STUDIES IN THE NEGATIVE GLOW

REGION OF THE HELIUM DISCHARGE

being a thesis for the degree of

Doctor of Philosophy

submitted by

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The research described in this thesis was undertaken initially in connection with the elucidation of the processes governing the interaction between high frequency electro-magnetic fields and d.c. gas discharges. It had been established experimentally that the negative glow region of the discharge gave by far the greatest contribution to this interaction, as described by the author in a recent paper*, and consequently it was desired to obtain as much information as possible concerning the electron density and energy distributions in the negative glow.

Although a considerable amount of information about this region of the discharge was obtained by Professor K.G. Emeléus and his group at Queen's University, Belfast in the early 1930's, recent improved probe methods now make it possible to obtain more accurate and reliable information than was possible before. The emphasis in this thesis is on the newer probe techniques employed, and in the interpretation of the results, aided by spectro-photometric measurements of the spectral line intensities in the glow. In addition modern methods of vacuum technique have made

it possible to ensure a very high degree of gas purity, so that the results should not be complicated by traces of impurity in the gas.

The thesis is divided into three main sections. Section A deals with the electron energy distribution function in gas discharges and its significance, the general theory of probes, and a review of previous investigations in the negative glow region of a d.c. glow discharge, including a short note on experiments made by the author using microwave cavity techniques. Section B is concerned with the experimental probe techniques and apparatus developed for this research and a discussion of the results, while Section C deals with the supporting spectroscopic evidence as to the energy and density distributions. An appendix is added giving some actual experimental readings and mathematical formulae employed in the thesis. It may be noted that the graphs and drawings have been reproduced on double size paper in order to enable them to be studied in conjunction with the text.

It is a pleasure to the author to record here his sincere thanks to Mr. W. E. J. Farvis of the Engineering Department, University of Edinburgh for his constant advice and encouragement in this work, and also to Professor N. Feather of the Natural Philosophy Department, University of Edinburgh. In addition the author must express his indebtedness to Messrs. Ferranti Ltd., Edinburgh, who have provided the facilities for carrying
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SECTION A: GENERAL INTRODUCTION

CHAPTER I: THE ELECTRON ENERGY DISTRIBUTION FUNCTION IN AN IONISED GAS

The electron velocity or energy distribution function is the most important single relation in the study of the behaviour of electrons in a gaseous discharge. Knowledge of this function permits the determination of such statistical properties of a gas as the rate of ionisation by electron collision, electron mobility, rate of diffusion and mean electron energy.

Two limiting assumptions can be made in problems concerning the movement of free electrons among gas molecules; either there is no energy loss of the electrons by collision with the molecules or the electrons are in thermal equilibrium with either the gas molecules or with each other due to electron-electron interaction. The first assumption is only valid when the molecules are infinitely massive with respect to the electronic mass, or when the gas pressure is so low that the mean free path of the electrons between molecular impacts is longer than the dimensions of the apparatus. The second assumption leads in either case to a Maxwellian distribution of velocities and is generally true only when the electric field intensity is very small and electron velocities are very low, or in the case of electron-electron interaction, when electron densities are very large. Collisions between
electrons and gas molecules are nearly elastic up to the first excitation potential, the electron energy loss actually being approximately \((\frac{2m}{M})E\) where \(m\) and \(M\) are the mass of the electron and molecule respectively. In addition to these so-called 'elastic' collisions, at higher electron energies we can have 'inelastic' collisions due to excitation of the vibrational levels of molecular gases or, at higher energies still, excitation of the electronic levels and ultimately ionisation with the removal of electrons from the orbital shells.

A comprehensive account of the various theoretical forms of electron energy distribution function derived by several workers over a period of years up to 1939, and the fundamental assumptions made in these derivations, is given in the book by L.B. Loeb, 'Fundamental Processes of Electrical Discharge in Gases', Chapter 5. In these introductory remarks, therefore, it is considered necessary only to give a brief account of the principal derivations, including one or two subsequent to Loeb's account, and to show graphically how the normalised probability or distribution function \(W(E)\) varies with the electron energy \(E\) for these derivations. \(W(E)\) is defined as the number of electrons with energies between \(E\) and \((E + \Delta E)\) divided by the total number of electrons.

The function deduced by J.C. Maxwell for a steady state distribution of energies among an assemblage of particles in thermal equilibrium may be written

\[
N_dE = \frac{2N \sqrt{E}}{\pi^{1/2} (kT)^{3/2}} \cdot e^{-E/kT} \cdot dE
\]

(1.1)
where $N_{a,E}$ is the number of particles of a total $N$ having an energy between $E$ and $(E + dE)$ and $\overline{kT}$ represents the most probable kinetic energy of a particle. We may rewrite the equation in probability form as

$$W(E)_{dE} = \frac{2}{\pi^{1/2}} \frac{\sqrt{E}}{(\overline{kT})^{3/2}} \cdot e^{-E/\overline{kT}} \cdot dE$$

The first rigorous attempt to derive an expression for the electron energy distribution in a gas discharge in the presence of a d.c. field and with the electrons subject to elastic collisions was made by Druyvesteyn(1). His principal assumptions can be summarised as follows:

1. The gain in velocity per free path is small compared to the velocity in the path. This implies a lower limit for the gas pressure.
2. The electrons lose at each molecular impact an average energy $\overline{E} = (2m/M) \cdot E$, where $m$ and $M$ are the mass of the electron and molecule respectively and $E$ is the electron energy.
3. The mean free path ($\lambda$) of the electrons is independent of velocity. This neglects the Ramsauer(2) effect.

Using the condition of equilibrium in a field of intensity $X$, Druyvesteyn obtained finally

$$W(E)_{dE} = 2\cdot1/2 \left[ \frac{2m}{M} \right]^{1/2} \cdot \frac{\overline{E}^{1/2}}{X^2} \cdot \frac{1}{\pi^{1/2}} \cdot \frac{1}{\overline{kT}} \cdot e^{-E/\overline{kT}} \cdot dE$$

If now we take the case of a discharge in helium

$$\frac{2m}{M} = 2\cdot7\cdot10^{-4}$$

and the gas kinetic value of $\lambda$ is

$$\lambda = \frac{1}{\pi \sigma^2 N' \cdot p} = \frac{1}{25 \cdot p}$$

where $\sigma = $ molecular radius $= 1.5x10^{-8}$ cm. for helium

$N' = $ Loschmidt's No. $= 2.71x10^{19}$ molecules/cm

at N.T.P.
\( p = \text{pressure in millimetres} \)

This gives
\[
\omega(\varepsilon) d\varepsilon = 0.5 \varepsilon \left( \frac{X \varepsilon}{p} \right)^{3/2} \varepsilon^{1/2} \left( \frac{X \varepsilon}{p} \right)^{2} d\varepsilon \tag{1.2}
\]

J.A. Smit\(^3\) was the first to obtain general equations on the principle of detailed balancing of energy loss and gain, including elastic, ionising and exciting collisions and allowing for variable (Ramsauer) free paths. He also allows for the energy of agitation of the gas molecules but neglects electron-electron interaction. The Maxwellian and Druyvesteyn distributions appear as particular solutions of the general equations. These are too detailed to reproduce here but a plot of \( \omega(\varepsilon) d\varepsilon \) against electron energy for helium with \( \left( \frac{X}{p} \right) = 3 \text{ volts/cm./mm.} \) is reproduced in Fig.1; his values of elastic, excitation, and ionisation cross-section are taken from the results of Maier-Leibnitz\(^4\).

The theoretical investigations of Holstein\(^5\) represent the most comprehensive work to date on this subject, and he was the first to consider in detail the effects of a.c. fields on the energy distribution. The analysis is, however, limited to cases in which the elastic collision cross-section for electron-molecule collisions is large compared to the inelastic cross-section. The basis of Holstein's work is the Boltzmann transport equation\(^6\), which is of fundamental importance in many problems connected with the velocity distribution of electrons and molecules in a gas. Holstein employs a diffusion cross-section to represent the contribution of elastic scattering, and not the Ramsauer cross-section.
Some account of his results is given in the Appendix (A).

A recent paper by Barbier gives expressions for the energy distribution, drift velocity and electron temperature of slow electrons in helium and argon, based on the Holstein theory. Assuming that the excitation cross-section is 0.01 times the diffusion cross-section for electrons whose energy corresponds to the first excitation potential, Barbier obtains the normalised probability curve for $\frac{\chi}{\beta} = 3$ volts/cm./mm. which is reproduced in Fig.1.

It is now interesting to compare the normalised probability curves for the Smit and Holstein theories in Fig.1 with the corresponding curve for the Druyvesteyn theory for $\frac{\chi}{\beta} = 3$ volts/cm./mm., and for a Maxwellian distribution with the peak probability occurring at the same level of electron energy, that is, corresponding to a value of $kT$ equal to twice the value of electron energy at the peak in the distribution. This gives $kT = 6eV$.

Equation (1.2) yields for a Druyvesteyn distribution with $\frac{\chi}{\beta} = 3$ volts/cm./mm.

$$\mathcal{w}(E)_{\chi E} = 0.10E^{1/2} e^{-0.028E^2} dE$$

and (1.1) yields for a Maxwellian distribution with $kT = 6eV$

$$\mathcal{w}(E)_{\beta E} = 0.0765 E^{1/2} e^{-E/6} dE$$

Fig.1 illustrates the much broader and flatter distribution obtained with the Maxwellian form. The Smit and Holstein distributions do not differ greatly whereas the Druyvesteyn elastic collision form is considerably narrower.
In concluding this chapter it might be useful to refer to the work of Llewellyn Jones\(^8\), in which he derives an empirical formula for the electron energy distribution to account for the observed intensity variation in the spectral lines of a helium discharge in a uniform electric field, with \((\chi/p)\) less than 6 volts/cm./mm. He gives the number of electrons \(dn\) in an energy interval \(dq\) as

\[
dn = N \left( A \frac{q}{\sqrt{2}} \frac{e^{-0.4q^2}}{q} + B \frac{q}{\sqrt{2}} \frac{e^{-3q^2}}{q} \right) dq
\]

where \(q = E/E_0\), \(E_0\) being the mean electron energy,

\[
A = 0.7736 \quad \text{and} \quad B = 3.896 \times 10^{-3}
\]

It may be noted that the Druyvesteyn equation (1.2) can be written in terms of the mean energy \(E_i\) as

\[
dn = (N) \frac{q}{\sqrt{2}} \frac{e^{-0.55q^2}}{q} dq
\]

using the fact that for a Druyvesteyn distribution in helium, \(E_i = 1.43 \times (\chi/p)\).

