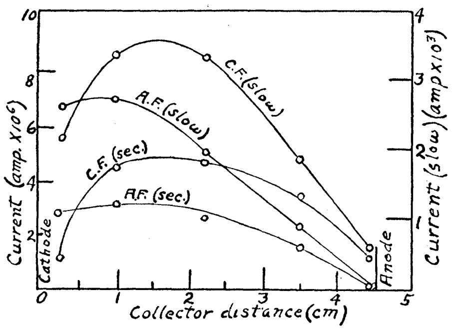

FIG. 5. Random electron currents to the two collector faces.

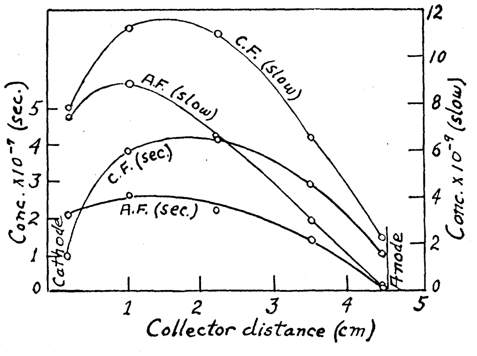

FIG. 6. Concentrations of slow electrons and secondaries.

portions of the semi-logarithmic curves.[6] In comparison with Fig. 3 the curves of Figs. 2 and 4 show a marked variation in the strengths of currents to the two collector faces at different collector positions, while the slopes of the straight portions of the curves and hence the energies are seen to vary but slightly, either for the two faces or for different positions of the collector. Nor were determinations of space potential different for the two faces by more than a fraction of a volt except very near the cathode as in Fig. 2 where the curve of currents to the cathode face became less distinctive in character as might be expected. In Fig. 2 it is also seen that near the cathode the secondary currents to the anode face are considerably greater than to the cathode face, while in the other curves the reverse is true, the difference increasing toward the anode. As the area of the collector was only about one-eightieth the cross section of the tube, it is thought that it did not appreciably disturb the discharge and there was never any visible disturbance except at several volts above space potential.

Although mean energy values for any one collector position do not show variations between the two faces greater than the experimental error, however, as the currents to the two faces vary systematically so do also the calculated concentrations. These concentrations should not be thought of as concentrations exactly at the surface of the electrode or its sheath but rather as average values for a region extending as far as the mean free path distance in front of the collector face. Hence, although the distance between the collector faces may be negligibly small, the distances between these regions may be appreciable and, as a drift due to any kind of gradient is represented by more electrons or positive ions crossing unit area in one direction than in the other per unit of time, the collector measures this drift.

Nearer the cathode where the primary beam was stronger the characteristic curve of the current to the anode face showed a slight rise similar to that of the cathode face. This was probably due to primary electrons elastically scattered but, at the same time, if the average energy of the secondary electron group is high and if the group is Maxwellian, an appreciable number of these may also reach the collector. If primary current values are read from the curve to the cathode face at potentials for which there is an appreciable secondary current as given by the current curve to the anode face, then a correction should be made by subtracting this current to the anode face from the current to the cathode face and, where the cathode and anode faces receive different intensities of secondary current, this amount should first be multiplied by the proper ratio.

In calculating the electron concentrations from the semi-logarithmic curves the current values for the secondary and slow electron groups were extrapolated to space potential and, to get the current due only to the slow electron group at space potential, corrections must be made for both the primary and secondary currents. Curves representing current values thus obtained for the secondary and slow electron groups are shown in Fig. 5. The corresponding concentrations are shown in Fig. 6.

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[6] Darrow, *Electrical Phenomena in Gases*, p. 351.

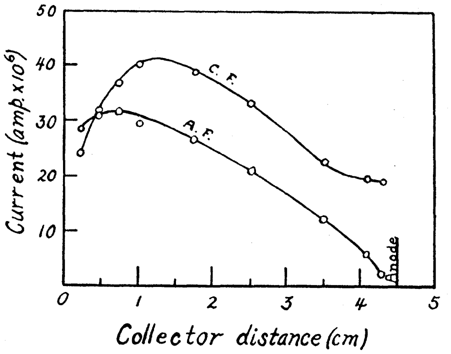

FIG. 7. Random positive ion currents to the two collector faces with an arc current of 10 m.a.

