COLLECTOR MEASUREMENTS IN THE POSITIVE COLUMN

OF THE GLOW DISCHARGE IN NEON,

ARGON AND HELIUM.

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Thesis by

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CONTENTS.

TABLE II

SUMMARY.

The LANGMUIR method for the use of sounding electrodes in low pressures discharges, has been applied for a study of the positive column in Ne, Ar and He. The electrons are found to have a Maxwellian distribution of velocities, with an average velocity as high as 11v, the equivalent temperature increasing with decreasing pressure. It is suggested that the wall plays an important part in the realization of the random velocity distribution; qualitatively, secondary effects in the sheath on the wall can account for the presence of LANGMUIR's fast electrons. The positive ion currents do not show saturation with increasing accelerating voltage on the collector, and the calculated values from the space charge equations come out 50% of the measured ones. This cannot be accounted for by a disturbing effect due to the collector. The increase is probably caused by an electron emission from the metal with subsequent impact ionization in the sheath, the secondary electrons being liberated by positive ion impact on the metal. Different other possibilities are also discussed. A general discussion of this type of discharges at very low pressures is given.
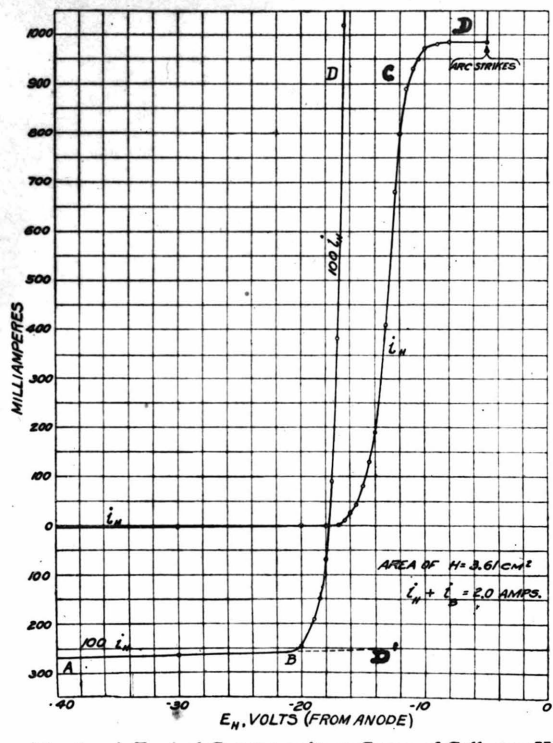
Fig. 4.   A Typical Current-voltage Curve of Collector H

INTRODUCTION.

Measurements with sounding electrodes, brought into the path of the discharge, have been made already by the early investigators in the field of electrical conduction through gases (HITTORF). It was generally admitted that the potential taken by an insulated collector, or one to which no current was flowing, corresponded exactly to that of the space opposite to this auxiliary electrode. These sounding electrodes have especially been used for the determination of the cathode fall.

In a series of articles LANGMUIR 1,2,3), LANGMUIR and MOTT-SMITH 4) established a correct theory of this method for determining space potentials, and showed that in mercury the values obtained by earlier investigators were often probably several volts wrong.

The method of LANGMUIR can be most easily summarized by analyzing a typical curve of the measurements in the mercury arc at low pressures (fig.1). In this example the current flowing to a plane collector is plotted against the voltage impressed on it, the latter measured with respect to the anode. The most striking feature of this kind of curves is their asymetrical aspect. Similar curves were

published, a short time before the results of LANGMUIR appeared, by SCHENKEL and SCHOTTKY 5). They were obtained by these authors in measuring the currents flowing to the iron cover of the commercial mercury rectifiers, when this was given different potentials with respect to one of the electrodes. The metallic cover acts thus as a large collector, and when insulated is charged up to a potential of about 10V above that of the cathode. The parts AB and CD of the curve represented in fig. 1, show a saturation character, while for $V_a = -18V$, the current in changing its direction increases considerably. The current is taken positive when it corresponds to electrons flowing from the gas into the collector.

SCHENKEL and SCHOTTKY, who obtained with their experimental arrangement only the parts CB and AB of the characteristic, suggested CB to be due to electrons flowing to the walls and AB to electrons liberated by photoelectric effect, this hypothesis explaining the saturation character of the part AB. DÄLLENBACH and JAHN 6), who had obtained with a collector the whole characteristic, pointed out that this hypothesis led to an efficiency of the photoelectric effect, which had never been observed directly. They supposed the part AB to be due to positive ion currents without giving a reasonable explanation of its saturation. To this SCHOTTKY 7) answered that he had in mind a new effect, which he called "conductive photoelectric effect". It might now be considered somewhat as a combination of collisions of the

second kind 8) and K.T.COMPTON's photoimpact 9,10). Although
this effect could perhaps have an efficiency of the right or-
der of magnitude it had to be given up for the interpretation
of the results in mercury after the publication of LANGMUIR's
work. We shall however have to consider it afterwards.

LANGMUIR proved the parts AB and CD to correspond, the
one to positive ion currents, the other to electron currents,
their saturation being due to limitation of the currents by
space charge. We shall begin with the interpretation of the
transition part BC.

Suppose the electrons to have a motion at random with
a velocity distribution corresponding to MAXWELL's law.
This hypothesis can be very easily checked experimentally
and is generally verified in the positive column of the glow
discharge. Then the concentrations of the electrons n^- and $n^{-'}$
at two points in the space where the difference in potential
energy is E_p, are according to BOLTZMANN's principle in the
ratio:

$$\frac{n^{-'}}{n^-} = \epsilon^{-\frac{E_p}{KT}} \longrightarrow \boxed{1}$$

If the collector is slightly negative with respect to
the surrounding space, it attracts positive ions and repels
the electrons, and becomes surrounded by a positive space
charge which screens the discharge from the charge on the
collector surface. If the latter reflected the electrons,
E_p in equation (1) being $= (-e V)$, we could apply BOLTZMANN's
principle and write:

$$n'_- = n^- \epsilon^{\frac{eV}{KT}} \longrightarrow \boxed{2}$$

Now the collector absorbs the electrons at least partially, so that the equilibrium condition is no longer satisfied. However we may still make use of BOLTZMANN's principle, provided the thickness of the positive ion sheath covering the electrode is small compared with the mean free path of the electrons, because then the electrons striking the surface are coming from parts of the discharge where MAXWELL'S distribution is still realized.

If n^- is the concentration of the electrons, $\overline{v^-}$ the average velocity of their motion at random, we may write for the current density due to this motion;

$$j^- = {}^1A_4 \cdot n^- e \overline{v^-} \longrightarrow \boxed{3}$$

This is easily derived by considering that half of the electrons are going to the surface element, and that averaging of the velocity over all directions equally probable, introduces also a factor $\frac{1}{2}$. Now $\overline{v^-}$ being everywhere the same because of the temperature equilibrium, the ratio of j^- at two places with different potential energy, will be given by equation (2). We may then write for the electron current flowing to the collector negative with respect to the space

$$i_- = A j^- \epsilon^{\frac{eV}{KT}} \longrightarrow \boxed{4}$$

In this formula:

$i^- =$ current flowing to the collector (amp)

$A =$ surface of the collecting sheath (cm^2)

$\bar{j} =$ electron current density in the discharge (amp/cm^2)

$\epsilon =$ base of natural logarithms

$e =$ charge of the electron ($4,774.10^{-10}$ ESU $= 1,592.10^{-19}$ Coul.)

$V =$ potential of the collector with respect to the gas

$k =$ BOLTZMANN constant ($1,372.10^{-16}$ erg/$1°$ K)

$\bar{T} =$ Equivalent temperature of the electrons.

The equivalent temperature of the electrons is determined by the relation for the kinetic energy:

$$e\bar{V}_e = \frac{m^- \overline{v^2}^-}{2} = \frac{3\,kT}{2} \quad \boxed{5}$$

$$\text{or } \bar{V}_e = \frac{3\,kT}{2\,e} \longrightarrow \boxed{6} \qquad \text{and} \qquad \overline{v^2}^- = \frac{3\,kT}{m^-} \longrightarrow \boxed{7}$$

If $\bar{V}_e$ is expressed in volts, then $e/k = 11600$ degree/volt. The average velocity to be used in equation $\boxed{3}$ is connected in the case of a Maxwellian distribution to $\overline{v^2}$ by the relation

$$\overline{v}^- = \overline{v^2}^- \cdot \frac{8}{3\pi} \longrightarrow \boxed{8}$$

Combining $\boxed{7}$ and $\boxed{8}$ gives $\overline{v}^-$ as a function of $\bar{T}^-$

$$\overline{v}^- = \sqrt{\frac{8\,k\bar{T}^-}{\pi\,m^-}} \longrightarrow \boxed{9}$$

It is to be remarked that formula $\boxed{4}$ holds only for negative values of V , because the positive ions cannot run against any appreciable retarding fied due to their small kinetic energy compared with that of the electrons. Furthermore the current density of the electrons is so much larger than that of the positive ions that it is impossible to measure the velocity distribution of the ions with a simple

plane collector.

When the potential V is made more negative, part AB, the electrons are no longer able to reach the surface of the collector and the current consists only of positive ions, which strike the limiting surface of the sheath (due to their own motion) and are then captured. The collecting surface for a plane collector in mercury being almost independent of the voltage V, even without guard-ring, this explains the saturation character of the part AB, and we may write for the current:

$$i^+ = A\, j^+ \longrightarrow \boxed{10}$$

In the discharge the positive ion space charge is visible as a dark layer, whose thickness x can be measured. Now if the mean free path of the positive ions is large compared with the value of x, we can apply the ordinary space charge equation CHILD 11), LANGMUIR 12), SCHOTTKY 13,14,15), which gives a relation between the current density on the collector i^+, the thickness x and the voltage V :

$$i^+ = \frac{\sqrt{2}}{9\pi} \cdot \sqrt{\frac{e}{m^+}} \cdot \frac{V^{3/2}}{x^2} \longrightarrow \boxed{11}$$

In deriving this equation it is assumed that the velocity of the particles entering the sheath is negligible. This approximation is certainly not allowed for the electron currents, and we can take into account the Maxwellian distribution by using the following formula due to LANGMUIR 16).

$$i = \frac{\sqrt{2}}{9\pi} \cdot \sqrt{\frac{e}{m}} \; \frac{V^{3/2}}{x^2} \left[1 + 2.66 \sqrt{\frac{kT}{V}} \right] \longrightarrow \boxed{12}$$

Expressing i in amp/cm^2, V in volts, x in cm, and calling (m/m_o) the ratio of the mass of the charged particle to that of the electron, m_o, we get:

$$i = \frac{2.336 \times 10^{-6}}{\sqrt{m/m_o}} \; \frac{\gamma^{3/2}}{x^2} \left[1 + 0.0247 \sqrt{\frac{T^+}{\gamma}} \right] \longrightarrow \boxed{13}$$

In this expression γ is the potential of the collector with respect to the space opposite to it, T^+ the corresponding temperature of the positive ions, which is unknown and cannot be determined by means of a simple plane collector. LANGMUIR made an estimation of T^+ from measurements with cylindrical collectors. Assuming a reasonable value for T^+ the theory can be checked and was found to be correct in mercury.

The potential difference between the space opposite to the collector and the anode, which deduced from V, as plotted in fig. 1, gives us the value of γ to be introduced in formula $\boxed{13}$, can be found by means of the part BCD of the curve. The current BC consists partly of electrons, partly of positive ions, and to find the real electron current we can extrapolate AB to BD', adding the values of the corresponding current to the measured current. Taking now the logarithms of both sides of equation $\boxed{4}$, and remembering that (A_j^-) is a constant for a given run because the total current is kept constant:

$$\log_e i^- = ct + \frac{eV}{kT^-} \longrightarrow \boxed{14}$$

i.e. plotting the logarithm of the electron current against the retarding voltage we must get a straight line, if the electrons have their velocities distributed according to MAXWELL's law. From the slope S of this line we can deduce T^-. Introducing decimal logarithms we have:

$$S = \frac{\log_{10} i^-}{V} = \frac{e}{kT^-} \cdot \frac{1}{2.303}$$

$$T^- = \left(\frac{e}{k}\right) \cdot \frac{1}{2.303\, S} = \frac{11\,600}{2.303 \times S} \cdot {}^{\circ}K \longrightarrow \boxed{15}$$

The values of T^- obtained in this way come out very high, for mercury at low pressures as high as 50,000°K.

Equation $\boxed{4}$ is obviously valid only as long as the collector is at a lower potential than the space opposite to it. As soon as it is at a higher potential it attracts the electrons and the current, now limited by a negative space charge (part CD), is given by:

$$i^- = A\, j^- \longrightarrow \boxed{16}$$

where:

A = collecting area.

j^- = electron current density in the discharge (eq. $\boxed{3}$).

But equation $\boxed{16}$ gives in the semi-logarithmic diagram where log. i^- is plotted against V , a parallel to the axis of V , and the point where the break in the curve occurs corresponds to the space potential. Fig. 6 gives such a diagram for Neon.

A similar relation to equation $\boxed{13}$, now between i^- and the thickness x of the dark layer holds also in this case:

$$i^- = 2.336 \times 10^{-6} \frac{\gamma^{3/2}}{x^2}\left[1 + 0.0247\sqrt{\frac{T^-}{\gamma}}\right] \longrightarrow \boxed{17}$$

Here the simple space charge equation may certainly not be used, because the temperature T^- can have very large values.

Finally when the potential increases till the point D is reached, ionization by collision sets in, the space charge breaks down, and the current can increase indefinitely.

This is the essential part of LANGMUIR's theory for the use of plane collectors. It has been checked by LANGMUIR himself, by SCHOTTKY and von ISSENDORF 17), partly by DÄLLENBACH, GERECKE and STOLL 18), and found correct in mercury. We shall see that for the noble gases Neon, Argon and Helium, the theory has to be partly modified.

It must be kept in mind that LANGMUIR's theory holds only when the thickness of the space charge x is small compared with the mean free path of the charged particles, else these make too many collisions in the layer and the phenomena become very complicated. This limits the application of these considerations to discharges at very low pressures. A first attempt towards application of collector measurements to higher pressures has been made by SCHOTTKY and von ISSENDORF 19, 20, 21).

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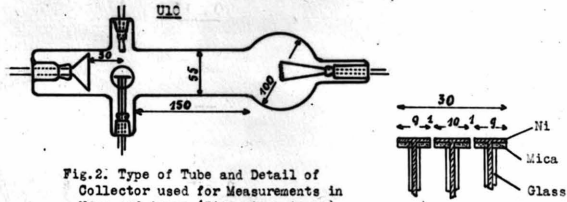
Fig.2. Type of Tube and Detail of
Collector used for Measurements in
Neon and Argon (Dimensions in mm).