Llewellyn Jones found that the above empirical distribution gave values of mobility in the positive column agreeing reasonably well with experimental determinations, between the limits \(0.5 < (\chi/p) < 3\) in volts/cm./mm.
By studying the current-voltage characteristics of a small electrode or probe immersed in a gas discharge it is possible to gain some knowledge of the average energies and energy distributions of the electrons. This method of study was first instituted by Langmuir and Mott-Smith (9) and later developed by Langmuir (10) and other workers. The primary requisite of the probe is that it must not alter the field to any appreciable extent, and that therefore its effective resistance must be large compared to that of the medium in which it is to be used. This criterion is generally satisfied in the plasma regions of discharges.

By making the assumption of a Maxwellian distribution it is possible to evaluate the average energy and density of the electrons and positive ions and the plasma or space potential in the discharge. When the collector potential is very negative with respect to the surrounding gas it receives only positive ions, but at less negative potentials electrons can also be collected, at first only the fastest or most energetic electrons but, as the potential is increased (algebraically) still further, slower electrons also begin to be collected. For an assumed Maxwellian distribution it may be shown that the electron current \( \dot{i}_- \) to a probe may be written

\[
\dot{i}_- = eAN_+ \frac{\sqrt{\frac{kT}{2\pi m}}}{e^\frac{-eV}{kT}}
\]
where $A$ is the probe area, $N_-$ is the electron density, $T$ is the electron temperature and $\mathcal{V}$ is the retarding potential (with respect to plasma potential).

The log $i_-$ versus $\mathcal{V}$ curve is thus linear for a Maxwellian distribution with the slope given by $\frac{e}{kT}$, $k$ having the value of 11,600 degrees/volt, or if we express $kT$ in electron-volts, as in this thesis, the slope simply gives the reciprocal of $kT$.

As the probe potential is made more positive still the total probe current becomes zero, or in other words the electron and positive ion currents become equal. This corresponds to the potential which an isolated probe drawing no current would assume, and is referred to as the 'wall potential'; owing to the much faster diffusion of electrons than positive ions it is seen that this potential is negative with respect to the plasma potential. At plasma potential (i.e. $\mathcal{V} = 0$) we may write

$$\left( i_-, \right)_{\mathcal{V} = 0} = eAN_\text{-} \frac{kT}{2\pi m}$$

an equation used to evaluate $N_-$ in the results below. This value of $\mathcal{V}$ is given by the sudden kink in the semi-logarithmic plot, brought about by the building up of a negative space charge sheath when the potential of the probe becomes positive with respect to the plasma. This break point is not always very sharp, especially for cylindrical probes, owing to the fact that the relatively large sheath thickness causes rapid variation of current density with voltage. The value of plasma
potential is taken below as the intersection of the extrapolated space charge saturation region of the log \( i_\text{-} \nabla \) curve with the extrapolated curve at more negative potentials.

Druyvesteyn\(^{11}\) has extended the applicability of probe measurements to cases in which the distribution is not Maxwellian. Assuming that an electron with a given velocity must have an angle of incidence upon a sheath surface less than a limiting value, determined by the retarding potential, to register as current, and that the probability of electron reflection at the surface does not vary greatly with electron energy, Druyvesteyn shows that the velocity distribution can be written as

\[
N_{\alpha \nu} = \frac{4m}{\pi e^2 \Delta} \cdot E \cdot \frac{d^2 i}{dE^2} \cdot d\nu
\]

(in e.s.u.)

where \( N_{\alpha \nu} \) represents the number of electrons with velocities between \( \nu \) and \( (\nu + d\nu) \), \( A \) is the probe area and \( i \) the probe current. We can write this in energy form as

\[
N_{\alpha E} = \frac{1}{A} \cdot \left( \frac{8m E}{\epsilon^3} \right)^{\frac{1}{2}} \cdot \frac{d^2 i}{dE^2} \cdot dE
\]

where \( N_{\alpha E} \) represents the number of electrons with energies between \( E \) and \( (E + \alpha E) \). In practical units this can be written

\[
N_{\alpha E} = 0.52 \cdot 10^{-11} \cdot \frac{1}{A} \cdot \left( \frac{8m E}{\epsilon^3} \right)^{\frac{1}{2}} \cdot \frac{d^2 i}{dE^2} \cdot dE \quad (1.6)
\]

In other words to find the distribution of energies directly it is necessary to measure the second derivative of current with respect to voltage at varying points on the current-voltage characteristic. This operation, which is very difficult and liable to error when
performed graphically, is made much easier by the method of Sloane and Macgregor\(^{(12)}\) which employs the principle that if a small a.c. potential

\[ a = a_0 \sin(\omega t) \]

be applied at any point on a curve

\[ i = f(E) \]

such as a probe characteristic, the resultant increase in d.c. current, \(\Delta i\), can be written to a first approximation as

\[ \Delta i = \frac{a_0^2}{4} \cdot f''(E) \]

Thus \(f''(E)\) can be simply determined.

The plasma potential is taken as that probe potential at which the value of \(\Delta i\) becomes zero, negative values of \(\Delta i\) being meaningless on the basis of equation (1.6). While this method of measuring the energy distribution is useful when the probe currents are large and the corresponding values of \(\Delta i\) are appreciable, it will be shown later that in the conditions in the helium negative glow investigated in this thesis its usefulness is limited to probe voltages not more than about three volts negative with respect to plasma potential. Beyond this level of probe voltage the values of \(\Delta i\) are too small to be measured, (less than 0.0001 \(\mu\)A) if the amplitude of the injected signal is to be kept sufficiently small to avoid distortion of the calculated distribution. In other words the Druyvesteyn analysis under the present conditions is limited in applicability to electrons with energies not more than three electron-volts.
A discussion of the sources of error and limitations inherent in the use of simple Langmuir probes is given in Loeb (P251 et seq.), and it will suffice here to summarise these briefly.

(a) Probes are useless in regions of rapidly varying fields as in the cathode dark space and near corona points. There is always some disturbance of the plasma by the probe in spite of the space charge sheath.

(b) Some electrons lose energy by collision with molecules in the sheath and some are reflected beyond the probe.

(c) Secondary emission from the probe due to metastable, positive ion and photon bombardment of the cathode is often considerable.

(d) The gas pressure is limited to a level such that the mean free path of the electrons is large compared to the probe diameter. Kinetic theory gives the electronic mean free path in helium as 0.047" at 1mm. pressure and so the probe diameter should not be much in excess of 0.005".

In addition to the above there is a fundamental objection to the Langmuir method of analysis, in which it is necessary to extrapolate the positive ion region of the current-voltage curve to less negative potentials in order to obtain the contribution due to the electrons. This extrapolation involves a considerable amount of uncertainty, particularly so for fast electrons where the differences between the extrapolated positive ion region and the measured curve are very small, and is
12.

meaningless when the diameter of the space charge sheath surrounding the probe is much larger than the probe diameter.

Boyd(13,14) has developed a small screened probe in the form of a grid with a collector behind it, which makes it possible to eliminate this extrapolation and obtain semi-logarithmic characteristics with the electron, positive ion and secondary emission components separated from one another. Although Boyd’s work was directed chiefly towards obtaining accurate information about positive ion temperature and concentration, otherwise unobtainable by the older Langmuir technique, the screened probe is also very useful in obtaining the electron component, particularly at high energies. In this case a positive potential of about 80 volts with respect to plasma potential is applied to the collector and the grid potential is made negative with respect to the plasma potential. The secondary emission component from the grid appears as a residual electron current when a large negative voltage is applied to the grid; this is never more than a very small percentage of the total random electron current. The probe results reported in Section B of this thesis were taken with a screened probe, similar in principle to that of Boyd but differing somewhat in design.

Among recent developments in the design of probes may be mentioned the floating double probe developed by Johnson and Malter(15). This obviates the limitation in the use of single or Langmuir probes that the plasma
potential follows that of the most positive electrode it can contact. The pair of probes are joined to a variable potential source which 'floats' with respect to the discharge, thus reducing the influence on the discharge to a minimum. The methods employed to determine electron temperature and density are, however, only applicable to a Maxwellian energy distribution and an ideal plasma, where electron and positive ion densities are exactly equal.
CHAPTER III; SURVEY OF PREVIOUS RESEARCH IN THE HELIUM NEGATIVE GLOW

The generally accepted picture of the conditions in the Crookes' or cathode dark space and negative glow regions of a d.c. discharge, as discussed by Morse(16) and others, can be summarised briefly as follows.

Electrons produced at the cathode by positive ion bombardment or other means are accelerated through a region of positive ion space charge, the cathode dark space, where the field is very strong and across which, indeed, practically the entire fall of potential takes place. These electrons are accelerated to such high velocities that the probabilities of ionisation and excitation become very small and the cathode dark space is, as the name implies, a region of low luminosity. As the electrons move into the anode side of the dark space the potential gradient declines rapidly and they cease to gain energy from the field and begin to lose it in atomic and molecular collisions and ultimately in ionisation and excitation. Thus within a very short distance the resulting cumulative ionisation produces a marked increase in the visual light intensity, which corresponds to the cathode edge of the negative glow. As is apparent from spectroscopic measurements of the discharge (see Section C of this thesis) the increase in light intensity at the edge is rather more gradual than would appear visually. There is a region of maximum luminosity in the negative glow near the
cathode side. The anode end of the negative glow is a region of comparatively low luminosity and contains many free and slow moving electrons, building up a strong negative space charge which lowers the field. Beyond this region on moving towards the anode the electrons again begin to gain energy from the field and enter the so-called Faraday dark space. The anode side of the negative glow is much less clearly defined than the cathode side, owing to the much larger spread in electron energies in the former case.

The electrical conditions in the negative glow, at gas pressures of the order of 1 mm. Hg. and with the cathode fall of potential not far from normal, were investigated by Emelius and his group some years ago, and were the subject of several papers. In their experiments single Langmuir probes were employed and information was obtained from the resulting semi-logarithmic plots about the electron energy and density distributions in the glow. The form of these plots can be interpreted as being due to the existence of three Maxwellian groups of electrons, with widely differing values of electron temperature and density. The fastest or primary group is detected by the upward bend in the positive ion characteristic on reducing the retarding potential, and the difference between the extrapolated linear positive ion characteristic and the experimental curve is taken as the primary electron current. In a similar way another slower or 'secondary' group was detected and also the slowest and most
concentrated group, termed the 'ultimate' electrons. It may be noted at this point that Emeléus and Brown\(^{19}\) were unable to disprove the possibility that the upward break in the positive ion characteristic might be due to a change in the type of motion of the positive ions, from an almost free fall through the thin sheaths present with small collecting voltages up to a type of mobility motion through the thicker sheaths with higher collecting voltages. This type of explanation of the existence of a 'primary' group can be ignored in the experiments reported in this thesis where screened probes are employed; in this case the electron contribution is obtained directly without allowing for the positive ion component.