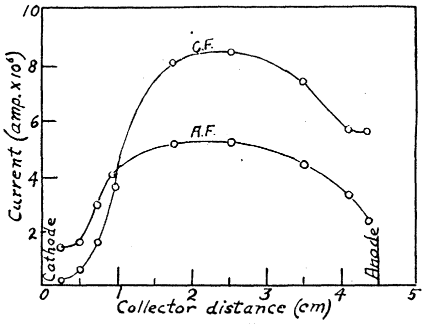

FIG. 8. Random positive ion currents to the two collector faces with an arc current of 1.0 m.a.

In Fig. 1 it is seen that the positive ion current is considerably greater to the cathode face than to the anode face. Two very simple explanations at once suggest themselves. The collector electrode may cast a "shadow," though none is visible, or else there may be a real drift of positives in the anode direction either with or against a field. The collector, of course, does intercept the primary beam and any other agency following an essentially rectilinear path from cathode to anode but if the difference in currents were due to such an effect it should increase in the direction of the cathode. However, just the opposite is true as may be seen from the data of Fig. 7 which represents random positive ion currents to the anode and cathode faces of the collector taken from a separate set of readings at nine different collector positions in which only the positive ion branch of the curve was measured in order to obtain more readily the variation with position. Indeed it is seen that in a region near the cathode the relative magnitudes of the currents to the two faces are reversed and the collector evidently measures a real drift. This reversal is even more clearly seen in the curves of Fig. 8 which were taken with one-tenth the usual current through the arc and it is especially to be noted that the point of intersection has moved farther from the cathode.

Langmuir[7] has considered the possibility, in a different type of tube, of the positive ions drifting toward the cathode thus causing more ions to strike the anode face of a spherical collector than the cathode face. Visual observations of the thickness of the sheath, however, failed to show that the effect on the sheath was significant. In the present experiment such asymmetry would be zero for the region where the two curves of Fig. 8 intersect but would increase in both directions from it. This region might be expected to correspond closely to a region of maximum concentration but it always appeared somewhat nearer to the cathode. The curves of Fig. 6 represent concentrations of both the secondary electron group and the slow group as calculated from the currents to the separate faces of the collector. All of these curves show that the concentrations attain a maximum value and though such values are not sharply marked they indicate the existence of a region of maximum ionization from which it appears that electrons and positive ions may diffuse in both directions. For a discharge with one-twentieth as much current flowing through the tube, the concentrations of the slow electron group decreased proportionately but the concentrations of the secondary group decreased much less and the energies did not change appreciably.

In a field-free space all groups would diffuse freely toward the anode from the region of maximum concentration but actual measurements under the conditions mentioned showed a reverse e.m.f. of 4 to 5 volts total between the anode and the region of maximum ionization, the gradient increasing near the anode. Electrons were therefore diffusing against this field and positive ions were moving with it. The ratio of the random electron current to the total current through the tube was greater than twenty to one in the region of maximum concentration but the

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[7] Langmuir, Gen. Elec. Rev. **27**, 812 (1924).

random electron current dropped at the anode to almost exactly the value of the current through the tube, the reverse field apparently limiting it to the proper value.

Complete sets of measurements of the collector characteristics were also made when longitudinal magnetic fields ranging up to 240 gauss were applied to the discharge, in order to find what effect these fields would have upon the apparent grouping of the electrons. Such fields produced marked changes in the visible appearance of the discharge and the collector electrode cast a sharply defined visible shadow in the direction of the anode. Under such conditions the asymmetry of the collector currents was considerably changed and it became especially difficult to distinguish between electrons of the primary and secondary groups incident upon the cathode face of the collector.

In the presence of the strongest magnetic field the positive ion currents to both collector faces increased by a small amount. So also did the currents due to the slow electron group and the secondary current to the anode face of the collector. These small increases were due partly to the fact that the discharge was restricted to a smaller area of cross section by the magnetic field. On the other hand the ratio of the secondary currents to the cathode and anode faces appeared to increase by as much as four or five times, the random distribution at the cathode face being completely disturbed. Measurements in the shadow indicated, in spite of the presence of large numbers of positive ions and slow electrons, that recombination was a negligible factor in producing luminosity.

MEAN FREE PATHS

Mean free paths for the primary electrons in a discharge have been calculated by Langmuir and Jones[8] from data obtained at varying gas pressures and fixed electrode distances and Maxwell[9] has used a movable Faraday cage for similar measurements. In the present experiment data were obtained by keeping the vapor pressure constant and varying the positions of the collector electrode. Values of the primary current for which the energy loss is not too great when plotted as a function of the distance from the cathode thus give a decay curve to which the simple Langevin equation $i = i_0 e^{-(x/l)}$ may be applied and, if plotted semi-logarithmically, the points lie on a straight line. The mean free paths so obtained under present conditions ranged from extremes of 1.5 to 1.9 cm and averaged close to the kinetic theory value for 45°C. This marks the approximate distance from the cathode to the region of maximum ionization previously mentioned.