Ni
Mica
Glass
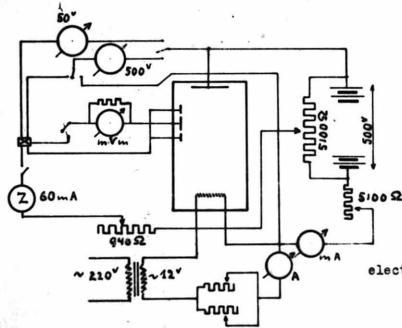
Fig.3. Diagram of
electrical Connections.

II

MEASUREMENTS IN NEON AND ARGON.

In this chapter a brief discussion of the experimental method, together with some typical results obtained in Neon and Argon, will be given. The data for Helium will be considered in the next chapter.

This investigation was originally started at the suggestion of Dr. F. M. Penning, to find out if LANGMUIR's theÿ was applicable to the positive column of the glow discharge in the noble gases. From the very beginning the results showed a marked discrepancy from what one should expect on the basis of that theory. It was the aim of the present investigation to find a rasonable interpretation of these peculiarities.

EXPERIMENTAL METHOD AND ARRANGEMENT.   RESULTS.

The measurements were carried out in the positive column of the glow discharge (with hot cathode to obtain larger currents), in Neon and Argon using collectors with Nickel, Carbon and Magnesium surface. Fig. 2 fives form and dimensions of the tubes used, fig. 3 a diagram of the electrical connections. To avoid the edge corrections which are al-

ways more or less uncertain, the collector had a guard-ring, the current measured being that to the central part.

The collector showed a heavy sputtering due to the bombarding of the positive ions, even with small accelerating potentials. This proves conclusively that the current collected for negative potentials consists at least partly of positive ions. The metal deposited on the walls causing an appreciable absorption of the gas, an additional volume (6 liters) was added to keep the pressure constant during the whole run. The pressure variations which amounted to 50% and more were thus reduced to a few percent.

1. Measured current: i_m.

The current measured directly will be called in the following i_m, the current computed by means of equation $\boxed{13}$ from the space charge thickness x, will be designated i_c. "i_m" is measured and plotted as a function of the voltage V_a on the collector with respect to the anode.

The curves $i_m = f(V_a)$ show a definite increase of i_m with decreasing potential V_a. The difference of i_m for $V_a = -400V$. and $V_a = -100V$:

$$\left[(i_m)_{400} - (i_m)_{100} \right]$$

increases with increasing current through the tube; the ratio:

$$\left[\frac{(i_m)_{400} - (i_m)_{100}}{(i_m)_{100}} \right]$$
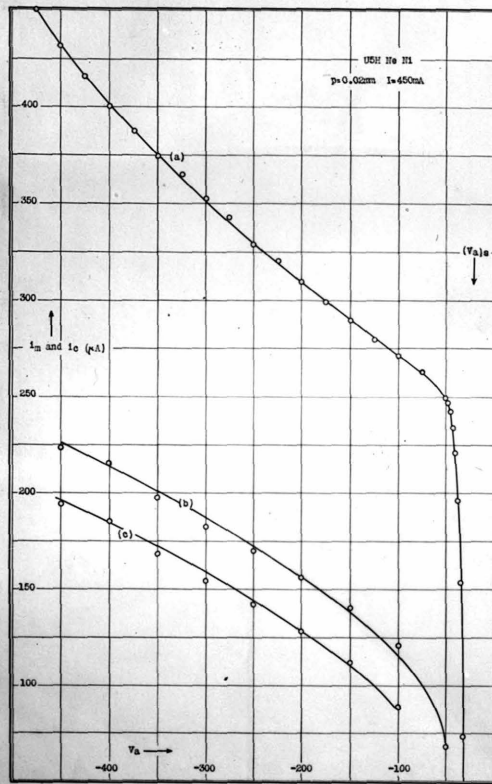
Fig.4. Measured Collector Current i_m (a), calculated Current i_c for $T'=T''$ (b) and
$T'=1/7\ T''$ (c) as a Function of V_A.

however decreases with increasing total current I (Table I).

Fig. 4 (a) gives an example of these characteristics
$i_m = f(V_a)$ for high negative potentials of the collector.
(U5, run H, total current I = 450 mA, p = 0.02 mm Neon, Ni col-
lector). For Neon and Argon the part of the curve for
$V_a > -100$ V. is a straight line. This peculiar behaviour was
shown by practically all the curves. In table I will be found
the slopes S of the straight part in μA per volt. These
values must be considered somewhat more in detail, since they
can give us information about the process which causes the
increase of i_m. The slope S is seen to rise almost linearly
with I up to a total current of 250 mA, from there on it is
practically constant. Reducing to the same value of i_m
to find the action per incoming ion for different current
densities on the metal, i.e. calculating $100 \, S/(i_m)_S$ for each
of the runs, these ratios are found to decrease when the
current density increases. This procedure in comparing the
data for different values of I, is only justified when the
process responsible for the increase of i_m is some action on
the metal. If the process takes place in the dark layer, one
has to divide by $\sqrt{i_m}$ (dividing by i_m to reduce to same
current and multiplying by $\sqrt{i_m}$ to transform to corresponding
values of x). $100 \, S/\sqrt{(i_m)_S}$ decreases somewhat with increa-
sing I, but presents a slight maximum for I around 200 to
250 mA.

Each run was taken twice, once in increasing (algebraical-
ly), and once in decreasing V_a, the mean of the two values,

which generally differed only slightly, being taken for the computations. Some runs, especially in Argon, showed marked discontinuities in i_m without any apparent reason. It happened that those discontinuities were present in one half of a run, while the other half was quite normal. Perhaps they are connected with a kind of flashing which can sometimes be observed on highly negative collectors. The flashing is probably due to the building up of a small cathode spot, because of traces of impurities on the metal, which favorise the electron emission. After such flashing one finds on the metal similar marks as those left by the cathode spot of a moving arc.

The point in the i_m curve where the current becomes zero corresponds to the potential for which the number of positive ions collected is exactly equal to the number of electrons able to run against the retarding field. It is the potential the collector would take if it were insulated. This potential, taken with respect to the anode is approximately constant: for Neon -30 to -35 v, for Argon -20 to -24 v. For the runs taken with tube U5 ($p = 0.02$ mm Neon, total current I varying from 100 to 500 mA), there is a slight increase with increasing I from -35v to -31v. A possible explanation will be given afterwards (§5).

2. <u>Calculated current</u>: i_c .

   a/ <u>Measurement of the sheath thickness</u>: x .
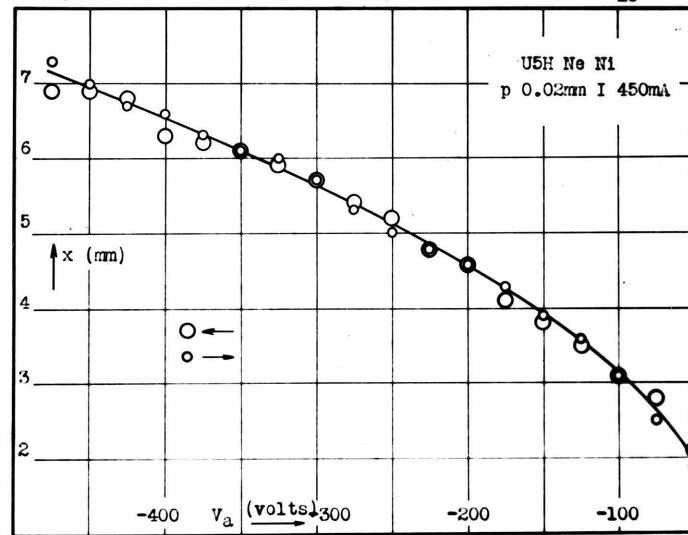
Fig. 5. Measured Thickness of the Space Charge Sheath x_m as a Function of V_a.

To realize an exact measurement of the sheath thickness a plane window was adjusted in a side tube normal to the collector. To avoid the reflection on the opposite wall another side tube was added, ending in a bulb, frosted inside and blackened outside. In this way it was possible to observe accurately the edge of the dark space. The measurements were done with a Zeiss reading microscope.

The mean of the values x , measured in the two half runs, was taken and plotted against V_a ; for the computations the value given by this curve $x = f(V_a)$ was used. Fig. 5 gives the measurements of x for run U5 H.

Formula $\boxed{13}$ giving the relation between i_c , V_q and x was somewhat transformed for the actual computations. i_c was expressed in μA, x in mm, and instead of calculating the current per cm^2, that flowing to the central disk (diameter 10 mm) was evaluated. The values thus calculated are plotted as i_c .

Possible error in i_c due to errors in x.

Several errors can occur in the estimation of x .
1. The plate inside the guard ring, which constitutes the collector, may not be in the same plane as the latter; this will cause the edge of the dark space not to be completely plane and parallel to the metal surface.
2. It is rather difficult for the glassblower to have the tube connected in such a way that the plane of the collector

is perfectly horizontal. The axis of the telescope may
not be parallel to this plane.

3. What must be taken as the edge of the sheath?
There exists a gradual transition of the dark layer to the
body of the discharge, this probably being due to the elec-
trons which penetrate into the positive space charge because
of their own motion. In fact one ought to take the upper
boundary of the two, if this interpretation is right, but
the lower one was chosen because it was much sharper. In this
way a systematic error is made in taking the thicknes too
small, so that according to formula $\boxed{13}$ the calculated current
will be _too_ _large_. This is an essential point to be observed
in the following discussion.

There is of course, even with the sharp transition
chosen, some uncertainty in the interpretation of the visual
boundary of the dark sheath. The aspect of the edge is much
like that of the negative glow in a discharge with cold cathode.
SEELIGER and his pupils 1) have studied the transition between
cathode dark space and negative glow. They find that the sharp
edge appears to be at the place where the visual intensity is
changing at the maximum rate, and that the region in which the
light itself reaches its maximum is about twice as far from
the cathode. Furthermore, spectral analysis has shown that
the maxima for different lines often occur at different dis-
tances from the cathode. These conclusions may to a certain
extent be applied to our case where we have in fact an arti-

ficial cathode placed in the positive column. This means that for a plane collector the real thickness of the layer would be larger than the measured value, and again the calculated current would be too large.

4.   There remains to consider the accidental error in the measurement of x . From fig. 5 it may be seen that in taking the possible error to be 0.2 mm, our estimation is certainly not too small. Furthermore, as already pointed out, the values x_{cm} given by the drawn curve were taken for the actual computations. Admitting then 0.2 mm as maximum accidental error, the possible error in the computed current i_c can be rather large for small values of x (low values of V_q and large values of I), e.g. for $x = 4mm$ as high as 30%.

It is rather difficult to take into account the possible errors pointed out in the first and second paragraphs. As has been shown in the third paragraph the real thickness of the sheath is probably larger than the measured value x , and consequently the value of the positive ion current calculated from the latter is too large.

b/   Determination of the voltage V_q .

As has been pointed out pge 7, the voltage V_q to be introduced in formula ⑬ :

$$i = \frac{2.336 \times 10^{-6}}{\sqrt{m/m_0}} \cdot \frac{V_q^{3/2}}{x^2} \left[1 + 0.0247 \sqrt{\frac{T^+}{V_q}} \right] \longrightarrow \boxed{13}$$

is that of the collector with respect to the gas and not V_a which is measured between collector and anode. We can find V_g by subtracting from V_a the drop of potential $(V_a)_S$ between anode and space opposite to the sounding electrode. The latter can be found from the semi-logarithmic diagram as explained in the introduction pge 8. Fig.6. gives an example of such a diagram for run U5 H.

In this case the space potential equals $(V_a)_S$ = -21.4 v. This potential drop remains practically constant for all the runs made with tube U5 (see table I). The values are scattered around the average value of -21 v and no definite relation with one of the other measured quantities could be found. For the noble gases the potential gradient in the positive column decreases somewhat with increasing current through the tube 2) 3). These measurements of the gradient have however been done at rather high pressures, where cumulative effects are more likely to occur, and it is not certain that these conclusions hold for pressures of a few 1/100 of a mm. If present, this effect is in our case probably compensated by an increase in the anode drop.

Relative error in i_c due to the error in V_g.

The absolute error in the determination of the space potential is taken ± 1V. With this value as upper limit the relative errors in i_c become rather small (< 1%) for ~~larger~~ high values of V_g. For low potentials V_g they become more

important and reach for $V_\alpha = -50v$ about 5% both for Argon and Neon.

It is to be remarked that in the diagrams where the voltages are plotted as abcissas, the value with respect to the anode V_α is taken. In the calculations the corrected value V_q is of course used. To have in the diagrams the potentials with respect to the space as abcissas, it is sufficient to shift the vertical axis to the left so as to have the zero at $(V_\alpha)_s$, for instance with run U5 H at -21.4 v (see fig. 4).

c/   <u>Determination of</u> T^+.

It is not possible to determine with a plane collector of the form used the equivalent temperature of the positive ions, mainly because the ion currents are very small compared with the electron currents (see pge 5). LANGMUIR I 4) gives a method based on the use of cylindrical collectors of small and large diameter compared with the thickness of the space charge. Afterwards TONKS, MOTT-SMITH and LANGMUIR 4) MOTT-SMITH and LANGMUIR 5) have developed a theory for the use of collectors with a hole, which make it possible to measure the velocity of the positive ions. But no measurements with these kinds of collectors having been made in these experiments, we are obliged to make a reasonable assumption for T^+.

Although our knowledge about the motion of positive
ions is rather limited, it is very probable that their
thermal energy in the positive column is much smaller
than that of the electrons. The mass of the charged par-
ticles being of the same order as that of the atoms with
which they collide, we may expect the ions to loose an
appreciable amount of their energy in every collision.
K. T. COMPTON 6) finds in treating the ions and atoms as
spheres of equal mass, and applying the energy and momentum
principles, that the mean energy loss at a collision is
half the energy before impact and that the average deflec-
tion is through an angle of 45°. According to this calcu-
lation a final state is rapidly approached in which the
energy of the ion is 2W before and W after impact, where
W is the average gain of energy between two collisions.
Some difficulty arises from the fact that the mean free
path of an ion is not accurately known. DEMPSTER 7) and
his pupils DURBIN 8) and KENNARD 9) find abnormally long
free paths for alkaline ions of rather high velocity in
the noble gases, while recent work by RAMSAUER and BEECK
10, 11) gives for velocities of a few volts values for λ^+
smaller than those calculated by means of the kinetic
theory. But it is not certain that this conclusion will
hold for ions of the noble gases colliding with atoms of the
same gas. This remark applies also to the determination
of the loss of energy at impact 12), so that we do not have

direct experimental data from which the final velocity of
the ions could be calculated.