The average energy of the primary group was found by Emeléus to be of the order of 20 to 35 electron-volts, irrespective of the gas used or the applied potential, and the maximum concentration of the ultimate group about \(3 \times 10^7\) electrons/cc. with a discharge current of 3 m.a. in a tube 4 cm. in diameter. The brightest part of the negative glow coincided approximately with the maximum concentration of the ultimate group. It was found that the concentration of the primary group fell off much more rapidly than the concentration of the two slower groups. The size of the probes employed, however, certainly violated the requirement mentioned in Chapter II, namely that the diameter of the probe be small compared to the mean free path of the electrons; in one case the collector
used was an iron sphere 0.32 cm. in diameter.

Emeléus put forward the theory that the primary group is formed in the cathode side of the negative glow from a faster and probably directed stream of electrons entering it from the cathode dark space. The existence of a maximum in concentration and luminosity in the middle of the negative glow was assumed to be connected with the full development of the primary group, which was found to have a random Maxwellian velocity distribution. The explanation of the presence of a fast primary group well into the Faraday dark space was the subject of a later paper by Emeléus and Duffendack⁷, in which it was inferred from spectroscopic information that collisions of the second kind between normal and metastable atoms are of primary importance, the metastable atoms being formed by absorption of resonance radiation from the negative glow. No definite theory was put forward for the existence of the two slow groups, though it was believed that in gases which exhibit a Ramsauer minimum in the electron free path the slow electrons will tend to be maintained in two groups, of greater and less energy than that corresponding to the minimum free path. This type of explanation is discussed in Section B Chapter II(d) and is shown to be invalid in helium.

In concluding this chapter a brief account is added of some early work carried out by the author, in which microwave probing techniques were employed to determine electron density in the negative glow.
Although this method of approach to the present problem was discontinued for reasons which are given below, the recently developed microwave methods of investigating the properties of both d.c. and r.f. gas discharges are becoming of increasing importance in many other fields of research.

Basically these microwave experiments consisted in the measurement of the shift in resonant frequency and the change in amplification factor (Q) of TM 010 resonant cavities in both the 3-cm. and 10-cm. bands, due to the presence of a d.c. discharge in an axial quartz tube introduced through the cavity end walls. An account is given in Appendix (B) of the relation between the electron density and frequency shift for given values of cavity resonant frequency and the dimensions of the cavity and the discharge tube. It will be noted that this analysis is only valid when the electron collision frequency is much less than the microwave field frequency and if the collision frequency is independent of electron energy, implying that the electron energy distribution has no effect on the observed phenomena.

In order to avoid undue disturbance of the cavity field the holes in the end plates must be kept small compared to the cavity diameter, which sets a serious limitation on the diameter of the discharge tube which can be employed (about 5mm. for a cavity in the 10-cm. band), preventing direct comparison between probe and microwave measurements in the same tube. Another
disadvantage of this method of studying the density in the negative glow is that the electron density varies rapidly in this region of the discharge, making it essential to keep the height of the cavity very small if measurements are to be taken over a reasonably small region of the discharge in relation to the length of the negative glow. This requirement unfortunately competes with the necessity for a high cavity Q, in order that a high degree of sensitivity in the measurement of small frequency shifts should be obtainable.

These fundamental disadvantages of the microwave method of study were responsible for its abandonment in the present research. Nevertheless, in order to provide some idea of the orders of magnitude involved, results of one typical experiment with a TM 010 cavity in the 10-cm. band are given in Fig. 2. The cavity diameter is 2.780" and the height 0.50", the Q being about 6000. The end holes are 0.21" diameter through which passes a silica glass tube filled with helium at 2mm. pressure, the discharge current being 300 μA. The position of the various regions of the discharge in the silica tube are noted in the figure, in which the frequency shift and electron density (calculated on the assumption of the dominant electron removal mechanism being recombination) are plotted as functions of position in the cavity. Even although the density is integrated over such a large distance as 0.5" the results do indicate the great increase in electron density on entering the negative glow from the
positive column.

Note: These results may be compared with those of Udelson and Creedon (Phys. Rev. 88, 145, 1952) who measured the electron density in the various regions of a glow discharge in a 10-cm. re-entrant cavity, using the change of cavity conductance as represented by the voltage standing wave ratio at resonance.
SECTION B: PROBE MEASUREMENTS

CHAPTER I: EXPERIMENTAL APPARATUS AND TECHNIQUES

a. The Vacuum System

A portable vacuum unit was developed specially for this work and is shown in the two photographs in Fig. 3, with a discharge tube mounted in position. The entire system is constructed of glass with the exception of the Edwards' silicone oil diffusion pump, which is backed by a rotary oil pump. A large oven, capable of baking the largest discharge tube employed up to a temperature of at least 450°C, is mounted on a rack above the vacuum system so that it can be raised or lowered on to an asbestos base. The oven temperature is indicated by a meter in series with a thermocouple projecting into the oven. Apiezon 'N' grease is used to grease the taps, it being considered unjustified to employ any of the known greaseless tap constructions, which entail a great amount of added complication.

A new type of manometer employing a pressure-sensitive diaphragm, the movement of which is recorded by a capacity bridge, has been constructed. This is similar to that originally described by Alpert, Matland and McCoubrey (22), but with an improved method of construction which has been the subject of a recent note by the author (23). The manometer has the great advantage that the pressure gauge, in this case a McLeod gauge, can be completely isolated from the vacuum system, thus eliminating the usual problems of
contamination and condensation. The manometer is shown in section in Fig. 4 and the details of the vacuum seal are shown in the inset. When pure gas is introduced into the vacuum system a similar pressure of air is admitted on the McLeod gauge side of the diaphragm by means of a needle valve, until the diaphragm assumes its null position as indicated on the capacity bridge; the air pressure is then measured on the McLeod gauge. In addition to the needle valve inlet, a line to the backing pump is also provided on the manometer side, so that the air pressure can be correctly regulated. It has been found possible to register pressures of $10^{-2}$ mm. with maximum sensitivity, with a pressure of 1 mm. indicating full scale deflection on the instrument. The beryllium-copper diaphragm is very resistant to sudden large pressure differences and the null position has changed little over a considerable period of time.

The McLeod gauge employed is capable of reading from $10^{-5}$ mm. to 1 mm. pressure, the mercury level being raised or lowered by a two-way tap leading to either an air inlet via a needle valve or to the backing pump. Higher pressures than 1 mm. can be read on a conventional U-tube manometer. The helium gas employed was obtained from the British Oxygen Company and is classed as spectrally pure; an arrangement of taps enabled small quantities of the gas at atmospheric pressure to be introduced into the evacuated system.

*Fielden Proximity Meter, Type PM2 (Fielden Electronics Ltd.)*
b. The Discharge Tubes

Two different designs of discharge tube were employed in this work and are designated below as tubes A and B (Figs. 5 and 6). In both cases the electrodes and probes are capable of being moved magnetically. Tube A is demountable so that the electrodes can be easily removed and cleaned or replaced if necessary.

Tube A is built in three sections which are joined together by steel flanges, the vacuum seals being provided by soft aluminium alloy (Bermabright) gaskets set into grooves in the flanges. Pressure is exerted on these gaskets by means of eight clamping bolts arranged symmetrically round the flange circumference. To each flange there is brazed a Kovar ring, tapered at the end to allow a Housekeeper seal to be made between the rings and the Kodial glass tube sections, which are 1.25" external diameter with a 0.05" wall. The electrodes are 3/80 stainless steel (a magnetic alloy) discs of 1.062" diameter, mounted at the end of stainless steel rods. These rods can slide in tubes of the same material which are held centrally in the flange sections of the assembly. Attached to the other end of these tubes are the electrode leads, consisting of Kovar rods sealed into re-entrant Kodial glass cups. On one end section is mounted the exhaust tube and on the other a barium getter assembly in a side tube. The end sections are about 3" long and the entire tube 18" long. A Langmuir probe assembly, capable of radial movement and a screened probe assembly, capable of both
radial and angular movement, are mounted at the centre of the tube, diametrically opposite each other. These are described in detail below.

Tube B is a larger diameter, C9 glass assembly built in one section. The tube diameter is 2.560" and the electrodes, again of 3/80 stainless steel, are 2.460" diameter. The tubes, into which slide the rods attached to the electrodes, are maintained centrally by means of the spring-loaded arrangement pressing on the side walls, shown in the photograph. The maximum length between the electrodes is 7" and the overall length of the tube is 16". The Langmuir and screened probe assemblies are again mounted diametrically opposite at the centre of the tube.

c. The Probe Assemblies

The screened probe assembly shown in Fig.7 differs considerably in construction from that originally described by Boyd(13).

One of the chief problems to be overcome was that of brazing a fine grid of tungsten wires only 0.0008" thick and spaced at 250/inch across the grid aperture, in the present case 0.046" diameter. This was accomplished by taking a section of Kovar rod 0.072" in diameter and drilling a central hole 0.062" in diameter some way into the section. A 0.046" hole was then drilled in the wall of the tube thus formed, very near to the end of the central hole. The tube was wound with the tungsten wire in a machine at the required spacing, and the ends secured. This was placed in
a hydrogen furnace after being painted with copper oxide, so that the tungsten wires were copper brazed in position to the Kovar tube. The latter was then cut just beyond the limit of the central hole, the overall length now being 0.100", so that the section formed the grid cap shown in Fig. 7. This cap is fitted on to the end of a 0.062" diameter Kovar tube which carries a length of insulating (Sillimanite*) sleeving. Along the central hole of this sleeving passes a lead to the nickel collecting disc in the grid cap, the plane of the disc being parallel to the wires across the grid aperture. The Kovar tube is glass sheathed to insulate it from the discharge, the sheathing continuing all the way from the grid cap to the asymmetrical stainless steel slug mounted in the side arm of the discharge tube. The grid cap is coated with hot-setting araldite wax of low vapour pressure, leaving only a narrow rim round the grid hole, in order to prevent the grid support from drawing an excessive electron current. The stainless steel slug is ground away on one face so that the asymmetry produced makes it possible to rotate the slug magnetically as well as move it radially. Several beryllium-copper leaf springs are screwed to the ends of the slug, ensuring a suitable degree of friction with the walls of the side tube to overcome the restoring force produced by distortion of the piano-wire springs connected to the

* George Bray & Co. Ltd.
collector and grid leads.