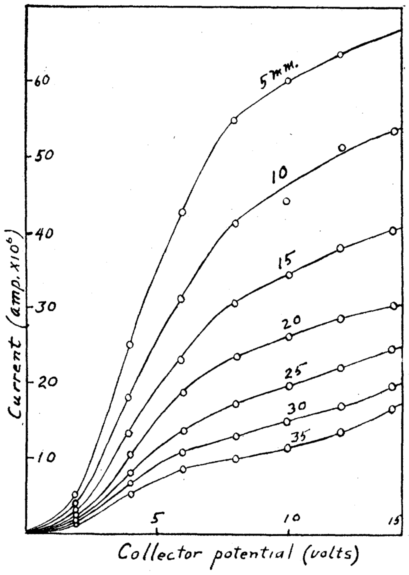

FIG. 9. Primary electron currents showing variation with energy and distance.

DISCUSSION

The curves of Fig. 9 represent a separate set of current-voltage characteristics showing the rise in current due to the primary beam and its variation with electrode distance. The primary beam has a velocity distribution due in part to varying initial velocities and to the voltage drop in the filament, if to no other reason, and the current usually began to rise *sharply* at from 1 to 2 volts positive with respect to the filament although this rise might have been expected to occur at nearer zero potentials. At potentials more than 4.9 volts higher than this, the curves change rapidly in slope and the transition to

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[8] Langmuir and Jones, Phys. Rev. **31**, 401 (1928).

[9] Maxwell, Proc. Nat. Acad. Sci. **12**, 509 (1926).

those portions of the curves representing the more completely scattered or secondary group becomes noticeable. Because there are several types of inelastic collisions by which the electrons may lose energy and because of the velocity distribution of the primary electrons, this transition is complex and gradual. In the secondary group electrons are continually passing from higher to lower energy states and, in view of this and the many constraints present in the tube, it is surprising that this group appears to be so near a purely random or Maxwellian distribution as is evidenced by the straightness of the semilogarithmic plot.

In the same year that Killian[10] suggested the possibility of an excess of high speed electrons to explain effects he observed, Druyvesteyn shortly after suggested a deficiency of electrons with speeds higher than the mean as compared with a true Maxwellian distribution in order to explain the deviation of his curves from the rectilinear. This result he obtained by a double differentiation of his curves. The experimental conditions were different in the two cases but, because the mechanism for increasing energies is evidently much less effective than the mechanism for reducing energies by inelastic collisions, the latter effect in a discharge would seem more probable. Druyvesteyn's data, however, were taken with a discharge between a hot filament and anode with a quite short wire collector under conditions in which the presence of secondary and most likely primary electrons could scarcely be either avoided or corrected for. Curves similarly deviating from the rectilinear have been called the "*S*" type by Seeliger and Hirchert[11] and the deviation has been ascribed by them to impurities in the gas or on the walls of the tube.

The present authors have used a quite short unshielded wire collector near the cathode, of the type used by Druyvesteyn, and have obtained curves in mercury vapor similar to those obtained by him in argon and neon. But when the same discharge was studied with the double plane collector described above the separate electron groups became more distinctly marked. Further study with another collector, a double wire collector, the two wires nine millimeters long separated by a mica strip, gave results similar to the plane collector except for a smaller apparent primary current. Effects were also studied at different spacings of anode and cathode. So long as the spacing was sufficient for a definite positive column to form and so long as the collector was in that region the curves retained their usual character, but in a more typical glow type of discharge or with the short wire collector and with spacings of much less than the electron mean free paths, there was much less differentiation of electron groups. The electrode spacings in Druyvesteyn's experiments were not large and the curves of his Fig. 6 show considerable variation for different collector positions. It seems, in view of the type of discharge and the kind of collector used, that at least part of the curvature he obtained may have been due to the asymmetry of the discharge.

In conclusion, it appears that although energies of secondary or slow electrons vary but slightly when measured from different directions, the concentrations may differ greatly and the energy transfer per second across unit area will likewise vary. Hence energy distributions may be far from isotropic and the deviations may appreciably affect certain types of results. It also appears that, in the discharge studied, a region of maximum ionization occurs at a distance from the cathode of the order of magnitude of the mean free path for the electron, from which electrons and positive ions migrate in both directions.

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[10] Killian, Phys. Rev. **35**, 1238 (1930).

[11] Seeliger and Hirchert, Ann. d. Physik **11**, 817 (1931).