LANGMUIR takes for the temperature of the positive
ions in mercury 5,000°K, when that of the electrons is
30,000° K to 40,000° K, which means that as a first approxi-
mation $T^+ = 1/7\, T^-$ is taken. The value of ι_c was computed with
that approximation, but also in taking the temperature of the
ions equal to that of the electrons. Formula $\boxed{13}$ shows that
this last assumption gives too large values for ι_c, if,
as it is natural to suppose, $T^+ < T^-$. In the measurements
with He evidence has been obtained which confirms this
last statement.

The determination of T^- has been considered in the
introduction pge 8. Using formula $\boxed{14}$ and the slope $S = 1/10.6$
(from diagram 6), we find for run U5H an equivalent tempera-
ture of the electrons $T^- = 53,000°\,K$.

More recently LANGMUIR has come to the conclusion that,
although the electrons have their velocities distributed ac-
cording to MAXWELL's law, this is not the case for the ions.
Their energy will depend only on the potential through which
they have fallen, except for possible losses by impacts with
the molecules, i.e. the ions will be accelerated in moving
from the axis of the tube towards the walls. In the positive
column the main drop of potential along the radius of a
cylindrical tube, normally to the axis, will be concentrated
in the positive ion layer on the glass. Between the edge
of this sheath and the axis the difference of potential is

probably of the order of 1 or 2 volts 14), so that the hypothesis $T^+ = T^-$ will still give too large values for i_c.

Relative error in i_c due to errors in T^+.

The current i_c has been computed on the assumption that $T^+ = T^-$ (curve b fig. 4), and also on the hypothesis $T^+ = \frac{1}{7} T^-$ (curve c fig. 4). As may be seen from the diagram the difference between the values computed on these two assumptions is appreciable, the first giving larger currents; in the following discussion these are always used.

For the run U5 H the differences have been calculated in percent of $(i_c)_{T^+ = T^-}$ and are given for some values of V_a in the following table:

V_a(w/r to anode)	Decrease in i_c.
450	13%
350	15
250	19
150	21
50	32

This uncertainty in T^+ is one of the main causes of possible errors in i_c.

3. Comparison of i_m and i_c.

In comparing the measured value i_m with the calculated value i_c, we find

$$i_m > i_c \quad \longrightarrow \quad \boxed{18}$$
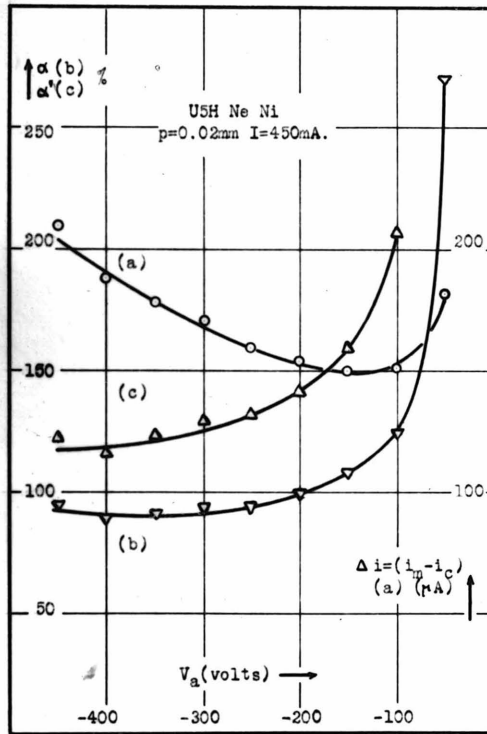
Fig. 7. Variation of (i_m-i_c) curve (a),
α for $T^+=T^-$ curve (b) and α' for $T^+=1/7\ T^-$
curve (c), with V_a.

The difference $(i_m - i_c)$ for run U5 H has been plotted on diagram 7 (curve a), as a function of the potential of the sounding electrode with respect to the anode. The larger value of i_c, namely that corresponding to $T^+ = T^-$ has been taken for the calculation of the difference.

To have a certain measure of this difference, we put:

$$100 \left(\frac{i_m - i_c}{i_c} \right) = \alpha \longrightarrow \boxed{19}$$

α gives thus in percent of i_c the difference between i_m and i_c. Curve b of fig. 7 shows the variation of α with the voltage V_a for $T^+ = T^-$, and curve c the same variation when $T^+ = \frac{1}{7} T^-$. ($T^+ = 8,000°$ K for the case of U5 H, see pge 21). With this second assumption α becomes still greater.

It is remarkable that α increases rapidly when the potential of the collector with respect to the anode approaches -50v, which represents with respect to the space a voltage of about -20v for Neon and -30v for Argon. For the latter the increase is even more pronounced than for the first, we find for Argon values of α larger than 300%.

As pointed out before (†20), the mean free path for the ions was found by RAMSAUER and BEECK to decrease with their velocity below 30v. This means that they are making more collisions in the layer before reaching the collector, consequently the measured thickness of the space charge ought to be less than the calculated values, but the opposite is found. When the accelerating voltage for the ions becomes as small as

25v, the threshold of potential, which possibly exists at the outer edge of the sheath, since the ions come in with a certain velocity, might produce this effect (see § 4^b). Finally, the potential difference between the space opposite to the collector and the anode $|V_a|_s$, as determined from the log i^- diagram (fig.6) might be too large, if the part of the curve above (-21v) has to be considered as a transition region. Although this is rather improbable (see § 5), a decrease in $|V_a|_s$ would raise the calculated values, especially in the neigbourhood of the space potential. For higher accelerating potentials the effect of this change in $|V_a|_s$ is rather small. Taking e.g. $|V_a|_s =$ -10v, the increase of i_c for $V_k = -450v$ is only 4.9%, for $V_k = -50v$ it amounts however to 52% of the original value; the new values for α being respectively $\alpha_{450} = 84$ (95) and $\alpha_{50} = 119$ (270).

Errors in the determination of α.

The values of i_m may be considered to be measured with an accuracy of 0.5% (mV meter), but the uncertainty in i_c is rather large due to the errors in x, V_q and T^+. The relative error in i_c will be minimum when V_q is large, because the relative error in x^2 and $V_q^{3/2}$ is then small (x is large with V_q). For high current density the accuracy becomes less because x gets smaller.

When we take all those factors into account the relative error in α can reach 50% and more. For instance for Neon, assuming an electron temperature of 50,000° K, $V_a = -50v$ and

$x = 4$ mm we find about 35%. When we consider however the curve $\alpha = f(V_a)$, a reasonable estimation would give 10-15%, at least for high voltages, and for low values of $(-V_a)$ the points lie on a continuous curve, which has the same form for all the runs. A close examination of the curves $i_c = f(V_a)$ leads also to the conclusion that for $V_a <$ -150v we may take an accuracy of 10-15%.

To this is still to be added the systematic error due to the unsharp transition of the layer into the body of the discharge (pge 16) and the uncertainty in the temperature of the positive ions (pge 19). The correction to be applied for the initial velocities of the positive ions when they enter the space charge, amounts to 27% for V_a= -450v, and to 107% for V_a= -50v (Run U5H), of the values without correction term, when we assume $T^+ = T^-$. These are the values estimated for Neon, but for Argon where the temperatures are not so large the correction is less.

4. Variation of α, i_m and i_c with V_a and I.

   a/ $\alpha = f(|V_a|)$.

When α is plotted as a function of V_a (the total current in the tube being kept constant), it is found that α increases slightly with decreasing V_a, except for very small values of V_a where it increases rapidly with increasing V_a. The curve keeps the same form but is slightly shifted upward
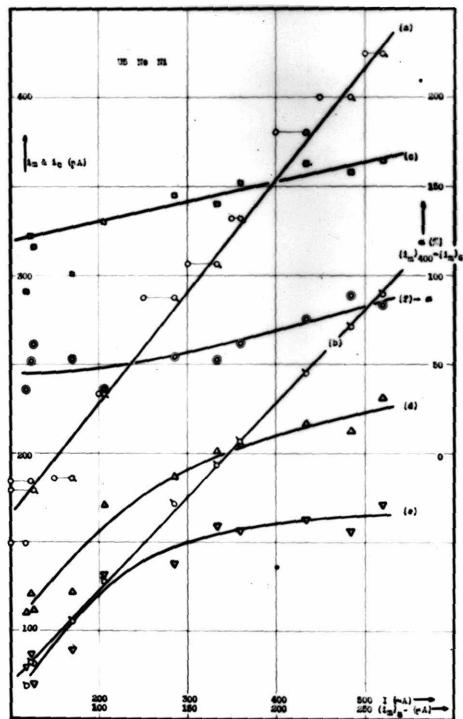
Fig. 8. Measurements in Beam: ⊕ $(i_m)400$ Curve (a), ⊕ $(i_m)200$ Curve (b),

⊖ $(i_m)_{400} - (i_m)_S$ Curve (c), ⊕ $(i_c)_{400}$ Curve (d), ▼ $(i_c)_{200}$ Curve (e), as a Function of $(i_m)_S$

○ $(i_m)_{400}$ plotted as a Function of I_w

as a whole with increasing total current I . The differences
however are rather small, of the order of a few percent.

b/ $\alpha = f(I)$.

When we plot i_m , i_c and α, as a function of the current
density, or, which amounts to the same, as a function of the
total current through the tube I , V_a being kept constant,
several peculiarities appear.

"i_m" is not simply proportional to the current I , although
the general variation can perhaps be represented by a straight
line. The points fit a linear dependency much better when,
instead of plotting as abcissas the values of I , we take the
extrapolated current $(i_m)_s$ for the space potential. The dis-
crepancies are however still too large to be accounted for
by errors in the measurement of i_m . The error introduced,
because the small variation of the space potential for the
different runs is not taken into account, since we keep V_a
constant instead of $V_g = \left[V_a - (V_a)_s \right]$, is also too small. In
some of the runs there could be seen some tendency to stri-
ation forming in the positive column. These layers, which
are probably due to slight impurities in the gas, may be
the cause of these irregularities. Fig. 8 gives the values
of i_m for $V_a = -400v$ (curve a) and $V_a = -200v$ (curve b).
For curve (a) the points ⊙ represent $(i_m)_{400}$ as a function
of I , the points ⊕ $(i_m)_{400}$ as a function of $(i_m)_s$. Curve (c)⊡
gives the differences $\left[(i_m)_{400} - (i_m)_s \right]$ as a function of $(i_m)_s$.

" i_c " is not simply proportional to I either , but increases for low total currents and afterwards becomes almost constant, as if it tends to a saturation value. This might be due to a saturation of the positive ion currents. To test this point, the calculated currents i_c were plotted for lower accelerating potentials V_q . Curves (d) and (e) of fig. 8 represent respectively i_c for V_a = -400v and V_a = -200v. Unfortunately the spreading of points is such that no definite conclusion can be drawn, although the effect of the smaller potential V_q , if present, ought to be rather pronounced.

In this discussion of $"\alpha"$ it was tacitly assumed that the space charge is only due to ions coming from the main discharge, and the effect of their collisions in the layer was neglected, else the CHILD-LANGMUIR equation cannot be used. The difference $\left(i_m - i_t\right)$ represents under this hypothesis a secondary emission from the metal plate, and the ionization by impacts of these electrons in the layer is supposed to be negligible. Now, both these assumptions, based on the fact that the thickness x is small compared with the mean free path of the ions and electrons, can be questioned, especially the latter one. As soon as an appreciable number of new ions, which need not be very large compared with the ion current from the main discharge, is formed, the simple space charge equation has to be modified. This is probably the case as will be shown in Chapter IV.

It is rather difficult to understand on theoretical

grounds the saturation of i_c , if this is supposed to be the ion current coming from the discharge. For rather high pressures the current in the positive column I will be proportional to $\left(n^- \cdot \frac{dV}{dz} \right)$, where n^- is the concentration of the electrons and $\frac{dV}{dz}$ the gradient along the axis. Now, if $\left(\frac{dV}{dz} \right)$ varies only slightly with I , n^- will be proportional to I . If there are no negative ions, we must practically have $n^+ = n^-$ consequently $n^+ \propto I$. The number of ions striking the dark layer will be $\propto \left(n^+ \overline{v^+} \right)$, and since $\frac{dV}{dz}$ varies only slightly with I , the same will be the case for $\overline{v^+}$, and the number of incoming ions must in first approximation be $\propto I$. It is not certain that these conclusions will hold for the low pressures as used in our experiments. The electron distribution is possibly no longer isotropic, and the equation: $I = S \cdot k \, n^- \frac{dV}{dz}$ would no longer hold. Recent work of KILLIAN 14) shows that in the mercury arc at very low pressures, this equation is still satisfied.

Curve (f) of fig. 8 gives the values α for the collector potential $V_a = -400v$, as a function of the current $(i_m)_S$ (tube U5). It is remarkable that for the runs measured at the end (U5 AI and U5 AII) with $I = 100mA$, the values of i_m differ so much from that for run U5 A, measured at the beginning with the same I , while the values of i_c are practically the same for the three runs. Run U5 B shows a somewhat similar behaviour to U5 A compared with the runs at higher current densities.

5.   <u>Electron temperatures:</u> T^-.

The electron temperatures found in the different runs are listed in table I. In all cases, with possibly one or two exceptions, the diagrams for log. i^- plotted against V_a gave straight lines, as ought to be the case if the electrons have their velocities distributed according to MAXWELL's law (pge 8).

In comparing the values of the table it is seen that T^- for Neon is much larger than for Argon, about twice as high. A decrease of the pressure from 0.01 mm Hg to 0.002 mm Hg almost doubles the electron temperatures in Argon (see table I Run U6D and U6E). When the current density in the discharge increases the temperature T^- has a tendency to decrease. These facts are in agreement with the results obtained by LANGMUIR in mercury.

The question of a possible relation of the electron temperatures with the critical potentials of the gases used, and how the MAXWELL distribution might be brought about, will be taken up in more detail when discussing the results in Helium.

It was seen pge 24, that the increase in $"\alpha"$ for values of V_a near to the space potential $\left(V_a\right)_s = -21.4v$ could be corrected, when $\left(V_a\right)_s$ was taken much smaller e.g. -10V. The part of the log. i^- curve above -21.4V must then be considered as a transition part, and the real space potential would be around -10V, or perhaps even -5V. Now the average velocity

in volts of the electrons as given by the straight line below
-21.4V is 6.9V; the lowest critical potential in Neon is
around 16V, while the ionization potential is 21.5V. This
means that most of the ionization, necessary to supply the
ions for neutralizing the negative space charge, must be of
a cumulative type, either by successive impacts or combined
action of the resonance radiation and electron impact. This
could perhaps be tested experimentally by studying the spec-
trum of the discharge at different pressures, because the high-
er levels of the atoms must be excited (recombination in the
positive column under the present conditions can be neglected),
if these cumulative effects are important. At pressures as
low as 0.02 mm Hg this is very improbable, especially since
the loss of ions to the walls is relatively more important;
the lower the pressure the higher the electron temperature
(consequently the charging up of the walls) and the longer the
mean free path of the electrons and ions (facilitating their
escape from the path of the discharge). To this is still
to be added that for Neon the probability of excitation is
rather small 15). A study of the positive column in Neon at
higher pressures 16) has shown that the ionizing impacts and
the 18V impacts are of the same order of magnitude, the
excitation of the levels at 16V being very small. On these
grounds we believe that the part of the $\log . i^-$ diagram above
$(V_a) = -21.4V$ represents another class of electrons, whose
average velocity as deduced from the slope would be 11.9V.