The Langmuir probe assembly shown in Fig.8 is quite similar to that employed by Emelius and his group, and consists of a 0.005" tungsten wire mounted in a G9 glass tube which is a sliding fit in the side tube arm. The glass tube is tapered at the end projecting into the discharge tube down to a diameter not much greater than the wire end continues thus for a distance equal to the discharge tube radius. At the end it is belled out to a diameter of about 0.020" over a 0.20" length, ensuring that the positive ion sheath forming on the insulating surface at floating potential does not interfere with the collection of electrons by the 0.255" length of wire projecting beyond the sheathing. This arrangement also has the advantage that any sputtered material from the probe settling on the glass sheathing does not alter the effective probe area. A similar magnetic slug arrangement to that described above for the screened probe is provided.

d. Processing Methods

Before mounting the electrodes and associated metal support pieces in position, they were outgassed by placing them in a hydrogen furnace for some time at a temperature of 1000°C. The electrode surfaces were subsequently carefully polished to remove scratches. After assembly of the complete tube it was baked up to about 400°C in the large oven for a period of some hours. The tube was then filled with a few millimetres of helium and a discharge current of several milliamps run
between the main electrodes for a period of an hour; this process was repeated several times, the gas being pumped away on each occasion. The final gas filling was then introduced into the tube and the barium getter fired.

Except for the results given later for the effects of variation of helium gas pressure in tube B, measurements were made with the tube sealed off from the vacuum system. No evolution of gas from a leak or other cause could be detected over a period of many weeks. Results were taken in all cases with an auxiliary discharge tube, joined to the main tube, passing a large current between magnesium electrodes; the sputtered magnesium further ensured the purity of the gas content. It may in addition be noted that the spectroscopic data reported in Section C confirm that the gas purity is very high.

e. Circuit Details

A sketch of the circuit used to measure the probe characteristics, adaptable to both Langmuir and Druyvesteyn methods of analysis, is shown in Fig. 9.

In the Druyvesteyn method a 1000c/s a.c. signal derived from a beat frequency oscillator is injected between the anode of the discharge tube and the grid of the screened probe via a make-before-break switch K and a large condenser C, the latter being designed to prevent the flow of d.c. current along this branch of the circuit. The amplitude of the injected signal is monitored with the aid of an oscilloscope, and the d.c.
voltage between anode and grid is registered on a valve voltmeter, fitted with a polarity reversing switch. This variable grid potential is derived from the battery shown in the figure, the voltage on the collector being fixed at about +80 volts with respect to the anode. A balancing circuit for a sensitive micro-ammeter in the lead to the collector is provided so that the steady collector current through the meter for any particular grid voltage can be set to zero, and the increase in current ($\Delta i$) then registered on injecting the 1000c/s signal. The total collector current is registered on a separate multi-range meter. In the Langmuir method of analysis only the current through the latter meter is registered as the grid potential is varied.

The limitation in the sensitivity of the Druyvesteyn method of analysis is set by the ability to detect small changes in current $\Delta i$. The results given in Chapter III of this section were obtained with the aid of a very sensitive Tinsley galvanometer with a sensitivity of 1900mm. deflection/$\mu$A, so that full scale deflection corresponds to about $10^{-7}$ amps. Before this instrument was available, however, attempts were made to use a modulated a.c. injection signal and to amplify the resultant frequency giving the second derivative of current with respect to frequency. In practice it was not found possible to build a sufficiently high gain selective amplifier to amplify the frequency giving $f''(\alpha)$ and reject the very much larger signal at a different frequency, proportional to $f'(\alpha)$. 
SECTION B.
CHAPTER II : DISCUSSION OF EXPERIMENTAL RESULTS USING LANGMUIR ANALYSIS

a. Axial Variation in Distribution

The results discussed below in detail are for a 600 μA discharge in tube A filled with 0.58mm. of helium, the anode-cathode potential drop being 900 volts, so that the discharge conditions were well into the abnormal cathode fall region. Langmuir characteristics of the two probe assemblies were taken for different axial positions in the negative glow, with the radial penetration constant at 13mm.

The negative glow was bluish-white in colour and extended from the cathode dark space edge to a region not far from the anode, where the Faraday dark space was observed. The cathode dark space was dark green in colour extending over 13mm. and a faint pinkish cathode glow about 1mm. in extent was present near the cathode. The anode-cathode distance was maintained at 64mm.

A typical semi-logarithmic characteristic taken with the screened probe grid facing the cathode is reproduced in Fig.10. In this curve the steady collector current with high retarding potentials on the grid, attributed in Section A: Chapter II to secondary emission from the grid, has been subtracted from the measured values to give the true electron current. Referring to the figure, the linear section AB, attributed to a fast 'primary' electron group, is extrapolated to BD.
and this is subtracted from the curve BC to give the 'secondary' group contribution represented by the line EF. Similarly the 'ultimate' group is obtained by extrapolation of this line to less negative potentials. The plasma or space potential is taken as the intersection of the saturated region and the linear section at more negative potentials. All three groups can be represented by Maxwellian distributions, with temperatures given by the slope of the lines corresponding to each group and concentrations given by extrapolating the lines to space potential (see equation 1.5).

Except near the cathode dark space edge, where the ultimate and secondary group densities fall rapidly, the concentrations of the ultimate, secondary and primary groups throughout the negative glow are approximately in the ratio of $10^4:10^2:1$, and the temperatures in the ratio of $1:10:10^2$ respectively.

The variation in the temperature and concentration of the three groups, with the screened probe facing the cathode under the above conditions, is given in Fig.11. On moving into the negative glow from the cathode dark space (referred to below as C.D.S.) it will be noted that the primary electron temperature falls sharply at first and then more slowly but steadily throughout the negative glow. The temperature of the secondary group varies in the same manner, while the ultimate group temperature varies little with axial position after falling somewhat near the C.D.S. edge, although there appears to be a definite minimum of temperature near
the brightest part of the glow. The concentration of the primary group is reasonably constant over the greater part of the glow, determination of the concentration near the C.D.S. edge being difficult owing to the rapid rise in primary temperature. The rise in concentration detected further into the glow is perhaps due to the contribution of the secondary electrons to the primary group, and the inability to distinguish between the groups when the temperatures are so similar. The secondary group exhibits a maximum in concentration some 8 mm. into the glow, while the ultimate electrons rise in concentration to a steady level beyond 15 mm. into the glow. Fig. 12 indicates the variation of space potential and secondary emission current with axial distance. Near the visual edge the exact height of the maximum in potential is indeterminate owing to the small change in curvature of the probe characteristic at space potential in that region, the ultimate group not being detectable there.

Temperature and concentration variation of the groups throughout the negative glow, with the screened probe grid facing the anode, is given in Fig. 13. It will be seen that both the ultimate and secondary concentrations near the C.D.S. edge are much larger than for the previous case with the probe grid facing the cathode, while further into the glow the ultimate group is lower in concentration. Comparison of the two sets of data indicates the presence of a considerable electron drift from the region of maximum concentration.
towards the C.D.S. edge. This drift of electrons must be maintained by the electric field and the concentration gradient of the electrons in this region. There would appear to be some secondary and ultimate electrons present even on the C.D.S. side of the edge, with the concentration of the ultimates falling off more rapidly than that of the secondaries. As regards the temperatures of the groups, it may be observed that the secondary group temperature falls off more slowly than when the probe grid faces the cathode, particularly so near the C.D.S. edge where the level is much higher in the latter case. The ultimate group temperature falls steeply from a level of about 1.2 eV. at the C.D.S. edge.

No primary group is detectable anywhere in the negative glow with the probe grid facing the anode, the secondary group continuing linearly in the semi-log plot down to currents less than 0.01 μA. This indicates the directivity of the primary group, a conclusion supported by another observation. The secondary emission current from the probe grid is only about 0.07 μA, varying little with axial position, whereas it is much higher when the probe grid faces the cathode (Fig. 12). This secondary emission is primarily due to bombardment of the negative grid by positive ions produced nearby. The effect will be much more in evidence when the probe faces the cathode than the anode if our assumption of a directed primary stream of electrons is correct; when the probe faces the anode the gas volume adjacent to the grid will be shielded from the intensely ionising
primary group and the positive ion bombardment of the grid consequently reduced. The actual variation in collector current with the probe facing both anode and cathode with large retarding grid potentials, for two different values of collector voltage, is given in Fig.14. The effect of varying the collector voltage is seen to be of secondary importance. Examination of the relation between collector current and collector voltage with the grid potential held at -40 volts confirms that this residual current is attributable to secondary emission from the grid due to positive ion bombardment and not to penetration of the potential barrier at the grid by very fast primaries.

Using a very sensitive galvanometer the primary electron semi-log. plot, with the probe facing the cathode, was continued down to a current of $5 \times 10^{-3} \mu A$, corresponding to a retarding potential of about 120 volts. No deviation from the linear relationship, which might indicate a non-Maxwellian distribution, was observed. This curve is shown in Fig.15, the probe being 7mm. from the C.D.S. edge and the electron temperature corresponding to the slope of the line being 28 eV. The discharge conditions are identical to those described previously. We may therefore infer from these results that the primary group has a definite Maxwellian distribution of drift velocity, the isotropic random component being negligible.

Experiments were also performed in tube A under identical conditions with the unscreened Langmuir probe
assembly described previously. Similar values of secondary and ultimate electron group temperatures and concentrations to those given with the screened probe assembly were obtained. The primary group could not be resolved with any certainty, however, owing to the positive ion extrapolation necessary. Indeed it was not possible to be certain even of the contribution of the more energetic secondary electrons to the probe current, which indicates the great advantage of the screened probe method of analysis. In addition it was impossible to separate the drift and random effects near the C.D.S. edge, as was possible by rotating the screened probe.

The validity of the assumption that the potential on the grid of the screened probe does not appreciably alter the plasma potential was checked by measuring the effect of the variation of grid volts on the characteristics of the Langmuir probe assembly. The two probe assemblies were placed about 1.5mm. apart in the centre of tube A. It was found that the Langmuir probe characteristics were practically independent of screened probe grid volts over a voltage range from about -3volts to -100volts with respect to anode; with more positive grid volts there was a slight decrease in Langmuir probe current, certainly not more than 5%. One can therefore safely neglect the effect of the screened probe grid voltage on the surrounding plasma.

b. Radial Variation in Distribution

In order to obtain a more accurate picture of the
radial density and energy distribution of the electrons in the negative glow, measurements were taken in the larger diameter (64mm.) tube B described previously.

Fig.16 gives semi-logarithmic plots of electron current-grid voltage for a 1mA discharge in 0.70mm. helium. Only the saturation, ultimate and part of the secondary regions are shown for each value of probe penetration; The primary group, while still detectable, is much less prominent because of the lower current density and lower cathode fall (450 volts). The curves are taken with the probe facing the cathode, 23mm. from the C.D.S. edge. From the experimental curves (those shown are representative of a larger number) it is possible to find how the secondary and ultimate group concentrations and temperatures, as well as the space potential, vary radially in the negative glow.

It is evident at once from inspection of the curves that the secondary group temperature remains constant with radial position, while that of the ultimate group, after changing little over a radius of 15mm. from the tube axis, suddenly increases sharply on approaching the walls. At the same time an increasing rate of change of space potential is apparent on approaching the walls, in conjunction with a rapid decrease in electron concentration. Now the C.D.S. boundary with the negative glow was not in fact a plane perpendicular to the tube axis but did exhibit some curvature, being concave towards the anode. The centre of the boundary was about 5mm. nearer the
cathode than at the walls. If now the probe readings are taken with the distance between the probe and the C.D.S. edge in a direction parallel to the tube axis held constant, quite a considerable modification of the ultimate temperature and concentration and plasma potential is produced. This is illustrated in Figs.17 & 18.

Now on the hypothesis that the rate of creation of new electrons per unit volume must equal the rate of diffusion, Schottky\(^{(24)}\) has shown that if the ionising coefficient \(J_i\) is assumed to be independent of spatial co-ordinates, implying no radial variation in energy distribution, the ambipolar diffusion equation may be written

\[
\nabla^2 n + \frac{J_i}{D_a} \cdot n = 0
\]

where \(n\) is the electron density and \(D_a\) is the ambipolar diffusion coefficient.

The solution of this equation, assuming that \(n\) is a function of \(r\) only, is given approximately by

\[
\n = n_o \cdot J_o \left( \frac{2.405 \cdot r}{R} \right)
\]

where \(n_o\) is the density at the tube axis and \(r\) is the radial position measured from the tube axis, \(R\) being the tube radius. \(J_o\) is the Bessel function of order zero.

Taking \(n_o = 700.10^7\) electrons/cc and \(R = 32\) mm. we obtain the curve which is shown in Fig.18 for the electron concentration against radial distance, on the basis of

\[
\text{Actually instead of } R \text{ we should write } (R + \frac{3}{4} \lambda) \text{ where } \lambda \text{ is the mean free path of the electrons; this correction can, however, be neglected in the present pressure range.}
\]
this equation. It will be noted that even the curve
giving the experimentally determined values of concen-
tration corrected for C.D.S. curvature differs consider-
ably from the theoretical distribution at greater
radial distances than about 20mm., although the
experimental and theoretical curves nearer the tube
axis are very similar. This appears to be about the
distance at which the corrected values of temperature
increase rapidly (Fig.17), thus violating one of the
conditions on which the above equation was derived.

The plasma potential \( V_r \) at distance \( r \) from the
axis can be written as

\[
V_r - V_o = -\frac{kT_e}{e} \cdot \log \left( \frac{\rho_r}{\rho_o} \right)
\]

if ambipolar diffusion theory applies.

Taking \( \rho_o = 700 \times 10^7 \) electrons/cc, \( kT_e = 0.27 \text{eV} \) and
\( V_o = +0.60 \) volts with respect to the anode, values of \( V_r \)
against \( r \) have been calculated and are given in Fig.18.
The corrected experimental values and the theoretical
values of \( V_r \) again agree well up to a radial distance
of about 20mm., where the increase in temperature
causes a considerable deviation in the two curves.

Howe\(^{(25)}\) discusses the radial electron distribution
for the case in which the ionisation processes are
cumulative in nature. In such a process an electron
raises an atom to an excited state and then ionises
the excited atom in a second collision. In this case
the rate of ionisation is proportional to \( \rho^2 \), the
resultant density distribution having been solved by
Spenke\(^{(26)}\), giving

\[
\rho_r = \rho_o \cdot \rho^2 \left( 2.92 \frac{r}{R} \right)
\]
This type of density distribution gives a curve not very different from the Bessel function distribution; for radii less than 20mm, the latter distribution, corresponding to direct ionisation, gives a better fit with the experimental points. Later spectroscopic data indicates that such a cumulative ionisation process is unlikely.

We can conclude from all this evidence, therefore, that if allowance is made for the curvature of the C.D.S. edge, the ultimate electron radial density distribution and the plasma potential are characteristic of ambipolar diffusion in the negative glow up to radii of the order of 20mm. from the axis of the discharge tube of radius 32mm. Beyond 20mm. the sudden increase in electron temperature causes a deviation from the ambipolar diffusion condition and a more rapid decay in electron density. The aperture in the side wall of the discharge tube through which the probe assembly is introduced should have the opposite effect of increasing electron density above the ambipolar value near the walls, and cannot therefore be responsible for the observed effect. Little change in the temperature of the secondary group is noticeable throughout the whole range of measurements.

c. Variation with Discharge Current and Gas Pressure

The following results, presented in tabular form, were taken in tube A with a pressure of 0.50mm. helium, the discharge current being variable. The probe grid faced the anode so that no primary group was detectable,
and the distance between the probe and the C.D.S. edge was maintained at 6.5mm. with the probe penetration about 10mm. Some small adjustment had to be made in the position of the probe with respect to the electrodes in order to maintain the probe-C.D.S. edge constant with variation in discharge current. It may in fact be shown that the relation

\[ \frac{i D^2 P}{V^2} = \text{constant} \]

holds for any particular gas, where \( D \) is the width of the cathode dark space, \( i \) is the current density, \( P \) the gas pressure and \( V \) the cathode fall of potential.
<table>
<thead>
<tr>
<th>Discharge Current (µA)</th>
<th>Voltage Drop (eV)</th>
<th>Temperature (eV)</th>
<th>Concentration (els/cc×10⁷)</th>
<th>Plasma Potential w.r.t. anode</th>
<th>Secondary Emission Current (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Secondary</td>
<td>Ultimate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>1060</td>
<td>3.35</td>
<td>0.332</td>
<td>8.26</td>
<td>1055</td>
</tr>
<tr>
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<td>3.35</td>
<td>0.304</td>
<td>7.25</td>
<td>940</td>
</tr>
<tr>
<td>400</td>
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<td>3.35</td>
<td>0.267</td>
<td>6.15</td>
<td>840</td>
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<tr>
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<td>530</td>
<td>3.35</td>
<td>0.232</td>
<td>4.87</td>
<td>588</td>
</tr>
<tr>
<td>200</td>
<td>440</td>
<td>3.35</td>
<td>0.207</td>
<td>3.88</td>
<td>333</td>
</tr>
</tbody>
</table>
No variation in temperature of the secondary group with discharge current is detectable, while the temperature of the ultimate group falls steadily with decrease of current. The concentration of the ultimate group varies nearly linearly with tube current.

The observation of the independence of the secondary group temperature with discharge current and cathode fall of potential was confirmed by a later experiment with tube B, the helium gas pressure being 0.37mm. This experiment was performed with the probe grid facing the cathode so that primary electrons were detectable. A rapid increase of primary temperature with cathode fall of potential was noted, a typical increase being from 22eV to 60eV with increase of cathode fall from 670 to 1050 volts. The ultimate temperature and concentration again showed the same form of variation with tube current.

A second series of experiments was made in tube B, this time maintaining a constant discharge current of 2mA and varying the helium gas pressure over a range between 0.17 and 1.5mm. At each pressure screened probe characteristics were taken for several positions in the negative glow, with the probe grid facing the cathode in each case. The discharge conditions were as below:
It will be noted that the cathode glow increases rapidly in extent as we move further into the abnormal cathode fall region with reduction in pressure.

A very marked dependence of the temperature and concentration of the ultimate group with gas pressure was noted, the temperature increasing and the concentration decreasing rapidly with decrease of gas pressure. To take specific values, with the probe 14mm. from the C.D.S. edge, the ultimate temperature was 0.41eV and the concentration \(600 \times 10^7\) electrons/cc for a gas pressure of 0.83mm, while with 0.17mm helium the temperature was 0.74eV and the concentration \(43 \times 10^7\) electrons/cc.

While at the higher pressures similar semi-logarithmic curves to those described previously were obtained, showing three definite electron groups, at the lower pressures considerable curvature of the secondary group occurred when the retarding potential was between 5 and 10 volts. A typical characteristic illustrating this effect is shown in Fig. 19, the helium
gas pressure being 0.17mm. and the probe 25mm. from the C.D.S. edge. At higher retarding potentials than 10 volts the semi-logarithmic plot was quite linear. It is believed that a characteristic of this type can be interpreted as being due to the superposition of a secondary group with considerable drift velocity on a primary group. Further evidence as to the existence of a fast primary group was supplied by the considerable secondary emission current at the lower pressures. At 15mm. from the C.D.S. edge, the secondary emission current rose from 0.10µA at 1.5mm. pressure to 0.46µA at 0.17mm. pressure. Chao and Tang\(^{(27)}\) discovered an electron group in the Faraday dark space region of a glow discharge with a semi-logarithmic plot showing a distinct downward bend at high retarding potentials; they interpreted the corresponding distribution as being due to the superposition of a fast electron drift velocity on an isotropic Maxwellian distribution. In the present case the electron drift velocity will be much less at the higher pressures and this effect should become less evident, as indeed the experimental results indicate. It is also noteworthy that if the discharge current is reduced at the lower pressures, so that the conditions become nearer the normal cathode fall, the semi-logarithmic plot shows distinctly less curvature.

In trying to interpret the form of the semi-logarithmic electron current plot at low pressures it must be remembered, however, that it is quite possible
that the electron distribution in the high energy region is other than Maxwellian. Even if this were the case it does not seem possible to resolve the characteristic into one electron distribution of known form; it would still be necessary to assume that two discrete groups of electrons were present to explain the type of curve obtained.

d. Physical Significance of the Electron Groups.

Of the three groups of electrons with approximately Maxwellian distributions detected by screened probe measurements in the negative glow, the interpretation of the existence of the fastest or primary group would appear to be the most straightforward. The directivity of this group has been well established, and the electrons must have acquired their high velocities by acceleration in the very strong field in the cathode dark space, and so must have originated in the cathode-cathode glow region of the discharge. Some of the energy gained from the field is, however, lost in collisions in the dark space which emits a dark greenish light, presumably due to collisions involving fast primary electrons. It may be observed that the directivity of this primary group does not agree with the earlier work of Emeléus and Brown who found a fast electron group with an approximately isotropic distribution. As they point out, however, measurements with their Langmuir probes in the high energy region were very liable to error, for reasons discussed in Section A: Chapter II.
It is interesting to compare the present results with the investigations of Brewer and Westhaver\(^{(28)}\), who employed magnetic deflection methods to show that primary electrons enter the negative glow from the cathode dark space with practically the full cathode fall of potential. In their experiments, which were designed to verify earlier work by Sir J.J. Thomson\(^{(29)}\), electrons coming from the cathode dark space passed through a knife edge slit in the discharge tube anode and were analysed magnetically with the aid of a willemite screen. The energy expended by the electrons in helium at 1mm. pressure in crossing the dark space, due to positive ion formation, was estimated to be only about 7% of the total electron energy gained in the dark space. As the negative glow was introduced across the slit some inhomogeneity of the beam was detected. However no estimate was made of the primary electron energy distribution in the negative glow; it would certainly be a most interesting experiment to see if the existence of a Maxwellian energy distribution could be confirmed by this means.