This would improve the energy balance quite appreciably.

It is seen from the table that the average energy of the electrons decreases somewhat with increasing I ; this might account for the decrease of $(V_a)_o$. The difference between $(V_a)_o$ and $(V_a)_s$ must be such, that the number of electrons striking in unit time the edge of the sheath with velocities larger than $\left| (V_a)_o - (V_a)_s \right|$, equals the extrapolated ion current for $(V_a)_o$. It can easily be seen that if the ratio of the electron current to the ion current remains the same for different I the decrease of T^- will reduce $(V_a)_o - (V_a)_s$, and since $(V_a)_s$ is practically constant, $(V_a)_o$ will decrease.

6.   <u>Differences</u> <u>with</u> <u>LANGMUIR's</u> <u>results</u>.

a/   The positive ion part of the volt-ampere characteristic is not a flat curve with saturation character as it ought to be according to the theoretical considerations in the introduction.

b/   The results obtained in these experiments gave $i_m > i_c$ while LANGMUIR finds a very good agreement in Hg.

c/   The electron part of the characteristic above the space potential is not a flat curve. This departure is especially marked for higher current densities.

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Notations.

I = current through the tube (mA).

$(i_m)_{400}$ = measured collector current for $V_a = -400v$ (μA).

$(i_m)_{100}$ = measured collector current (μA) for $V_a = -100v$.

$(i_m)_s$ = extrapolated pos.ion current at space potential $(V_a)_s$ (μA)

$\Delta i_m = (i_m)_{400} - (i_m)_{100}$

S = slope of the straight part of i_m curve above $-200v$ ($\mu A/v$)

$(V_a)_0$ = potential with respect to anode for which $i_m = o$

$(V_a)_s$ = space potential with respect to anode.

$(i^-)_s$ = electron current (μA) to the collector at $(V_a)_s$.

$(V_a)'_s$ = see pge 24 and pge 29.

$(i^-)'_s$ = electron current (μA) to the collector at $(V_a)'_s$.

$\overline{V}^-$ = average electron velocity in volt.

T^- = equivalent electron temperature in degrees K.

TABLE II

Run	I	ΔV	$(i_m)_{300}$	$(i_m)_{100}$	$(i_m)_s$	Δi_m	$\left\{\dfrac{\Delta i_m}{(i_m)_{100}}\right\}$	$100 S$	$(V_a)_0$	$(V_a)_s$	$(i^-)_s$	$(V_a')_s$	$(i^-)'_s$	$\overline{V^-}$
HELIUM $p = 0.1$mm Plane Collector: Ni.														
U16C23	100	65	90	66	56	24	0.36	13	−47.5	−28.5	2550	−22.5	4000	8.8
U16C25	200	70	169	131	119	38	0.29	19	−48.3	−29	3400	−24	7800	8.8
U16C24	300	70	232	190	175.5	42	0.22	21	**−48**.5	−30	4400	−24.5	12000	8.8
U16C22	400	73	316	261	244.5	55	0.21	27	−49	−33.5	4500	−26	17800	7.8
U16C21	500	73	380	319	298.5	61	0.19	30	−49	−31.5	7000	−25.5	21000	8.5
U16C20	600	72	450	379	353	71	0.19	37	−48.5	−34.5	6400	−26	24000	7.8
Helium $p = 0.04$mm Plane Collector: Ni.														
U16C17	200	73	144	103	88	41	0.40	20	−51	−28	2200	−21.5	5400	10.1
U16C16	300	75	202	160	145	42	0.26	21	−53	−30.5	4000	−25.5	8200	10.1
U16C19	400	74	253	200	182.5	53	0.27	25.5	−51	−30	4100	−21.5	13000	10.7
U16C18	500	75	298	244	226	54	0.22	25	−52	−29	5400	−21	15800	11.0
U16C15	600	79	387	312	289.5	75	0.24	34	−54	−34	7000	−27.5	20000	9.8
U16C13	400	90	277	224	210	53	0.24	26.5	−65	−46	4600	−39.5	13500	9.4
U16C8	400	65	272	218	200	53	0.25	26	−46.5	−23	2300	−15.5	8400	8.5
HELIUM $p = 0.1$mm Cylindrical Collector: Pt.														
U16B22	400	72	2220	1810	1510	−−	−−	−−	−40	−32.5	9400	−25	60000	6.0
HELIUM $p = 0.04$mm Cylindrical Collector: Pt.														
U16B19	400	74	1950	1570	1250	−−	−−	−−	−42.5	−32.5	8000	−22.5	50000	7.8

$(i_m)_{150}$ $(i_m)_{75}$

III

MEASUREMENTS IN HELIUM.

The measurements in Helium were started to check the
work done previously by changing the conditions in the
discharge tube, and to find out if the same discrepancies
in the behaviour of the positive ion currents existed also
in Helium. If this proved to be the case, one might look for
an interpretation based on some of the characteristic proper-
ties of the noble gases, e.g. the considerable potential
energy of their metastable states or their high ionization
potential.

Indeed pure Helium presented the same peculiarities, at
least qualitatively, i.e. the positive ion currents do not
show saturation and their measured values are larger than
those calculated by means of the space charge equations.

EXPERIMENTAL METHOD AND ARRANGEMENT.   RESULTS.

The tubes were practically of the same diameter as those
used in the earlier work, to make possible a comparison of
the data for the three noble gases. The collector with guard
ring was made of Nickel, the inner disk having a diameter
of 6mm (diameter of guard ring 15mm, distance between guard
ring and disk 0.5mm). In addition to this plane sounding

electrode another special collector was placed between the
first one and the anode. It consisted of two grids and
a bottom plate, placed in a side tube (ϕ = 2cm). The first
grid, flush with the open end of this side tube, was at the
same distance from the axis of the discharge tube as the
disk collector. The distance between the two grids, and the
grid and the plate, (all made of platinum) was 1.5 mm. This
additional collector was introduced to measure the gradient
in the positive column and to detect the secondary emission
from the bottom plate, if present.

The sputtering in Helium being much less than in Neon
or Argon, no additional volume was necessary to keep the
pressure constant during the runs.

1. Measured current: i_m .

As before, " i_m " is measured and plotted as a function
of the voltage V_a on the collector with respect to the anode.
In table II, at the end of this chapter, are listed some of
the results obtained with each of the collectors in Helium,
at two different pressures; p = 0.1 mm Hg and p = 0.04 mm Hg.
In the following the collector with guard ring will be desig-
nated "plane collector" (runs U16C), the collector with
the grids and plate (without guard-ring) "cylindrical col-
lector" (runs U16B).

a) $i_m = f(V_a)$ for plane collector.

(a) i_m U16C22 p=0.1mm I=400mA
(b) i_m U16C19 p=0.04mm I=400mA
(c) i_m U16B19 p=0.04mm I=400mA
(d) i_c U16C22 for $T=0$
(e) i_c U16C22 for $T=T$

(a)

300

(b)

(e)

200

(d)

i_m & i_c (μA)

100   2000

i_m (μA)

(c)

1500

V_a →

1000   -150   -100   -50
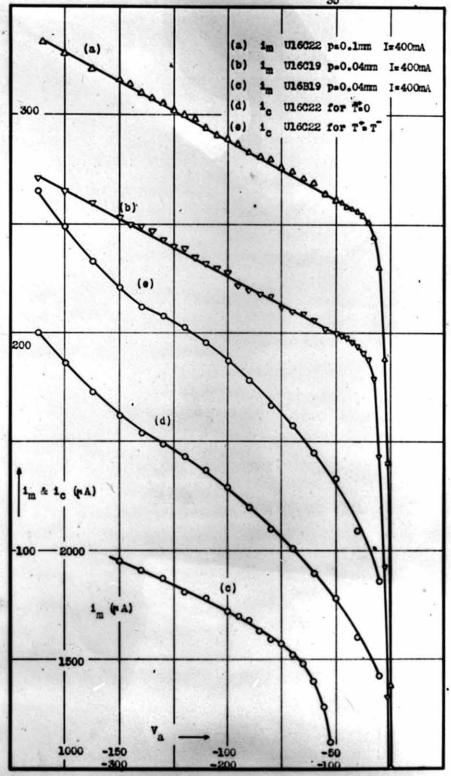   -300   -200   -100

Fig. 9. Measurements in Helium. (Curve (c) on different Scale).

All the diagrams for the runs listed in table II, representing $i_m = f(V_a)$ give, as in Neon and Argon, curves with a marked slope, i_m increasing with decreasing V_a. For low total currents I, the curves are practically straight lines, for higher values of I (500 and 600 mA) some of them are somewhat convex towards the axis of abcissas, similar to the curves in Ne and Ar. Fig. 9 gives the $i_m = f(V_a)$ diagrams for run U16C22 p = 0.1mm, I = 400 mA($\triangle$) and run U16C19 p = 0.04 mm I = 400 mA(∇). The two curves appear to be parallel. It may also be noticed that for the higher pressure, the currents to the collector are larger, for the same current I. This is in agreement with former observations in Argon (compare table I Run U6D and Run U6E).

The difference of i_m for $V_a = -300$v and $V_a = -100$v

$$\left[(i_m)_{300} - (i_m)_{100} \right]$$

increases with increasing current through the tube I; the ratio

$$\left[\frac{(i_m)_{300} - (i_m)_{100}}{(i_m)_{100}} \right]$$

shows a decrease with increasing I (Table II). This is the case for both pressures. For all the runs where the positive ion characteristic is a straight line, S (the increase of i_m per volt decrease of V_a) will be proportional to Δi_m $(100 S = \frac{1}{2} \Delta i_m)$. When we compare again the ratios $\left[100 S/(i_m)_s \right]$ and $\left[100 S/\sqrt{(i_m)_s} \right]$, $\left[100 S/(i_m)_s \right]$ is found to decrease somewhat

with I, while $\left[100 \, S/\sqrt{(i_m)_s}\right]$ is practically constant. This would indicate, that for He the increase of (i_m) is due to some action in the space charge layer, proportional to the number of incoming positive ions and to the thickness of the sheath.

The values of V_a for which the collector current is zero $(V_a)_o$ are seen to vary only slightly for each of the two pressures. (Table II).

It is interesting to compare the positive ion currents for a given value of I, in the different gases. According to the present theories of the positive column, practically the whole discharge current is carried by a continuous cloud of electrons moving down the tube from the cathode towards the anode. On this common drift motion of the electrons is superposed a thermal agitation. Thanks to this random motion, in which the velocities of the electrons are distributed according to MAXWELL's law, positive ions are formed which practically neutralize the negative space charge. It is this ionization which makes it possible to send large currents through the discharge tube with an applied voltage of only 60v. Now the electrons, because of their high mobility, diffuse out of the path of the discharge and charge the walls negatively; this charge on the glass sets up a transverse field which in turn draws the ions out of the discharge. The ions build up positive space charge sheaths next to the glass and reduce in this way the effect of the transversal gradient. Equilibrium conditions will then be

reached when the longitudinal gradient is such, that the elec-
tron cloud gets sufficient energy in going down the tube to
compensate by ionization the loss of electrons and positive
ions and keep up the temperature of the electrons (only the
electrons belonging to the tail of the MAXWELL distribution
can ionize and are neutralized at the walls).

If the electron temperatures were the same in the three
gases, it would suffice to have similar conditions, to com-
pare for the same I, the collector currents for pressures
inversely proportional to the electronic mean free paths,
i.e. $p_{Ar} : p_{Ne} : p_{He} = 1 : 1.76 : 2.7$ (This assumes the ion
mean free path proportional to that of the electrons).
The actual pressures were about in the ratio 1:2:4. The
table on the next page gives such a comparison for $I = 200$mA,
$I = 300$ mA and $I = 400$ mA.

According to the theory outlined above, one would expect
if the electron temperature and their current density were
the same for the three gases, the positive ion currents to
be (in first approximation at least) inversely proportional
to the square root of the ion mass i.e.:
$$[i_m|_s]_{Ar} : [i_m|_s]_{Ne} : [i_m|_s]_{He} = \sqrt{m_{He}} : \sqrt{m_{Ne}} : \sqrt{m_{He}} = 2 : 4.5 : 6.3.$$
The table shows that this is far from being the case, but
none of the two assumptions is really justified. The elec-
tron current density for a given value of I is not the same
in the three gases, it is not even constant for different
runs in the same gas with a given value of I and p.(See § 4).

Run	Gas	p(mm)	$\overline{V^-}$ (volts)	$\left. \|i^+_m\| \right)_s$ μA	$\left. \|i^-\| \right)_s$ μA	$(V_a)_s$ (volts)	$\rho = \dfrac{\|i^-_s\|}{\|i^+_m\|_s}$
$I = 200$ mA.							
U10C	Ar	0.01	2.6	161	2500(-19.5)		15.5
U10A	Ne	0.02	6.6	177	1060(-22)		6.0
U16C10	He	0.04	9.8	272	5280(-20)		19.4
					13340(-14.5)		49.0
$I = 300$ mA.							
U10D	Ar	0.01	2.7	243	3850(-19)		15.8
U10B	Ne	0.02	4.1	213	1100(-26.5)		5.2
U16C16	He	0.04	10.1	403	11100(-30.5)		27.6
					22800(-25.5)		56.5
$I = 400$ mA.							
U5G	Ne	0.02	7.9	217	1750(-21.5)		8.1
					6300(-15.5)		29.0
U16C19	He	0.04	10.7	507	11100(-30)		22.0
					34700(-21.5)		68.4

The currents in He are reduced to the same collector surface as in Ne and Ar. The second value of $(i^-)_s$ given for some runs (U16C10 etc.) corresponds to another value of the space potential, in case the second straight part of the electron diagram is considered as a transition region. Between brackets are the space potentials in volts with respect to the anode: $\|V_a\|_s$.