In addition to the fast primary group it has been confirmed that, as earlier workers had observed, there would appear to be two slower electron groups in the negative glow. Emeléus and Brown advanced the suggestion that the existence of two slow groups might be associated with the existence of a minimum in the Ramsauer electron free paths. While a sharp minimum does occur at about the mean energy of the secondary
and ultimate groups for the gases investigated by the above workers, namely neon, argon, krypton, xenon at about 1 mm. pressure, such a minimum in the case of helium, if present, is very small (see Loeb P649).

Loeb has suggested that the presence of plasma oscillations could easily lead to the detection of electrons with a much higher energy than the mean. The frequency $f_0$ of plasma-electron oscillations is given by

$$f_0 = \frac{N \epsilon^2}{\pi \eta}$$

where $N$ is the electron concentration and $\epsilon$ and $m$ the charge and mass of the electron. For $N = 10^{10}$ electrons/cc, a figure not far removed from that in the negative glow under the present conditions, $f_0 = 1000$ Mc/s. Attempts have been made by the author to detect the presence of plasma oscillations in the negative glow, using a very sensitive superheterodyne receiver with a band-width of 500–3000 Mc/s coupled to a probe projecting into the glow. Although a wide variety of discharge conditions were used, no oscillations were detectable in the entire wave-band. It therefore seems reasonable to neglect this suggestion of Loeb in the present research.

A more likely explanation of the existence of two slow groups, as discussed by Emeléus for a low pressure mercury discharge, seems to be that the secondary group corresponds to those electrons which have been ejected after the collision of the fast primaries with gas atoms. These electrons have not had time to reach thermal equilibrium with the slowest or ultimate electron group, which is produced by
the degeneration of the primary and secondary electrons in successive collisions to very low energies before removal by diffusion to the walls. Some support for this picture is provided by the screened probe measurements (Fig.11) indicating that the secondary electrons appear first on entering the negative glow from the cathode dark space and that the ultimate electrons are first detectable several millimetres further into the glow. This is presumably due to the fact that the primaries have to move some way into the glow in order to produce a copious supply of ultimate electrons by multiple collision processes.

One is left to explain, however, why the secondary group temperature seems to be more or less independent of the cathode fall of potential, which should be related to the primary group temperature, when the distance from the C.D.S. edge is held constant. The situation is further complicated by the fact that the secondary group temperature varies quite markedly with axial position in the glow. The possibility that the secondary group might be associated with photo-ionisation processes in the negative glow seems to suggest itself from this evidence, particularly in view of the fact that the secondary group concentration maximum occurs not far from the visually brightest part of the glow.
The Druyvesteyn method of analysis, which was described in detail in Section A: Chapter II of this thesis, was applied to the measurement of the electron energy distribution in the negative glow in tube A, the gas pressure being 0.50 mm. helium and the discharge current 600 μA. In order to compare the Druyvesteyn and Langmuir methods of analysis measurements were taken both of the collector current and of the increase in current \( \Delta i \) on injecting the a.c. signal. To aid in the measurement of very small d.c. current increases, the sensitive Tinsley galvanometer referred to previously was employed.

Complete tables of experimental data are given in Appendix (C) for the Langmuir analysis and for two different values of a.c. injection voltage with the corresponding Druyvesteyn analysis. In all cases the probe was 5 mm. from the C.D.S. edge and faced the cathode; the frequency of the a.c. signal was 1000 c/s.

The Langmuir analysis gave the space potential as +0.45 volts with respect to the anode, and the temperature and concentration of the ultimate group as 0.33 eV and 570.10 \( \gamma \) electrons/cc respectively. The semi-logarithmic curve for the ultimate region is shown in Fig. 20. The space potential is given in the Druyvesteyn analysis as the value of grid volts at which \( \Delta i \) becomes zero; this is +0.17 volts for the 0.1 volt a.c. signal.
and +0.18 volts for the 0.3 volt a.c. signal. The density values by the Druyvesteyn method are given by equation (1.7) of Section A.

Fig. 21 shows the resultant energy distributions for the two values of a.c. injection signal. It will be noted that only the ultimate group is detectable with the Druyvesteyn method, the values of $\Delta \sim$ even with the larger a.c. input signal being too small to be detectable for values of electron energy corresponding to the secondary and primary groups. Above about 0.75eV the distributions for both input signals are similar but at lower energies the curves are very different in form. That for the 0.1 volt signal appears to be roughly Maxwellian in form with a peak at 0.17eV; on the same graph a theoretical Maxwellian distribution is drawn with $\hbar T = 0.34\text{eV}$ and $n_e = 110.10^7$ electrons/cc, the value of density given by calculation from the peak value of the curve on the basis of a Maxwellian distribution.

It would appear that except at energies above about 1eV, where there are rather more electrons in the theoretical curve, the experimental Druyvesteyn curve for an injected a.c. signal of 0.1 volt and the theoretical Maxwellian curve are closely similar. It is also important to observe that the Langmuir and Druyvesteyn methods of analysis give very nearly the same values of electron temperature, in this case 0.33eV and 0.34eV respectively. The discrepancy in electron density is discussed below.

It is not in fact necessary to plot a complete energy distribution, employing the Druyvesteyn analysis,
to see if the distribution is Maxwellian or not. It is a simple matter to show that for a Maxwellian distribution the plot of $\log \frac{d^2}{dV^2}$ against $V$ is linear, and so all we need do is to plot $\log(\Delta i)$ against $V$ (where $V$ is the retarding potential in volts or the electron energy in electron-volts). This plot is quite linear for the 0.1 volt injection signal up to an energy of 1.0eV, agreeing with the complete distribution shown in Fig. 21.

The distortion introduced by the injection of an a.c. signal, the amplitude of which is appreciable in relation to the total width of the distribution, is exemplified by the distribution curve based on the 0.3 volt injection signal. Indeed it might appear from this curve that the distribution is not far from the Druyvesteyn elastic form given by equation (1.2) in Section A: Chapter I. This illustrates the necessity of having a very sensitive method of detecting the small d.c. current increments on injecting a suitably small a.c. voltage into the probe circuit. The sensitive galvanometer employed is probably almost as sensitive and as stable as the best possible electronic d.c. amplifier, and the restricted applicability of the Druyvesteyn method of analysis to the measurement of low energy, high density electron distributions is thus demonstrated.

It must be observed that the criterion for the determination of the space or plasma potential is quite different in the Druyvesteyn analysis from that employed...
in the Langmuir analysis, which is that the space potential is given by the intersection of the extrapolated saturation region of the semi-logarithmic plot with the extrapolated ultimate region. The Druyvesteyn criterion is equivalent to the determination of the value of retarding potential at which \( \frac{1}{\sqrt{2}} \ln \) changes sign and becomes negative. Fig.20 indicates that the breakaway point from the linear plot is indeed not far from the +0.17 volt value given by the Druyvesteyn analysis. Taking this value of space potential on the semi-logarithmic plot we obtain an ultimate density of about 200\( \times 10^7 \) electrons/cc, which is at least of the same order of density given by the Druyvesteyn analysis (110\( \times 10^7 \) electrons/cc).

Thus we can summarise by concluding from these observations that:

(a) The a.c. injection signal to the probe must be kept small compared to the width of the distribution in order to avoid severe distortion.

(b) The distribution of the ultimate group in the negative glow is approximately Maxwellian in shape though showing rather fewer high energy electrons.

(c) The temperature of the ultimate group is very similar for both Langmuir and Druyvesteyn methods.

(d) The space potential criteria in the two methods are different, but if allowance is made for this the values of electron density agree at least in order of magnitude.

(e) Only the ultimate group is detectable by the Druyvesteyn analysis, this being a disadvantage inherent in the method.
SECTION C: SPECTRO-PHOTOMETRIC MEASUREMENTS

CHAPTER I: EXPERIMENTAL APPARATUS AND RESULTS

Detailed examination of the line intensity of the cathode dark space and negative glow regions of a helium discharge has been made with the aid of a Hilger Littrow Spectrometer (type E492).

The spectrometer employed is an exceedingly sensitive instrument with a wide dispersion, it being possible to take 4 feet of exposures on one plate (24 different positions), covering a frequency range of 4000 \( \AA \). The focal length of the quartz lens is 170cm. Ilford Zenith plates were used to photograph the spectra, as these give the best compromise between high speed, low background density and small grain size, while giving a suitable density - log intensity curve. A Hilger microphotometer incorporating a selenium photocell was employed to measure the density of blackening of each spectral line, the line being moved transversely across a fine light pencil and the minimum transmission noted as a photometer scale reading. Before each reading was taken the zero, corresponding to zero transmission, was set by means of a shutter in the path of the light beam and the maximum transmission, corresponding to the background plate density, was set to 50 on the scale.

As the microphotometer deflection is not proportional to the light intensity but only to the plate density, a calibration is necessary and the resultant
density - log intensity curve is shown in Fig.22. This has been achieved by exposing the plate to an iron arc spectrum, the relative intensities of these lines being known by previous absolute calibration employing a logarithmic sector which rotates across the spectrometer slit. It will be noted that the useful range of density corresponds to minimum microphotometer readings between about 0.5 and 20.

The results described in this chapter were taken with a 600μA discharge in tube A, at a pressure of 0.58mm. of helium. The tube was mounted so that the spectrometer slit was situated symmetrically with respect to the axis of the tube. A series of ten exposures were taken with the tube in different positions, the first exposure being with the slit in line with a region 9mm. into the cathode dark space from the edge and successive positions being in the direction of the anode. The exposure time in all cases was 30 mins. As the frequencies of the lines of the iron arc spectrum, exposed on the same plate, were known exactly, it was possible to find the frequencies of the helium lines. Thirteen prominent Helium I lines are numbered on the photograph shown in Fig.23, the exact frequencies of the lines being determined from the M.I.T. Spectroscopic Handbook. The ten different axial positions of the tube are also numbered on the plate. A few additional faint lines detectable on the plate correspond also to Helium I, including two weak lines of the Singlet Sharp Series 4438Å (2^1P-5^1S) and 4169Å (2^3P-6^1S). No impurity lines
were detected. Details of the thirteen lines with the wavelengths and corresponding transitions are given in Appendix (D).