This can however be taken into account by comparing the ratios of the electron current $\|i^-\|_s$ and the extrapolated ion current $\|i^+_m\|_s$, both at space potential. The ratio ρ is found to be higher for Ar than for Ne, but compared with ρ_{Ne} the value for Ar is too high. According to the foregoing

considerations one would expect $\rho_{Ar} : \rho_{Ne} \simeq 1.4$ but the values
are 2.6 (I = 200 mA) and 3.0 (I = 300 mA). For He the values
for ρ are much too large as compared with those of Ar and
Ne. Incidentally it may be remarked, that if the electrons
and the ions were in thermal equilibrium, we ought to have
$\rho_{Ar} = 271$, $\rho_{Ne} = 197$ and $\rho_{He} = 85.8$. Similar discrepancies
led LANGMUIR to assume the presence of negative ions; recent-
ly however he has modified his theoretical point of view
as explained before (II P. 21).

It is rather difficult to make a qualitative estimation
of the influence of the different electron temperatures,
mainly because of the low pressures at which these measure-
ments have to be made to satify the condition $x < \lambda$. The
mean free path of electrons and ions is of the same order
of magnitude as the diameter of the tube, consequently none
of the mobility equations as derived in kinetic theory for
rather high pressures, can be used. The case is similar to
that met in the study of phenomena in rarified gases. This
objection is certainly to be considered for the motion of
the ions, since this will be mainly transversal, and to a
certain extent also for the electron motion.

Suppose two runs with same total current I but different
electron temperatures. If T^- is larger, the walls will be
charged up to a more negative potential, the ions will be
drawn more readily towards the walls but the ionization per
unit volume is larger so that the surface charge on the walls

is screened off more completely. On the other hand, T^- larger means smaller mobility, consequently more ions are needed to neutralize the negative space charge, but the electron loss to the walls is smaller. Now, for a larger electron temperature the gradient must be larger so that the drift velocity along the tube is increased. It will depend on the relation between the gradient and the electron temperature if the ion currents to the walls will increase or decrease with increasing gradient. This shows sufficiently that the phenomena are rather complicated. Furthermore, the consideration of electron mobilities in those cases does not seem to be justified, if we remember that the total length of the positive column is only about $5\lambda^-$ and the tube diameter $1.5\lambda^-$ in Ne at 0.02 mm.

In some of the preliminary runs in He, made with the plane collector at pressures of about 0.5 mm and rather high current densities, the positive ion characteristic was similar to those obtained by LANGMUIR in Hg. First this fact was believed to be connected with the value of the pressure, but after some runs and cleaning of the collector surface by sputtering, the diagrams all showed the characteristic increase of i_m with decreasing voltage V_a. Apparently the coating of the collector surface (nickeloxyde), removed afterwards by the sputtering, prevented any secondary emission. This hypothesis is supported by the fact that the successive runs gave curves of which the slope increased with

the gradual cleaning of the Ni surface. This seems to be the most reasonable explanation although it is in contradiction with the current idea that uncleaned surfaces emit more easily electrons, either by photoelectric effect 1) or by positive ion bombardment 2) 3). A direct experimental test can easily be made by comparing the characteristic of two collectors, one cleaned and the other intentionally oxydized, $\not{z}$all other conditions being equal.

b) $i_m = f(V_a)$ _for cylindrical collector._

The curves obtained with the grid collector were only taken from $V_a = 0$ to -150v. Curve c of fig. 9 gives such a characteristic (plotted on a different scale) for run U16B19, $p = 0.04$ mm, $I = 400$ mA ($\odot$ c). To compare the values of i_m with those obtained with the plane collector, we have to reduce the currents to the same collector area and take into account the edge corrections since no guard-ring was used. This can be done in the following way:

Supposing that the action of the charge on the collecting electrode doesn't extend beyond the boundary of the space charge, (as was done in the original articles of LANGMUIR), and calling the positive ion current density in the discharge j^+ (Amp/cm^2) we have for the measured current:

$$i_m^+ = A j^+$$

where A is the collecting surface in cm^2. When a collector

without guard ring is used, **A** is made up of two parts: the upper surface equal to that of the metal disk: πr^2, and the side surface $2\pi r x$, of the cylindrical space charge sheath, where x is the thickness. In first approximation the CHILD-LANGMUIR equation may be used to express x as a function of j^+ so that we can write :

$$i_m = j^+ \left[\pi r^2 + 2\pi r \sqrt{\frac{c V_g^{3/2}}{j^+}} \right]$$

or:

$$i_m = \underbrace{\pi r^2 \cdot j^+}_{B} + \underbrace{c_1 \sqrt{j^+}}_{S} V_g^{3/4}.$$

where: $C_1 = 2\pi r \sqrt{C}$.

If we plot i_m as a function of $V_g^{3/4}$, B is the value of the ordinate for $V_g = 0$ (V_g = potential with respect to the gas) and S the slope of the straight line. Since all the other factors entering into B and S are known, we have two ways of determining j^+. A third one is to find the point where $i_m = f(V_g^{3/4})$ intersects the axis of abcissas; then we have calling V_o the voltage corresponding to this point:

$$j^+ = \frac{4c}{r} V_o^{3/2}$$

The following table gives the value of j^+, in $\mu A/cm^2$, calculated by each of these methods, and also the value as estimated by extrapolation from the $i_m = f(V_a)$ curve for runs U16B22 ($p = 0.1$ mm, $I = 400$ mA) and U16B19 ($p = 0.04$, $I = 400$ mA).

	U16B22		U16B19
B . . .	493		395
S . . .	438		380
V . . .	486		413
$i_m = f(V_a)$.	481		397
Average .	475		396

	U16C22		U16C19
$i_m = f(V_a)$.	863		645

The last row gives j^+ (μA/cm^2) as found for the runs with the plane collector by extrapolation from the $i_m = f(V_a)$ curve.

Again the current density for the higher pressure is the larger. The values obtained by the four different methods for the B runs check rather well among each other, but their average differs by as much as 50% from the current density found with the plane collector.

Several explanations for this discrepancy are possible. If the measured current consists partly of positive ions and partly of electrons, liberated at the metal plate by one or other process, one may expect this to be more effective for the plane collector than for the cylindrical one, due to its special form. However, when we compare the values of the electron current density, these are also found to be larger for the electrode with guard ring. The foregoing explanation cannot account for this second fact, unless additional assumptions are made (weakening of the negative space charge on the collector due to slight ionization by the incoming electrons).

Another possibility is that the electron concentration and consequently also that of the ions, decreases in going from the cathode towards the anode. This is quite possible since the voltage across the tube ΔV, shows an increase with increasing total current I (Table II), and this increase is probably due to a variation of the anode drop from negative values to positive ones.(The filament current was kept constant for all the runs at p=0.1 mm, while for p=0.04 mm it was increased somewhat with I). If the present interpretation is right, the ratio of the positive ion current densities at the two collectors must approximately be equal to the ratio of the electron current densities. The following table shows how far this is realized.

	p	j^+	j^-	$(V_a)_s$	$\overline{V}^-$	j_P^+/j_c^+	j_P^-/j_c^-
P.C.	0.1	863	16500	-33.5	7.8		
			64000	-26			
						1.8	5.5-3.3
C.C.	0.1	475	2990	-32.5	6.0		
			19100	-25			
P.C.	0.04	645	15000	-30	10.7		
			46200	-21.5			
						1.6	5.9-2.9
C.C.	0.04	396	2540	-32.5	7.8		
			15900	-22.5			

The current densities are expressed in $\mu A/cm^2$. The two values given for j^-, correspond to the two values which it is possible to assign to the space potential; these are given in the column $|V_a|_s$ following j^-. The implicit assumption is made that the velocity of the positive ions in striking the outer

edge of the sheath varies in the same way as that of the electrons. Now it is seen that j_p^-/j_c^- is appreciably larger than j_p^+/j_c^+. These current densities are to a certain extent a measure of the concentrations of the charged particles in the discharge, so that we are forced to the conclusion that not only the concentration is different opposite to each of the collectors, but that the ratio n^-/n^+ changes also. This second conclusion is a serious difficulty, since we know that n^+ _must_ practically be equal to n^-, the differences compatible with the existing fields in the positive column being only a few percent. Correction for the fact that at the plane collector the average velocity of the electrons is found larger than at the cylindrical collector, which is nearer to the anode, would increase the discrepancy. This apparent contradiction against the practically zero space charge in the positive column, is due to the disturbing effect of the introduction of the collector in the discharge.

2. <u>Calculated current</u>: i_c .

The method followed in the calculation of i_c was explained in detail in § 2 of chapter II. Curve d of fig.9 gives the values of i_c for run U16C22 (p=0.1mm, I=400 mA) calculated from the simple CHILD-LANGMUIR equation $\boxed{11}$, curve e the values of i_c taking into account the temperature correction and assuming $T^+ = T^-$. This assumption gives perhaps a rather good approximation for the velocity of the ions in He, since their mass is much smaller than in Ne or Ar.

The accuracy of the measured value x_m for the space charge thickness, is much smaller in He than in Ne or Ar. The contrast between light and dark parts in the discharge is very pronounced in Ne, somewhat less in Ar, but decidedly less in He 3). To this is to be added that most of the runs in He were made with a thoriated tungsten filament as electron source, and this reduced greatly any contrast, because of the light emitted by the glowing filament. For these reasons, the calculated currents will not be considered in detail.

From fig.9 it may be seen that the calculated values i_c again come out too small as compared with the measured ones i_m (Compare curves d and e with curve a). The difference between i_m and i_c is also about 50% of i_m. The type of curve representing $i_c = f(V_a)$ changes suddenly for $V_a \approx -275v$, while there is no discontinuity to be found in the curve $i_m = f(V_a)$. This break is due to the fact that below $-275v$ the thickness x is practically constant, and consequently i_c will increase proportionally to $(V_q)^{3/2}$. This peculiar variation of i_c with V_q was found for all the runs made at the higher pressure ($p \approx 0.1$ mm), while for the lower pressure ($p = 0.04$ mm) i_c varies in the same way as was observed in Ne and Ar. Probably the mean free path of the ions becomes too small compared with x and their impacts in the sheath may no longer be neglected, and consequently the CHILD- LANGMUIR equation cannot be used.
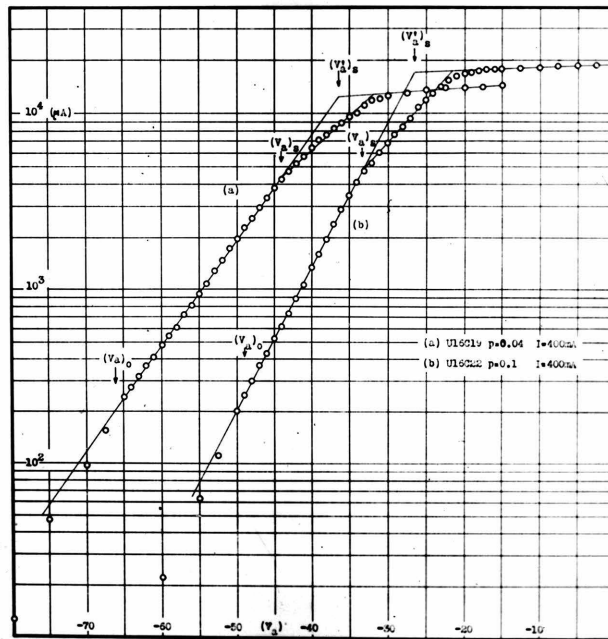
Fig. 10. Semi-logarithmic Plot of Electron Current: $\log_{10} I = f(V_a)$.
Curve (a) is shifted 15 volts to the left.

3.   Electron Temperature: T^-.

As explained in the introduction (pge 7) the semi-logarithmic plot of the electron current, measured with respect to the extrapolated ion current, will give us the electron temperature T^-, the space potential $(V_a)_s$ and the electron current density j^-.

The electron temperatures as derived from similar diagrams will now be considered somewhat more in detail, since they constitute a difficult problem in the interpretation of gas discharges at very low pressures, which so far has not been solved in a definite way. First it must be recalled that the whole length of the tube is only a few times the electronic mean free path λ^-, between 5 and 10 λ^-; e.g. for the runs with the plane collector in He the distance between cathode and sounding electrode is about 4 λ^-. How is it possible that, after going such a short distance, the electron cloud emitted from the cathode with practically uniform velocity, (save for small corrections according to RICHARDSON's theory), has acquired a perfect Maxwellian distribution? Fig. 10 gives two examples of such electron diagrams, curve a for run U16C19 (p = 0.04 mm, I = 400 mA) and curve b for run U16C22 (p = 0.1 mm, I = 400 mA). (Curve a is shifted 15v to the left). It may be seen that both are linear over a very wide range, for curve a e.g. from $V_a = -50v$ to $V_a = -30v$, while the average velocity as found from the slope is $\overline{V}^- = 10.7v$. Over this range the current

increases about from 200 ｈ A to 4000 ｈ A. This question of
the velocity distribution acquired by the electrons, has
been studied in detail by LANGMUIR 5) 6). He arrived at
the conclusion that the effect was not due to collisions of
the second kind with MS atoms and that it had nothing to
do with the presence of the walls. FRANCK proposed an
interpretation based on triple impacts 7) 8) (innere ReKom-
bination). This effect to be important, requires large
electron current densities, and it is doubtful whether
this interpretation can be used in our case. Furthermore
in his measurements on the scattering of electrons, HARNWELL
9) has not yet found these electrons which probably must be
scattered at random with rather high velocities. This may
however be due to the limited sensitivity of his apparatus.
THOMAS 10) has calculated the influence of the interaction
of charged particles according to the inverse square law;
a similar effect is undoubtedly important in the negative
glow, but this is probably not the case for the positive
column. On the other hand, the scattering of velocities in
the positive ion sheath around the cathode can be neglected,
as is shown conclusively by the work of LANGMUIR and JONES
11) on electron mean free paths in different gases.
PENNING 12) finds that the high velocity electrons are
always accompanied by oscillations 12), (under the experi-
mental conditions as used by LANGMUIR 5)), but it seems
not justified to conclude that there are always oscilla-
tions in the positive column.

Intimately connected with this question is the follo-
wing. When we neglect possible cumulative effects, which
must be small at the very low pressures used, the electron
cloud with an average velocity $\overline{V}^-$ of only 10.7v must
produce the necessary ionization to compensate the positive
ion loss to the walls. This will take out an appreciable
number of the high velocity electrons belonging to the tail
of the MAXWELL distribution. In addition to this the wall
opposite to the collector absorbs all the electrons whose
velocity component normal to the wall is $> |(V_a)_o - (V_a)_s|$,
where $(V_a)_o$ is the potential for which the current $i_m = 0$.
A path equal to the diameter of the tube (1 or 2 λ^-) seems
sufficient to reestablish the distribution. On fig. 6 it
may be seen that for Ne no change in the slope of the log i^-
diagram occurs below $(V_a)_o = -31v$, but for He (fig. 10) the
MAXWELL distribution seems to fail slightly for higher
retarding voltages than $|(V_a)_o - (V_a)_s|$, for both pressures. It
is significant however, that there are so many electrons
able to run against a retarding potential which is only a
few volts smaller than the potential across the tube
(73v and 74v). To explain the phenomena in the positive
column, it would be rational to introduce the effect of the
positive ion layer existing on the glass; this will be done
in § 5 of this chapter when discussing the conditions in the
positive column.
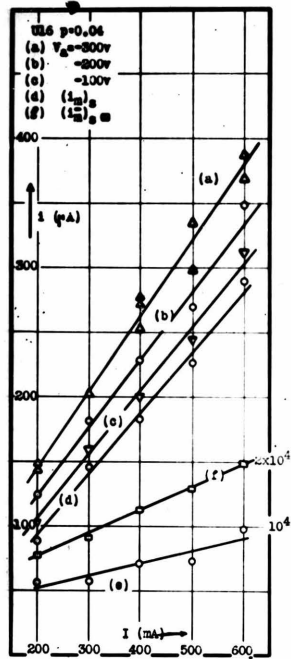
Some difficulty arises in the exact determination of the

Fig. 12. Measurements in Helium.
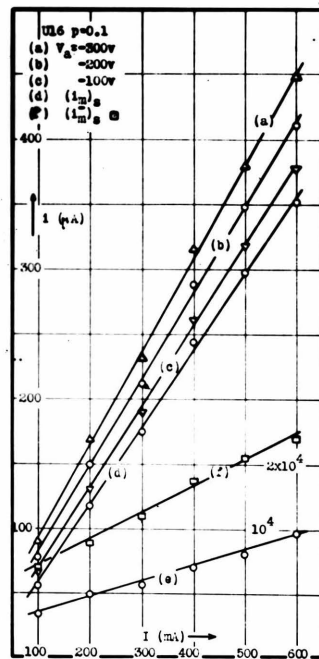
(e) $(i_m)_{300} - (i_m)_s$

Fig. 11. Measurements in Helium.

(e) $(i_m)_{300} - (i_m)_s$

space potential from the log $i^- = f(V_a)$ curves. Must the first break in the curve be taken for $(V_a)_s$ or must the part between $V_a = -30v$ and $V_a = -17v$ (curve a fig. 10) be considered as a transition region? In the second alternative we have to extrapolate the straight line above -30v and the saturation part below -17v and to take their intersection at -21.5v as giving the true space potential. The values found in this way will be denoted in the following $(V_a')_s$. The computation of i_c for run U16C22 has been made taking $(V_a')_s = -26v$ for space potential as found from curve b fig. 10. This view is supported by the fact that the voltage across the discharge tube decreases a few volts when the collector gets more and more positive with respect to the space; this shows that the large electron currents drawn out of the discharge (10% of I) disturb the potential distribution seriously. But this interpretation leaves us with the difficulty to account for the ionization by a group of electrons whose average velocity is only 10.7 volts.

4. i_m^+ and i_s^- as a function of I.

When we plot the measured current i_m to the plane collector as a function of the total current I, V_a being kept constant we obtain some interesting curves. Fig. 11 gives the data for the runs at $p = 0.1$ mm, curves a, b and c represent i_m for $V_a = -300v$, -200v and -100v respectively, while curve d gives the extrapolated currents at the space potential $(V_a)_s$.

It may be seen that all these four curves are practically straight lines. Curve $\underline{e}$ gives the values of the difference $\left[(i_m)_{300} - (i_m)_s\right]$ for various I. Here the deviations, although somewhat larger, may be considered as admissible given the uncertainty in the determination of $(i_m)_s$. Finally curve $\underline{f}$ represents (on a different scale) the electron currents at the space potential $(V_a')_s$, as determined by extrapolation from the linear and the saturation part of the $\log. i^- = f(V_a)$ diagram. The curve $\underline{f}$ again is seen to represent a linear function for the dependency of (i_s^-) on I. The only point which falls off the curve is that representing the electron current for I = 400 mA; it may be noticed that this is also the case for the positive ion currents at the different voltages, and that the deviation is in the same direction.

Fig. 12 gives the corresponding data for the runs made at the lower pressure p = 0.04 mm. Here the deviations from the straight lines are much more pronounced. Now in both cases the same precautions were taken to have absolutely pure He. For the runs at p = 0.1 mm the heating current of the filament i_f was the same for all the current densities, but for p = 0.04 mm it was increased somewhat with I. This is probably the reason for the scattering of the i_m values in the runs with He at the lower pressure and also in the Ne runs, where no attempt was made to keep i_f constant.

5.   Discussion of Results.

The discrepancy between i_m and i_c, and the increase

of i_m with decreasing V_a , will be considered in detail in the next chapter. This paragraph will be used to discuss some general conclusions, to be drawn from the experimental results, and to clear up some difficulties.

a)   Energy loss at the walls.

Energy is lost at the walls because the electrons in diffusing out of the discharge give rise to a transversal gradient, which draws the ions out of the discharge, in sufficient numbers to neutralize the electrons on the wall. The energy carried to the wall per electron is: $\frac{4}{3}\overline{V-}$, per ion $\left[V_i + \{(V_a)_s - (V_a)_o\} + 1 \text{ or } 2\right]$ volts. It is assumed that the energy liberated by the neutralization of a positive ion, is transformed into heat on the wall and not in radiation. This is probably justified, since in all the runs a dark layer on the glass could be observed, and it is not very likely that the energy corresponding to V_i will be emitted as a single quantum. $\left[(V_a)_s - (V_a)_o\right]$ gives the difference of potential across the sheath on the glass, and 1 or 2 v are added to take into account the velocity of the ions when they enter the space charge sheath. We have then for the energy liberated on the walls per cm length of tube per second:

$$W_w = S\left(j^+\right)_o \left[\frac{4}{3}\overline{V-} + V_i + \{(V_a)_s - (V_a)_o\} + 1 \text{ or } 2\right] \text{Watts}.$$

$S =$ inner surface of the tube per cm length.

It is interesting to compare this value with the
energy dissipation in the discharge per unit length per
sec. This will be:

$$W_v = I \times \frac{dV}{dz} . \text{ Watts.}$$

Where $\frac{dV}{dz}$ is the gradient and I, as before the total
current through the tube.

As an approximation we can take for the value of $(j^+)_0$
on the wall, that found for the plane collector at $(V_a)_0$,
i.e. the potential for which $i_m = 0$. For $\overline{V^-}$, $(V_a)_s$ and $(V_a)_0$
we also take the values found with the plane collector.
The following table gives W_w for different gases, pres-
sures and currents, and also W_w in percent of W_v.

Run	Gas	p (mm)	I (mA)	$\frac{j^+_0}{\mu A/cm^2}$	$\frac{W_w}{Watts}$	$\frac{W_v}{Watts}$	W_w/W_v
U5C	Ne	0.02	200	280	0.24	0.4	60%
U5C	Ne	0.02	400	590	0.49	0.8	61%
U6D	Ar	0.01	200	296	0.14	0.25	56%
U6E	Ar	0.002	200	182	0.11	0.35	31%
U16C17	He	0.04	200	311	0.41	0.64	64%
U16C15	He	0.04	600	847	1.06	2.16	49%
U16C25	He	0.1	200	422	0.50	0.60	83%
U16C20	He	0.1	600	1250	1.41	1.80	78%

These values must be considered as approximations,
since we do not know exactly $(j^+)_0$, $(V_a)_0$ and $(V_a)_s$ at the
wall. If the collector disturbs the potential distri-

bution seriously, the values of W_w as found will be too high. The gradient $\frac{dV}{dz}$ was estimated from the voltage across the discharge by deducing a reasonable value for the potential drop in the neigbourhood of the filament. The values obtained for W_v are probably rather good approximations since the ratios $\left(W_w/W_v\right)$ come very close to what one might expect from LANGMUIR's data for Hg (15-45%). The loss to the walls in percent of the energy dissipated in the discharge (both per cm length and per second) is seen to decrease somewhat with increasing I and decreasing pressure; and also with increasing mass of the ions. The relation of $\left(W_w/W_v\right)$ with I and p does not agree with the results obtained by LANGMUIR I 2) in mercury, but the decrease with p cannot be questioned in our case. The disturbing effect of the collector will certainly be more important for the lower pressures, so that the apparent increase in i_m for a given I would be larger. Possibly the fact that $(i_m)_{p=0.1} > (i_m)_{p=0.04}$ all other things equal, can be explained in the following way: when the pressure becomes rather small the electron velocity distribution is no longer isotropic, but has a large common component in the direction of the anode; this would decrease the electron loss to the walls and consequently also $(i_m)_s$. This possible anisotropy of the velocity distribution could be tested experimentally.

b)   Degree of ionization.

The electron concentration n^- (number of electrons per cc), in the discharge opposite to the collector, can be found from the electron current density j^- , by means of the formula:

$$n^- = 4.03 \times 10^{13} \frac{j^-}{\sqrt{T^-}}$$

This is easily derived by combining equations ③ and ⑨, given in the introduction (pge 4), and substituting the values of the different constants. T^-, in degrees K, is found from the slope of the log $i^- = f(V_A)$ diagram and j^- , in Amp/cm², from the value of the electron current at the space potential. The following table gives the electron concentration n^- for different runs, and also the number of atoms per cc., assuming for the gas a temperature of $t = 325°C$ (probably too low). In all the cases there is about 1 electron per 10^4 atoms.

Run	gas	p (mmm)	I (mA)	$n^-\cdot 10^{-9}$	$n\cdot 10^{-13}$	$\overline{V}^-$ Volts	$\overline{V}^+$ Volts	$j^-\cdot 10^2$ (A/cm²)	$j_z\cdot 10^2$ (A/cm²)
U16C19	He	0.04	400	6.25	7.4	10.7	0.9	4.46	1.4
U16C22	He	0.1	400	13	18	7.8	0.6^3	6.18	1.4
U5H	Ne	0.02	450	2.45	3.7	6.9	6.8 / 3.1	1.4	1.6
U6E	Ar	0.002	200	0.7	0.37	5.6	12.7 / 2.0	0.37	0.7

From the values found for n^- we can estimate the velocity of the positive ions. The electron concentration n^-

decreases from the axis of the tube towards the wall, but
the volumes are increasing with **r**. We may then consider
the values for n^- to give a good average, since the mean free
path is of the order of the diameter of the tube. Now, n^+
must be practically equal to n^-, and from:

$$j^+ = n^+ e \, \overline{v^+}$$

we can find $\overline{v^+}$. This would be the average velocity of the
positive ions if they all came in normally to the collector
surface. The value of the positive ion current density j^+
is derived from the extrapolated ion current $(i_m)_s$.

For He the ion velocities come out of the right order
of magnitude, but for Neon and Argon they are decidedly too
high. The two values listed for these last gases correspond
to different space potentials $(V_a)_s$ and $(V_a)'_s$, the lowest value
is obtained when taking $(V_a)'_s$. This discrepancy for Ne and
Ar is perhaps due to a disturbing of the discharge by the
collector, since the ratios (j^-/j^+) also came out too small,
as compared with the ratio (j^-/j^+) found for He.

The random current densities j^-, listed in the fore-
going table, must be compared with the drift current density
j_z, which equals the total current I divided by the cross
section of the discharge tube; j_z is given for each of the
runs in the last column of the table. For the runs in He
$j^- > j_z$, but for Ne and Ar $j^- < j_z$, especially for U6E. In
the case of U6E it is certainly no longer allowed to consi-
der the velocity distribution as isotropic; this explains

the large values of $\overline{V}^+$ as found for U5H and U6E and also the small ratio $\left(\dot{j}^-/\dot{j}^+\right)$.

If we try to compute from the data obtained so far, namely n^- and the gradient used before, the total current I, with the formula:

$$I = C . S . n^- k^- . \frac{dV}{dz}$$

where $k^- = 0.815 \frac{e\lambda^-}{m\sqrt{\overline{v^{-2}}}}$

I comes out too high by a factor of about 4 for both U16C19 and U16Ø22, for U5H the agreement is somewhat better, and for U6E the calculated value is too small, as might be expected since $\dot{j}^- < \dot{j}_x$. It cannot readily be seen which factor causes the discrepancy for He.

c) Electron temperatures.

In § 3 of this chapter it was pointed out that in the explanation of the MAXWELL distribution for the electron velocities, the action of the wall ought to be considered. It might be that part of the energy which is carried out of the discharge to the walls by the diffusion of the positive ions and the metastable atoms, is recovered by collisions of the second kind with electrons. The concentration of the electrons in the positive ion layer on the wall will be given by BOLTZMANN's equation:

$$n^- = n^-_0 \, \epsilon^{-\frac{eV}{\kappa T}}$$

Since most of the electrons are reflected, their velocity
must become very small at some distance from the edge of
the sheath, and this will increase the probability for a
collision of the second kind appreciably. It can readily
be seen that the electrons coming in at small angles with
the normal to the wall are most likely to suffer collisions
of the second kind; on the other hand the electrons hitting
the wall almost normally are easily absorbed. An electron
that has taken part in such a process, will come out of
the layer with superimposed on the image of its original
velocity, a velocity at random corresponding to V_R (MS)
of V_t (triple impact). Even if this process has a large
efficiency it will not disturb the Maxwellian distribution
seriously, due to the presence of the exponential in
BOLTZMANN's formula, which will enter in the expression of
the compound probability. In his measurements in the Hg arc,
LANGMUIR I3) found that the reflection of the electrons is
30% diffuse and attributes this to fluctuations in the space
charge, but these must be small since the currents to the
walls are rather large. The process under discussion
however may cause such a partly diffuse reflection, and also
lower the value of λ^- as derived from this kind of measure-
ments with the formulas given in the preceeding § . (Pge 57)

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Notations of Table II.

I = current in mA through the tube.

ΔV = voltage across the discharge.

$(i_m)_{300}$ = measured collector current for V_a = -300v (μA)

$(i_m)_{100}$ = measured collector current for V_a = -100v (μA).

$(i_m)_s$ extrapolated pos.ion current (μA) at space potential.

$\Delta i_m = (i_m)_{300} - (i_m)_{100}$

$(V_a)_0$ = potential with respect to anode for which $i_m = 0$.

S = slope of the straight part of the i_m curve ($\mu A/v$).

$(V_a)_s$ = space potential with respect to anode.

$(i^-)_s$ = electron current (μA) to the collector at $(V_a)_s$.

$(V_a)'_s$ = see pge 50.

$(i^-)'_s$ = electron current (μA) to the collector at $(V_a)'_s$.

$\overline{V^-}$ = average electron velocity in volt.