Tables giving the line density in terms of the minimum microphotometer reading and also the corresponding values of relative intensity for the more intense lines (4, 5, 6, 10, 11 and 13) are given in Appendix (D). The intensities rise to a maximum in all cases at positions 6 and 7, corresponding to 2 or 3 mm. into the negative glow. The relation between relative intensity and axial position for the two most intense lines (4 and 10) is used in the next chapter as a basis of comparison with screened probe measurements.

A second photograph (Fig. 24) was taken with a longer exposure of 2 hours in two positions:

(a) in negative glow, 18 mm. from the C.D.S. edge.
(b) in cathode dark space, 6.5 mm. from the C.D.S. edge.

Using this longer exposure it was hoped to verify whether any impurity or Helium II lines (the latter corresponding to the excitation of singly ionised helium) were present, and also to find the ratios of the intensities of the Helium I lines in the cathode dark space and the negative glow. Some agreement at least in order of magnitude between the latter information and the results of Lees (31), who measured the excitation probability of certain prominent Helium I lines, was sought. Lees's results are discussed at greater length in the next chapter and are employed
there to compare probe and spectro-photometric measure-
ments. Four of his experimental curves giving atomic
cross-section, when multiplied by the appropriate scale
factor, as a function of electron energy are given in
Fig.25.

The very low intensities of some of the lines in
the cathode dark space precluded direct measurement as
the values of density were too low to give reliable
intensity figures from the log I - density curve. One
can draw the following general conclusions from in-
spection of the measured intensity values, reproduced
in Appendix (D).

(1) There are no impurity lines present. Exposures of
longer duration are pointless as the plate background
is beginning to increase.

(2) None of the Helium II lines are detectable. This
is not surprising in view of the fact that the number
of atoms/cc at 1mm. pressure is $2.7 \times 10^{16}$, so that the
ratio of uncharged to charged atoms is greater than $10^6:1$.

(3) It is apparent that the intensity ratios in the
cathode dark space and negative glow agree at least
qualitatively. For instance the intensity ratio for
line 11 (4713.1Å) is much greater than that for line 9
(4387.9Å). This is in accordance with the fact that
the excitation probability curve for line 11 is very
much narrower in energy than for line 9; the wide
variation in mean electron energy between the two
regions should therefore produce a much larger intensity
ratio for line 11 than for line 9.
CHAPTER II: COMPARISON WITH SCREENED PROBE DATA

Important confirmation of the validity of the screened probe measurements reported in Section B of this thesis would be obtained if there was agreement in the values of line intensity as a function of axial position in the negative glow, obtained by spectro-photometric measurements, and by screened probe measurements in conjunction with the excitation probability data of Lees. These probe measurements gave the variation of the number and energy of the electrons with axial position in the glow (Figs. 11 and 13), assuming Maxwellian distributions in the groups, the discharge conditions being identical to those employed in the spectro-photometric measurements. Thus we can find for each spectral line the product of the atomic cross-section (or excitation probability) for electrons of a given energy and the number of electrons of that energy, as a function of electron energy in each group. By measuring the areas under the curves and adding contributions for each group we can obtain functions at each point in the negative glow which should be proportional to the total intensity of emission of particular lines.

Calculations of the above type were made using Lees's data for lines 4 (3888.6Å) and 10 (4471.5Å), the two most intense spectral lines. In each case the contributions of the primary group and secondary group (the latter taking account of the contributions with
the probe facing both anode and cathode) were calculated at distances 0, 2, 3, 5, 9 and 17mm. from the C.D.S. edge. The contribution of the ultimate group to excitation is negligible throughout the glow owing to the very low mean energies. Much the greatest contribution is in fact due to the secondary group of electrons. In this way the tables in Appendix (D) were obtained giving the expression (atomic cross-section × electron density) as a function of electron energy for the various axial positions. The graphs of four of these functions for the two lines are reproduced in Figs.26 and 27. The total area under these curves was now integrated by means of a planimeter, yielding the following areas in arbitrary units:

<table>
<thead>
<tr>
<th>Distance from C.D.S. edge (mm.)</th>
<th>( \lambda = 3886.6 ) Area under Curves (arbitrary units)</th>
<th>( \lambda = 4471.5 ) Area under Curves (arbitrary units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>69</td>
<td>36.3</td>
</tr>
<tr>
<td>2</td>
<td>128</td>
<td>57</td>
</tr>
<tr>
<td>3</td>
<td>110</td>
<td>50.5</td>
</tr>
<tr>
<td>5</td>
<td>63</td>
<td>26.5</td>
</tr>
<tr>
<td>9</td>
<td>36.2</td>
<td>14.7</td>
</tr>
<tr>
<td>17</td>
<td>12.4</td>
<td>6.9</td>
</tr>
</tbody>
</table>

The scales have been adjusted to give the best fit with the spectro-photometric values of relative intensity. The two sets of values are plotted as functions of axial distance in the discharge in Figs.28 and 29, and the best curve fitting both sets of points has been drawn
in each case. Although there are not many spectro-
photometric points near the brightest part of the
negative glow, it will be noted that the points deter-
mined by the two different methods lie remarkably close
to the mean curves. The peak in intensity of each line
lies about 2 mm. into the glow from the visual edge,
while the peak in total electron density lies about 6 mm.
into the glow, in qualitative agreement with the
observations of Emeléus and Harris (18). The diffuse
nature of the C.D.S. edge is evident in both curves,
being more diffuse for the 4471.5 Å line than for the
3888.6 Å line. This latter observation is in accordance
with the shape of the two atomic cross-section curves
of Lees; the more rapid change of cross-section with
electron energy for the 3888.6 Å line should produce a
more rapid change in light intensity near the C.D.S.
boundary, across which the rate of change in electron
energy with axial position is large. There are, of
course, no calculated values of relative intensity in
the cathode dark space owing to the inapplicability of
probe measurements in this region of the discharge.
SUMMARY

Detailed examination of the electron energy and density distributions in the helium negative glow, at pressures of the order of 1 mm. Hg., has been made with the aid of specially developed screened probes. These probes are basically similar to that developed by Boyd but differ in constructional details; they are capable of radial and angular movement in the discharge.

The presence of three electron groups with Maxwellian distributions of differing mean energies has been definitely established, confirming and extending earlier work by Emeléus and his group. Both Langmuir and Druyvesteyn methods of analysis are employed, and relatively good agreement obtained between the results, taking account of the different space potential criteria. It is, however, shown that the Druyvesteyn method is restricted in applicability to the measurement of low energy, high density electron distributions. The directivity of the fastest or primary group is demonstrated and these electrons appear to originate near the cathode and to be accelerated across the cathode dark space. There would appear to be a considerable slow electron drift from the region of maximum concentration towards the cathode dark space edge, this drift being maintained by the field and the concentration gradient. The physical interpretation of the existence of two slow electron groups is discussed
in view of the experimental data. Results are given for the axial and radial variation of the electron temperature and density of the groups and also for the variation with discharge current and pressure. Ambipolar diffusion is shown to be the controlling electron removal mechanism in the negative glow, although some deviation occurs near the discharge tube walls, where the electron temperature rises sharply.

Good agreement is obtained between spectro-photometric measurements of the relative intensities of the helium spectral lines and the intensities obtained from the screened probe data supplemented by Lees's figures for the excitation probabilities of the helium lines as functions of electron energy. No impurity or Helium II lines are detectable in the helium spectra.
BIBLIOGRAPHY

18. Emeléus K.G. and Harris : Phil. Mag. 4, 49, (1927)
30. Emeléus K.G.: The Conduction of Electricity Through Gases (Methuen Monograph)
APPENDIX

(A). The Holstein Distribution

The Boltzmann transport equation may be written as
\[
\left( \frac{\delta f}{\delta t} \right)_{\text{coll}} = \frac{\delta f}{\delta t} + \nabla_r \cdot \nabla_f + a \cdot \nabla_v f
\]
where \( \nabla_r \) and \( \nabla_v \) are the gradient operators in distance and velocity space, \( \frac{\delta f}{\delta t} \) represents the smooth local rate of change of the distribution function \( f \), while \( \left( \frac{\delta f}{\delta t} \right)_{\text{coll}} \) represents the rate of change due to collisions. \( a \) is the acceleration in the field.

Representing the number of electrons in the energy interval between \( u \) and \( (u+du) \) by \( u^2 f(u) \), where \( u \) is the square of the electron velocity, Holstein gives the steady state d.c. solutions for the isotropic portion of the energy distribution by the two differential equations:
\[
o = \frac{4a^2}{3} \frac{d}{du} \left( u \lambda_u \frac{df}{du} \right) + \frac{2m}{M} \frac{d}{du} \left( \frac{u^2 f}{\lambda_u} \right) + \sum_{k} \left( u + u_{ex} \right) \lambda_{k-1}^{-1} \left( u + u_{ex} \right) f(u + u_{ex})
\]
for \( u < u_{ex} \), and
\[
o = \frac{4a^2}{3} \frac{d}{du} \left( u \lambda_u \frac{df}{du} \right) + \frac{2m}{M} \frac{d}{du} \left( \frac{u^2 f}{\lambda_u} \right) - \frac{u - f}{\lambda_{ex}}
\]
for \( u > u_{ex} \),
where \( \lambda_u \) is the energy of the first excited level
\( \lambda_{ex} \) is the energy of the \( \lambda^{+} \) excited level
\( \lambda_{k}^{-1} \) is the mean free path between those excitation collisions which excite a gas atom to the \( \lambda^{+} \) level.
\( \lambda_{ex} = \sum_{k} \lambda_{k}^{-1} \) is the mean free path between exciting collisions. \( \lambda_{D}^{-1} \) is the diffusion mean free path, which is employed instead of the Ramsauer mean free path. The diffusion cross-section \( Q_{D}(u) \) represents the...
contribution of elastic scattering to the diffusion of electrons in position and velocity space. This bears the relation to the Ramsauer cross-section $Q_R(u)$

$$\frac{Q_D(u)}{Q_R(u)} = 1 - (\cos \theta)_{AV}$$

where $(\cos \theta)_{AV}$ represents the average cosine of the angle of scattering for an electron of energy $u$. 
(B). Microwave Cavity Theory

It may be shown that, when the electron collision frequency ($\nu_c$) is small compared to the field frequency ($\omega$), the imaginary component of the complex conductivity of the discharge may be written as

$$\sigma_i = \frac{\omega \epsilon^2}{\omega \omega_c}$$

where $\omega_c$ is the electron density.

Slater$^1$ has shown that the admittance $\check{Y}_d$ of a gas discharge contained in a microwave cavity may be represented by

$$\check{Y}_d = \check{g}_d + j \check{b}_d = \frac{\beta \int \sigma \frac{E^2}{d\nu}}{\omega_c \epsilon_0 \int |E|^2 d\nu}$$

where $\epsilon_0$ is the permittivity of free space, $\sigma$ is the complex conductivity of the discharge and $\beta$ is a coupling coefficient. The symbols $\check{g}_d$ and $\check{b}_d$ represent the discharge conductance and susceptance respectively and $\omega_c$ is the resonant frequency of the empty cavity.