TABLE I

Run	I	$(i_m)_{400}$	$(i_m)_{100}$	$(i_m)_s$	Δi_m	$\left\{\dfrac{\Delta i_m}{(i_m)_{100}}\right\}$	100δ	$(V_a)_0$	$(V_a)_s$	$(i^-)_s$	$(V_a')_s$	$(i_s^{-\,\prime})$	$\overline{V}^-$	T^-
			NEON	p=0.02mm	Ni									
U5A	100	149.2	68.4	58.5	80.8	1.18	20.5	−35	−22	550	---	--	9.1	70000
U5B	150	186.0	105.2	85.0	80.8	0.77	24.5	−33	−22	770	---	--	7.6	58000
U5C	200	233.6	127.7	103.0	105.9	0.83	30.5	−32	−20.5	1200	−17.2	2300	7.5	57000
U5D	250	287.7	171.5	142.5	116.2	0.68	36.0	−31	−19	1650	−17.2	2500	7.2	55000
U5E	300	306.6	193.2	166.5	113.4	0.59	34.0	−31	−21.1	1500	−15.7	4800	6.9	53000
U5F	350	332.2	206.7	180.0	125.5	0.61	36.0	−33	−20.5	2000	−14.2	6700	7.9	61000
U5G	400	380.4	245.0	217.0	135.4	0.55	34.5	−31	−21.5	1750	−15.5	6300	7.9	61000
U5H	450	400.2	271.5	242.0	128.7	0.48	36.0	−31	−21.5	2050	−13.2	10800	6.9	53000
U5I	500	424.5	289.9	260.0	134.6	0.46	37.5	−31	−21	2300	-----	---	6.9	53000
U5AI	100	184.1	81.7	61.5	102.4	1.26	25.0	−34	−18.5	840	---	--	9.2	71000
U5AII	100	179.1	81.0	63.0	98.1	1.21	22.0	−34	−20	700	---	--	9.3	72000
			NEON	p=0.02mm	C									
U6B	200	184.5	124.4	110.5	60.1	0.48	18.0	−35	−21.5	1150	---	--	8.4	64000
			ARGON	p=0.01mm	C									
U6D	200	175.4	121.1	109.0	54.3	0.45	14.5	−20	−15	1100	---	--	3.1	24000
			ARGON	p=0.002mm	C									
U6E	200	125.1	73.6	67.0	51.5	0.70	9.0	−23	−15.5	510	−11.0	1700	5.6	43000
			ARGON	p=0.01mm	Ni									
U10C	200	236.1	179.0	161.0	57.1	0.32	17.0	−24	−19.5	2500	---	--	2.6	20000

IV

DISCUSSION OF RESULTS

In the following paragraphs several possible explanations of the discrepancies with LANGMUIR's results in mercury are discussed.

1. General considerations.

As has been pointed out before, neither the uncertainty in the temperature of the positive ions, nor the fact that the dark layer has been measured too thin (due to the unsharp transition) can account for the difference $(i_m - i_c)$. Indeed both have been taken so as to give too large values of i_c.

Another possibility is that the measurements have been carried out with Neon that contained some Helium. Suppose that the mixture contains 80% Ne and 20% He. As a first approximation we can try to take this into account by introducing for M (the molecular weight) in formula $\boxed{13}$

$$\sqrt{m/m_0} = \sqrt{1834.M}$$

instead of 20.2 (Neon) : $(0.8 \times 20.2 + 0.2 \times 4) = 16.96$. This gives an increase of 9% in i_c, which is not sufficient to explain the differences of 80% and more. Furthermore the

Neon used contained only 5% He (max.). For a more accu-
rate estimation one ought to know the relative probability
of ionization for the components in the Neon-Helium mixture.
The ionization potential of Helium being higher than that
of Neon, it is probable that the ratio of the number of
ionized He atoms to the number of ionized Ne atoms is smal-
ler than the ratio for the neutral particles. To this is
to be added the fact that He ions seem to be able to ionize
neutral Ne atoms by a sort of collisions of the second
kind 1). On the other hand the mass of the He ions is
much smaller than that of the Ne ions so that their mobili-
ty will be larger, and consequently their relative contri-
bution to the positive ion currents to the walls rather
important. Spectroscopically the Neon used appeared quite
pure, and although this last argument is not conclusive in
the case under consideration, we are probably justified in
neglecting this correction.

When comparing the results obtained with tube U5, it
is found that α increases with increasing current density.
The different runs have been taken in the order of increa-
sing current I, and the sputtered metal layer on the walls
and the glass tubes protecting the lead-in wires of the
disk and guard ring became thicker and thicker. The
same is to a certain extent the case with the mica cover
on the lower side of the collector. This could cause
leak currents and to check this point the collector of tube

U5 was taken out after run U5AII and the resistance between different parts of the auxiliary electrode measured. It was found that the resistance was nowhere smaller than 50 MO (in air), and varied from 50 to 100MO. Under these conditions the leak currents could be at maximum of the order of 10 μA and we may neglect them for the following discussion.

As stated before a collector with a guard ring was used to avoid the edge corrections. These would be much larger in the noble gases than in mercury, because for a given voltage and current density the space charge layers are thicker due to the smaller mass and consequently higher velocity of the incoming positive ions. In LANGMUIR's experiments these corrections were rather small, and the collected positive ion currents increased only a few percent over a range of several hundred volts. The large slope of the $i_m = f(v_a)$ curve (fig. 4 and 9) makes it already very improbable that these edge corrections are responsible for the difference $(i_m - i_c)$; furthermore α increases with increasing current I, which definitely rules out this interpretation. Indeed the ratio of the side surface of the cylindrical space charge region to the top or bottom surface, i.e. that of the collector itself, decreases with increasing current i_m, because the thickness x decreases.

Finally the question arises whether formula $\boxed{13}$, which is derived for currents in vacuum, may be applied to this case. It could be that, at the pressure used, the positive ions

make still too many collisions in the dark layer, and even
may produce some ionization. This would cause a loss of
energy of the positive ions and reduce the thickness of the
space charge, while the measured value x_m is found to be too
large. Furthermore measurements of the mean free path of
the noble gas ions in their own gas, now in progress by
Prof. K. T. Compton and the Author, shows that for the
velocities under consideration, from 100 to 500 volts, the
mean free path is about twice the gas-kinetic value.

2. <u>Effect of the penetrating electrons into the positive
space charge</u>.

The equivalent temperature of the electrons is very
high, so that their kinetic energy corresponds to several
volts. Under these conditions quite a large number of
electrons will penetrate a certain distance into the positive
space charge. This is probably the explanation of the
unsharp transition between the dark layer and the body of
the discharge (p. 16).

If we suppose, for simplicity, the ordinary space charge
equation to be applicable, and take for the average energy
of the electrons $\overline{V^-} = 10v$, the distance <u>h</u> over which they
penetrate into the sheath can be estimated. For U5H (Ne,
p = 0.02 mm, I = 450 mA) we find when $V_a = -150v$, for instance,
h = 0.6 mm. These values of <u>h</u> are of the same order of
magnitude as those estimated visually but no attempt was

made to measure them accurately since the outer edge was not sharp enough to give reliable results. The values/of h come out rather high, because of the small potential gradient near the outer edge of the sheath.

The estimation of h is made on the assumption that the electrons, because of their small mass and consequent high mobility, do not alter appreciably the potential distribution in the space region. Dr. C. Eckardt, who suggested this interpretation for the unsharp transition, derived the space charge equation in which this effect was taken into account. The approximation was found to be justified.

It has been pointed out pge 16 that the value for x_m as measured is too small; but correction for this would make our i_c values still smaller, and they were already found to be only about one half of i_m. If the transition layer is really due to the penetration of the electrons into the sheath, the potential to be introduced in the space charge equation is approximately $V_a - [(V_a)_s + \overline{V^-}]$, where $\overline{V^-}$ is the average energy of the electrons; this will decrease i_c. But the ions will come into the dark part of the sheath with a certain velocity, namely the sum of $\overline{V^-}$ and $\overline{V^+}$, the velocity they had in striking the outer edge. This will increase i_c for a given value of x_m, the measured thickness. Taking these corrections into account the difference between i_m and i_c remains about 50% of i_m; as may be seen readily when remembering that in first approximation ~~the~~

the contribution of the electrons to the space charge in the transition region can be neglected.

Since no reasonable correction for any of the possible errors discussed so far, can explain the discrepancy between i_m and i_c , other possible interpretations will be considered below.

3. Secondary emission from the metal of the collector.

When we defined the value of α as $100\left(\frac{i_m - i_c}{i_c}\right)$, the assumption was tacitly made, that the difference $(i_m - i_c)$ is due to electron emission from the metal. Indeed, the calculation of i_c is based on the hypothesis that only the ions coming in from the discharge contribute to the space charge. Different possibilities as to the cause of such a secondary emission will now be considered.

a) Photoelectric effect.

This is the interpretation which SCHOTTKY I 4) originally adopted to explain the saturation of the positive ion part of the characteristic (p. 2). It proved untenable, as leading to an efficiency of the photoelectric effect altogether too high. Now this argument still holds in our case, since the difference $(i_m - i_c)$, we have to account for, is of the same order as i_m , namely about 50% i_m . A rough estimation shows that this effect will give too small an electron emission from the metal. Taking e.g. run U5H (Ne, $p = 0.02$ mm, $I = 450$mA)

the total energy dissipated per second will be $0.45 \times 65 = $ 27 Watt, ($\Delta V = 65v$, voltage across the discharge). Let us suppose that 50% of this energy is circulating in the tube as ultra-violet radiation, and that 0.001 of this falls per second on the collector surface. This is certainly too high because glass is a very poor reflector for the wavelength corresponding to the resonance radiation of Ne ($\lambda 750\text{Å}$), and most of the light is produced around the filament. The efficiency of the photoelectric effect of $\lambda 750\text{Å}$ is not known, but we can take as an approximation, giving at least the order of magnitude, the value found by SUHRMANN 2) for $\lambda 2225\text{Å}$ on platinum with adsorbed gas: $667 \times 0.24 \times 10^{-6}$ Amp/Watt. Combining this with the estimation of the energy falling on the disk per second, we find a current of about $0.2\mu A$.

b) <u>Positive ion impact.</u>

The liberation of electrons by impact of positive ions on a metal plate, has been the subject of many investigations, because the problem is of great importance in the theories of the normal cathode fall and the sparking potential. When an ion is neutralized at the surface of the cathode the emission of a secondary electron can be brought about in several ways:

1) the liberated ionization energy is emitted as radiation and in falling on the metal causes a photoelectric effect. This possibility was postulated by J. J. THOMSON 3)

and used as the basis of $\overset{a}{\vee}$ photoelectric theory of the sparking potential by TAYLOR 4) 5). In their measurements of the heat of condensation of positive ions on a metal surface K.T. COMPTON and VAN VOORHIS 6) 7) obtained strong evidence for this effect. However, direct measurements by DEAUVILLIER 8) showed the presence of far ultra-violet radiation in the negative glow, but he could detect no radiation of this type in the neighbourhood of the cathode.

2) if the ions fall on the cathode with considerable kinetic energy, they can possibly knock electrons out of the metal by a process similar to that which gives rise to secondary emission by electrons.

3) before being neutralized the ion may possibly liberate an extra electron (Compensation of the image force), in addition to the one needed for its neutralization, by electrostatic attraction out of the metal. This is the basis of a theory for the sparking potentials by HOLST and OOSTERHUIS 9).

Still other processes have been suggested; local heating of the metal (V_t) and subsequent thermionic emission (VON HIPPEL 10)) and pulling out of the electrons by high electric fields (LANGMUIR I 1, I 2)), but these are probably to be neglected in the case under consideration.

For our purpose we need only the number of electrons liberated per incoming positive ion, whatever may be in

detail the process leading to their emission. Practically all
the direct measurements of the efficiency of this process
have been done with positive ions of the alkaline metals 11),
the best work of this kind being probably that by JACKSON
III 2, III 3). He finds that for <u>clean</u> surfaces, the ions
must have velocities corresponding to several hundred volts
before any appreciable electron emission can be detected,
so that this must be due to the process sub 2). If the pro-
cess given sub 3) is the important, we might expect that a
necessary condition will be: $V_i \geqslant 2\varphi$, where V_i is the ioni-
zation potential of the gas and φ the work function of the
metal 12). In other words the noble gas ions are the only
ones which will give a secondary emission for most of the
common metals (Ni, Fe, etc.) where φ is about 5-6 volts.
This has been confirmed by measurements of PENNING 13) 14),
who finds that for Neon ions falling on Fe, Cu or Ag surfaces,
the secondary emission is of the order of 5-10% and increases
linearly with the accelerating voltage, while its absolute
value depends considerably on the condition of the metal sur-
face. The targets in his experiments stood in a fairly good
vacuum, obtained by differential pumping, while in our work
the metal is more likely to have an adsorbed layer of normal
and excited atoms, which might increase the secondary emission.
However, it is probable that this emission alone cannot account
for the difference $(i_m - i_c)$.

c)   Impact of metastable (MS) atoms.

This effect has been observed in mercury by WEBB 15), and studied by several of his students 16) 17);   CONSTANTI-NIDES interprets his observations on ionization in the after-glow of N_2, on the basis of this effect.

The process might be considered as a special type of photoelectric effect, where the energy necessary for the emission of the electron is brought to the metal in the form of potential energy of the impinging gas atom. Of course we do not know how the process really goes on; it is perfectly possible that in hitting the metal surface, the atom releases its potential energy in the form of radiation, with subsequent photoelectric effect.

From a qualitative estimation given below, it would follow that this process has a very high efficiency, of the order of unity; compared to this the normal photoelectric effect appears to have a very low efficiency. (p. 66). A reasonable explanation would be, that a quantum can perhaps penetrate quite a distance into the metal before being absorbed, while the MS atoms all transfer their energy to the outer layer of the metal atoms. In the second case the chance for an electron to get out of the metal, is much higher than in the first. This difference might still be enhanced by the abnormally large active area of the MS (in general excited) atoms, which has been found experimantally. 19)

The following estimation, due to Dr. W. DE GROOT, shows that MS atoms diffuse in sufficient number to the wall to explain the secondary electron emission, provided the efficiency of this process is rather high.

DORGELO II 16) investigated the conditions in the positive column of the Neon glow discharge, and found by intensity measurements that the number of ionizing collisions per second is of the same order as the number of 18v impacts, while the 16v levels are practically not excited by direct electronic impact. Let us suppose that about 50% of the energy dissipated per second in the positive column is used for 18v impacts; for run U5H, this will be 27 Watts. (p. 66). This is in qualitative agreement with the loss to the walls as estimated in chap. III p 53 . Now every 18v impact requires an energy of $\left(\frac{eV}{3\infty}\right)$ erg $= \frac{eV}{3.10^9}$ Joule, with $e = 4.77 \times 10^{-10}$ ESU and $V = 18v$, this gives $\sim 3.10^{-18}$ Joule, so that the total number of 18v impacts per second in the tube will be 6×10^{18}. Taking the volume of the discharge tube 1000 cc, we have for the number of 18v impacts per cc per sec: 6×10^{15}. Now the 16 level is 4 fold, and for simplicity we consider only the long-living MS state $S_5 (3 P_2)$, so that we can roughly estimate the probability for a transition from one of the 18v levels to the MS S_5 level to be $\frac{1}{4}$. (Transitions from the 18v levels to the ground state are forbidden). The number of MS atoms formed per second per cc is thus : $a \simeq 1.5 \times 10^{15}$.

The disappearance of MS atoms at the walls is governed

by the diffusion equation:

$$k \left(\frac{d^2 n^x}{dr^2} + \frac{1}{r} \frac{dn^x}{dr} \right) = -a$$

where: n^x = concentration MS atoms
r = distance from axis
$a = 1.5 \ 10^{15}$/sec.cc.

The influence of the life time is neglected because of the long free path, since it is known that a MS atom can suffer a large number of collisions with normal atoms of the same gas, without losing its energy 20) and consequently practically all the MS atoms will be destroyed at the wall.

Solving the foregoing equation we find for the concentration n^x as a function of the distance from the axis:

$$n^x = \tfrac{1}{4} \frac{a}{k} (R^2 - r^2)$$

R = radius discharge tube = 3cm
and for the number of MS arriving per sec per cm^2 at the wall:

$$\left(-k \frac{dn^x}{dr} \right) = \tfrac{1}{2} a R = 2.25 \times 10^{15} / cm^2 \ \text{sec.}$$

Supposing that each MS atom hitting the surface of the collector liberates an electron, this would correspond to a current of

$$\frac{2.25 \times 10^{15} \times 4.77 \times 10^{-10}}{3 \times 10^9} = 3.6 \times 10^{-4} A = 360 \ \mu A$$

and the differences found are of the order of 200 μ A.

4. <u>Ionization in the sheath.</u>

So far it has been taken for granted, that whenever the

thickness of the sheath x is smaller than the mean free path λ of the particles collected, any secondary effect in the sheath can be neglected. Now a small ionization in the sheath will have a large influence on the potential distribution and the thickness x. This ionization can be due to different causes:

a)   Photoelectric ionization of normal atoms.

b)   Photoelectric ionization of MS atoms.

c)   Ionization by mutual impact of 2 MS atoms.

These three possibilities have been considered in an article published by Dr. P. M. Morse and the Author 21). The principle of the method used is the following. In the first effect the rate at which the new ions are formed is constant over the whole thickness of the sheath. For hypothesis b) and c) this rate will depend on the concentration of MS atoms at every point in the sheath, and this is inversely proportional to the distance from the edge of the sheath. Consequently the rate of formation of new ions for case a) and b) will respectively be proportional to y and y^2, where y is the distance from the metal surface of the collector. Each of these relations contains of course an undetermined constant depending on the concentration of MS and the absorption coefficient. POISSON's equation is then solved by an approximation method, taking into account the contribution of the newly formed ions to the space charge. Hypothesis b) was found to fit the experimental data fairly well. However a direct experimental test performed by DE GROOT 22) gave a

negative result. Since the difference in energy between the MS levels and the ionization potential corresponds to about 5V, a gas containing MS Ne atoms must show a continuous absorption starting at about $\lambda 2500 \text{Å}$ and shading off towards the ultra-violet. The absorption that was found by DE GROOT came out much too small to account for the difference $(i_m - i_c)$. The only way in which hypothesis b) could be upheld, would be to assume that the efficiency for photo-ionization of MS atoms by radiation of $\lambda 750 \text{Å}$ is much larger than for $\lambda 2500 \text{Å}$; this is very improbable.

d)   <u>Ionization by positive ion impact</u>.

This effect will probably be rather small, especially for the low accelerating potentials, because of the small efficiency of the process. According to FRANCK 23), an ion with an energy of $2 V_i$ can, under favorable conditions, produce ionization but the probability of ionization is very small; this is confirmed by recent experiments of SUTTON 24). Then it could be that the incoming ions produce ionization of the MS atoms, and this process might be more efficient. However, if there were an appreciable number of impacts for the incoming ions, the sheath thickness would be decreased (the ions losing part of their velocity contribute more to the space charge), and experimentally x_m was found too large.

e)   <u>Ionization of sputtered metal by MS atoms</u>.

If the sputtered metal left the collector charged negative-

ly, the positive space charge would be weakened and the thickness increased; but recent work by VON HIPPEL 25) and BAUM 26) has shown that sputtered particles leave the metal uncharged. Another possibility is that the MS atoms coming from the discharge ionize the sputtered metal atoms; in this case the thickness of the sheath would be decreased and the fact that $x_m > x_c$ obliges us to discard this effect.

f) Impact ionization by electrons liberated by one of the processes sub 1)

Since the existence of the effects 1a) and 1b), electron emission by photoelectric effect and by positive ion impact, is not open to doubt, there will always be some ionization due to electron impacts in the sheath. This case was considered in the paper referred to before 21) but the ionization was considered as a function of the field strength. Now the mean free path λ^- of the electron in Ne is about 40 mm at $p = 0.02$mm (U5G), while the thickness of the space charge varies from $x = 2$ mm ($V_a = -50$v) to $x = 6.45$ mm ($V_a = -450$v) so that for $V_a = -450$v about 15% of the electrons coming from the metal have collided in the sheath; consequently successive impacts by one electron in the sheath may be neglected. If process 1a) or 1c) is causing a secondary emission, the electrons coming out of the sheath will practically all have the same velocity V_q, except for a small number formed in the layer, and the secondary emission must be almost independent of V_a (except for a

small correction due to the action of the secondary electrons in the discharge). If process 1b) is the main cause of the secondary emission, the number of electrons liberated per incoming positive ion must increase linearly with V_q 13). Furthermore, the additional ionization in the sheath will, for a given voltage, increase with the thickness of the sheath.

A qualitative estimation as to the order of magnitude of this effect can easily be made as follows. Suppose the measured current i_m for a given voltage V_q to consist of 3 parts: 1) i_1^+, the positive ions coming from the main discharge; 2) i_1^-, the secondary emission from the plate due to the incoming ion current i_1^+; 3) i_2^+, the current corresponding to the new ions formed in the space charge layer by the electron component i_1^-. Further approximations will be neglected.

$$i_m = i_1^+ + i_2^+ + i_1^-$$

i_1^+, is put equal to the extrapolated value $(i_m)_s$ of the measured current at the space potential. i_1^-, will be, according to the results obtained by PENNING 14) a function of of the form

$$i_1^- = i_1^+ \left[A + B V_q \right]$$

where A and B are undetermined constants. Finally i_2^+ is directly proportional to i_1^-, and depends on the voltage which determines the thickness x i.e. the number of impacts,

and also the probability of ionization $\varphi(V)$. The thickness is taken from the measurements, the probability of ionization from the determination by COMPTON and VAN VOORHIS [27] [28] in the form given by PENNING [29]. We have then:

$$i^+_2 = i^-_1 \cdot \varphi(V)\left[1 - e^{-x/\lambda^-}\right]$$

$$= i^-_1 \sqrt{\frac{V_q - V_i}{V_q}} \left\{\frac{x}{\lambda^-} - \frac{1}{2!}\left(\frac{x}{\lambda^-}\right)^2 + \cdots\right\}$$

So that we have finally for the current

$$i_m = i^+_1 \left[1 + (A + BV_q)\left\{1 + \sqrt{\frac{V_q - V_i}{V_i}}\left(\frac{x}{\lambda^-} - \frac{1}{2!}\left(\frac{x}{\lambda^-}\right)^2 + \cdots\right)\right\}\right]$$

It is implicitely supposed that all the electrons have a velocity V_q when they collide with the gas atoms in the sheath. This is only a rough approximation, which is partly justified by the fact that in the space charge layer most of the potential drop occurs near the metal plate. Another factor, which perhaps has to be taken into account, is the formation of Ne^{++} which might be rather important at these high accelerating voltages. Such ions would contribute less to the space charge per unit charge transported than Ne^+, and this might partly explain the fact that $x_m > x_c$. (Observation of spark lines opposite the collector?) This formula gives a very good agreement for all the runs in Ne. The following table gives some data as calculated for run U5G $p = 0.02$ mm, $I = 400$ mA.

The deviations between the measured and the calculated value of i_m are only a few percent. The constants A and B

are determined for each run from the values of i_m for $V_a=$ -100v

and $V_a=$ -200v. They are of the same order of magnitude as

the values determined directly by PENNING, which is all one

can expect, since they are known to vary with the conditions

of the metal surface. In these experiments A and B are found

to decrease with increasing current density; e.g. for $I=$

100 mA, $A=0.07^5$ and $B=2\times10^{-3}$. This would mean that at

about 500v every positive Ne ion liberates one electron.

From considerations referring to the energy balance at the

electrodes in a glow discharge, GÜNTHERSCHULZE 30) concludes

that for 420v on Fe, for 325v on Al and for 290v on Mg, every

positive ion in hydrogen liberates one electron, so that the

values for A and B may be considered as admissible.

The same type of calculations when applied to the data

obtained in Ar and He, does not give very satisfactory re-

sults. This must not necessarely mean that the underlying

idea is wrong since we neglect the excitation, which certain-

ly must be present, and is known to be very small in Neon

but large in Ar and He.

5. Conclusion

So far it has not been possible to determine definitely

to which one, or ones, of the effects discussed, those dis-

crepancies are principally due. Perhaps a direct study of

the secondary emission will enable a definite conclusion.

Experiments are now under way by the Author in which the se-

condary emission, if present, can be measured directly.

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<u>Table</u>.(pge 76).

U5G Ne Ni p≈0.02mm I≈400mA $(i_m)_s$=217µA.

A≈0.028 B≈1.1x10^{-3}

						in % of i_m			
V_q	x	i_m	i_1^-	i_2^+	Σi	i_1^+	i_1^-	i_2^+	$i_1^+ + i_2^+$
78.5	3.1	245	24.7	3.0	244.7	88.5	10.1	1.2	89.7
178.5	4.55	280.4	48.6	14.5	280.1	77.5	17.3	5.2	82.7
278.5	5.65	327.2	72.5	33.4	322.9	66.3	22.5	10.2	76.5
378.5	6.45	380.4	95.8	60.0	382.8	57.1	25.2	15.8	72.9

All currents in µA. $\Sigma i = (i_m)s + i_1^- + i_2^+$.

Appendix (p 50).

An estimation of the number of new ions formed per unit length in the tube, can be made in the following way.

Suppose the distribution of the velocities of the electrons in the discharge to be perfectly Maxwellian, then the number of electrons per cc having a velocity between (x) and (x+dx) is:

$$d_x N = 4\pi n^- \left(\frac{m}{2\pi kT^-}\right)^{3/2} \cdot e^{-\frac{mx^2}{2kT^-}} \cdot x^2 \, dx$$

the number of impacts made by these electrons per sec. is:

$$\left(\frac{x}{\lambda^-}\right) \times d_x N .$$

and the number of ionizing collisions per cc. per sec. will be

$$\left(\frac{x}{\lambda^-}\right) \varphi(x) \, d_x N$$

where $\varphi(x)$ is the probability of ionization. For $\varphi(x)$ we take:

$$\varphi(x) = B(x^2 - x_i^2) = b(V - V_i)$$

where x_i is the velocity of the electron corresponding to V_i. (G. SPIWAK ZS.f.Phys. 53 805 1929).

We have then for the total number of new ions formed per cc and per sec.:

$$\gamma b = \frac{4\pi B n^-}{\lambda^-}\left(\frac{m}{2\pi kT}\right)^{3/2} \int_{x_i}^{\infty} x^3 (x^2 - x_i^2) \cdot e^{-\frac{mx^2}{2kT}} \cdot dx$$

This integral can be solved by partial integration and due to the exponential only the term corresponding to the lower limit has to be considered. The result is:

$$\gamma b = \frac{2n^- B}{\sqrt{\pi}\,\lambda^-}\left(\frac{2kT}{m}\right)^{1/2} e^{-\frac{mx_i^2}{2kT}}\left[\frac{2kT}{m}\left\{\left(\frac{mx_i^2}{2kT}+1\right)^2+1\right\} - x_i^2\left(\frac{mx_i^2}{2kT}+1\right)\right]$$

Taking run U16C19 (He p=0.04mm I=400mA) and putting in the values for the different constants and data obtained before:

$n^- = 6.25 \times 10^9 /cc.$

$\lambda^- = 3.15$ cm

$B = 1.83 \times 10^{-18}$

$k = 1.372 \times 10^{-16}$ erg/degree.

$T^- = 82700°K.$

$m = 9 \times 10^{-28} gr.$

$x_i = 5.95 \times 10^7 \sqrt{24.6} = 2.95 \times 10^8$ cm/sec.

we get for $\gamma b : 2.86 \times 10^{15}$.

If we suppose n^- as given by experiment to represent an average for the electron concentration over the whole cross section, the total number of ions formed per unit length of the tube per second will be:

$$2.86 \times 28.3 \times 10^{15} = \underline{8.08 \times 10^{16}} .$$

this would correspond to a current to the walls per cm.length of tube

$$\frac{8.08 \times 10^{16} \times 4.74 \times 10^{-10}}{3 \times 10^9} = 1.28 \times 10^{-2} A = \underline{12800} \mu A$$

while according to the measured value of $(i_m)_s$ it would be:

$$\frac{6\pi \times 182.5}{\pi \times \overline{0.3}^2} = 12.2 \times 10^{-3} A = \underline{12200} \mu A$$

For the He runs at higher pressure the agreement between the calculated value of the ion current and the measured one (deduced from $(i_m)_s$), is also very good. For Ne the calculated value is only about 5% of the measured one, so that we are forced to the conclusion that in Ne either the cumulative ionization is very important, or the velocity distribution of the electrons is far from isotropic. The second alternative

is probably the right conclusion (p 30).

The calculation of the ion currents to the wall for the runs in He has been made taking the value of n^- corresponding to $(V_a)'_s$ as space potential (p 50). One would conclude from the numerical agreement that $(V_a)'_s$ is then the real space potential. However, when the total current through the tube I is computed with LANGEVIN's formula for the mobility (p 57), using the electron concentration and temperature found by experiment, it is the value for n^- corresponding to $(V_a)_s$ which leads to an exact numerical agreement. This question as to whether $(V_a)_s$ or $(V_a)'_s$ has to be taken as space potential will also be decided by the experimental work now in progress.