The imaginary part of the complex conductivity gives rise to a shift in the cavity resonant frequency and the real part lowers the $Q$ or amplification factor of the cavity. Either effect can be used to determine the electron density in the discharge, although the effect of changing the resonant frequency is the more useful experimentally owing to the higher accuracy with which this can be measured and the fact that for small ($\omega_c/\omega$), the case considered below, $\sigma_i \gg \sigma_r$ where $\sigma_r$ is the real part of the complex conductivity.

Rose and Brown$^2$ show that when the perturbation in

cavity frequency is small
\[ b_d = -2\beta \cdot \frac{\Delta \lambda}{\lambda_0} \]
where \( \Delta \lambda \) is the frequency shift from the centre wavelength \( \lambda_0 \).

If now the discharge is bounded by a container of smaller diameter than the cavity, we obtain the general formula
\[
\int_{\text{container}} n E^2 dV = \frac{8\pi^2 m e^2 \varepsilon_0}{\varepsilon^2} \cdot \Delta \lambda \frac{\lambda^3}{\lambda^3} \cdot \int_{\text{cavity}} E^2 dV.
\]
This equation can be solved for any particular cavity mode, that is any field configuration, and for any density distribution of electrons. For a TM010 cavity
\[ E_r = E_\phi = 0 \]
and \( E_z = E_0 J_0 (2.405 \tau / \rho') \)
where \( E_0 \) is the axial field at the centre of the cavity and \( \rho' \) is the radius of the cavity.

Two types of density distribution can be treated:
1. Electron density constant in the container, characteristic of the dominance of recombination processes, giving
\[ n = 6.1 \cdot 10^{12} \cdot \frac{\Delta \lambda}{\lambda^3} \cdot \frac{H}{\rho} \cdot \frac{1}{\rho^2 [J_0^2(2.4 \rho) + J_1^2(2.4 \rho)]} \]
where \( \rho = \tau / \rho' \), \( \tau \) being the container radius, \( H \) the height of the cavity and \( \rho \) that of the container.
2. Electron density governed by ambipolar diffusion, giving
\[ n = n_0 \cos \left( \frac{\pi z}{H} \right) \cdot J_0 \left( 2.405 \frac{\tau}{\rho_0} \right) \]
where \( n_0 \) is the density at the center of the cavity.
This gives the result
\[ n_0 = \frac{2.775 \cdot 10^3}{\sqrt{1.245 \rho^2 - 1.10 \rho + 0.02 \rho^2}} \cdot \frac{H}{\rho} \cdot \frac{\Delta \lambda}{\lambda^3} \]
(C). Druyvesteyn Analysis

The experimental results for the investigations described in Section B: Chapter III were as below:-

Langmuir Plot

<table>
<thead>
<tr>
<th>Grid Volts w.r.t. anode</th>
<th>Electron Current (μA)</th>
<th>Grid Volts w.r.t. anode</th>
<th>Electron Current (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.54</td>
<td>2.9</td>
<td>+0.11</td>
<td>27.0</td>
</tr>
<tr>
<td>-1.10</td>
<td>3.2</td>
<td>+0.20</td>
<td>36.5</td>
</tr>
<tr>
<td>-0.85</td>
<td>3.7</td>
<td>+0.31</td>
<td>50</td>
</tr>
<tr>
<td>-0.65</td>
<td>4.2</td>
<td>+0.58</td>
<td>70</td>
</tr>
<tr>
<td>-0.40</td>
<td>6.0</td>
<td>+1.0</td>
<td>86</td>
</tr>
<tr>
<td>-0.20</td>
<td>9.0</td>
<td>+1.5</td>
<td>100</td>
</tr>
<tr>
<td>-0.10</td>
<td>13.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>18.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With a screened probe grid area of $1.06 \times 10^{-2}$ cm$^2$ the Druyvesteyn equation (equation (1.6) of Section A) becomes

$$N_{dE} = 1580 \times 10^{-7} \Delta i \cdot E^{1/2}$$

where $\Delta i$ is in micro-amps and $E$ is in volts. We obtain the following density figures by this means.

A.C. voltage amplitude = 0.1 volts.

\[
\frac{V_{b}}{V} = +0.17 \text{ volts w.r.t. anode}
\]

<table>
<thead>
<tr>
<th>Grid Volts w.r.t. anode</th>
<th>$\Delta i$ (μA)</th>
<th>Retarding Potential $V = V_{p} - V_{b}$</th>
<th>$\sqrt{2}$</th>
<th>$\frac{N_{dE} \times 10^{7}}{0.01}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.08</td>
<td>0.004</td>
<td>1.25</td>
<td>1.12</td>
<td>7.1</td>
</tr>
<tr>
<td>-0.85</td>
<td>0.018</td>
<td>1.02</td>
<td>1.01</td>
<td>29.9</td>
</tr>
<tr>
<td>-0.63</td>
<td>0.044</td>
<td>0.80</td>
<td>0.89</td>
<td>62</td>
</tr>
<tr>
<td>-0.20</td>
<td>0.135</td>
<td>0.37</td>
<td>0.61</td>
<td>130</td>
</tr>
<tr>
<td>0</td>
<td>0.23</td>
<td>0.17</td>
<td>0.41</td>
<td>149</td>
</tr>
<tr>
<td>+0.11</td>
<td>0.22</td>
<td>0.06</td>
<td>0.25</td>
<td>88</td>
</tr>
<tr>
<td>+0.17</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A.C. voltage amplitude = 0.3 volts.
\( V_a = +0.18 \) volts w.r.t. anode

<table>
<thead>
<tr>
<th>Grid Volts w.r.t. anode</th>
<th>( \Delta i (\mu A) )</th>
<th>Retarding Potential ( V = V_p - V_a )</th>
<th>( \sqrt{V} )</th>
<th>( N^+_{de}10^{7}/cc )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.48</td>
<td>0.0028</td>
<td>1.84</td>
<td>1.28</td>
<td>0.58</td>
</tr>
<tr>
<td>-1.20</td>
<td>0.018</td>
<td>1.38</td>
<td>1.18</td>
<td>3.68</td>
</tr>
<tr>
<td>-1.00</td>
<td>0.067</td>
<td>1.18</td>
<td>1.09</td>
<td>12.7</td>
</tr>
<tr>
<td>-0.91</td>
<td>0.10</td>
<td>1.09</td>
<td>1.04</td>
<td>18.1</td>
</tr>
<tr>
<td>-0.57</td>
<td>0.46</td>
<td>0.75</td>
<td>0.87</td>
<td>70</td>
</tr>
<tr>
<td>-0.43</td>
<td>0.85</td>
<td>0.61</td>
<td>0.78</td>
<td>107.5</td>
</tr>
<tr>
<td>-0.31</td>
<td>1.20</td>
<td>0.49</td>
<td>0.70</td>
<td>146</td>
</tr>
<tr>
<td>-0.20</td>
<td>1.80</td>
<td>0.38</td>
<td>0.62</td>
<td>193</td>
</tr>
<tr>
<td>-0.03</td>
<td>1.70</td>
<td>0.21</td>
<td>0.46</td>
<td>136</td>
</tr>
<tr>
<td>+0.09</td>
<td>1.35</td>
<td>0.10</td>
<td>0.32</td>
<td>73</td>
</tr>
<tr>
<td>+0.14</td>
<td>0.80</td>
<td>0.04</td>
<td>0.20</td>
<td>27.8</td>
</tr>
<tr>
<td>+0.23</td>
<td>-0.30</td>
<td>-0.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**(D). Spectro-Photometric Measurements**

The thirteen lines identified on Fig. 23 can be classified as below:

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Wavelength (Å)</th>
<th>Series</th>
<th>Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3613.8</td>
<td>Singlet Principal</td>
<td>$2^1S-5^1P$</td>
</tr>
<tr>
<td>2</td>
<td>3705.0</td>
<td>Triplet Diffuse</td>
<td>$2^3P-7^3D$</td>
</tr>
<tr>
<td>3</td>
<td>3819.6</td>
<td>Triplet Diffuse</td>
<td>$2^3P-6^3D$</td>
</tr>
<tr>
<td>4</td>
<td>3888.6</td>
<td>Triplet Principal</td>
<td>$2^3S-3^3P$</td>
</tr>
<tr>
<td>5</td>
<td>3964.7</td>
<td>Singlet Principal</td>
<td>$2^1S-4^1P$</td>
</tr>
<tr>
<td>6</td>
<td>4026.2</td>
<td>Triplet Diffuse</td>
<td>$2^3P-5^3D$</td>
</tr>
<tr>
<td>7</td>
<td>4120.8</td>
<td>Triplet Sharp</td>
<td>$2^3P-5^3S$</td>
</tr>
<tr>
<td>8</td>
<td>4143.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>4387.9</td>
<td>Singlet Diffuse</td>
<td>$2^3P-5^3D$</td>
</tr>
<tr>
<td>10</td>
<td>4471.5</td>
<td>Triplet Diffuse</td>
<td>$2^3P-4^3D$</td>
</tr>
<tr>
<td>11</td>
<td>4713.1</td>
<td>Triplet Sharp</td>
<td>$2^3P-4^3S$</td>
</tr>
<tr>
<td>12</td>
<td>4921.9</td>
<td>Singlet Diffuse</td>
<td>$2^3P-4^1D$</td>
</tr>
<tr>
<td>13</td>
<td>5015.7</td>
<td>Singlet Principal</td>
<td>$2^1S-3^1P$</td>
</tr>
</tbody>
</table>

The following are the tabulated values of line density as minimum microphotometer readings and the corresponding values of relative intensity given with the aid of Fig. 22:
The discharge current was slightly in excess of 600 mA and the intensity figures have been corrected accordingly. *The exposure time in this case was 34 mins. instead of 30 mins. and this necessitated a corresponding correction to the intensity figures below.

The negative glow - C.D.S. edge occurred at about 9 mm. on the above scale.
<table>
<thead>
<tr>
<th>Exposure Number</th>
<th>Axial Movement (mm.)</th>
<th>Log I</th>
<th>4</th>
<th>Log I</th>
<th>5</th>
<th>Log I</th>
<th>6</th>
<th>Log I</th>
<th>10</th>
<th>Log I</th>
<th>11</th>
<th>Log I</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.115</td>
<td>13.0</td>
<td>0.515</td>
<td>3.27</td>
<td>0.505</td>
<td>3.2</td>
<td>1.25</td>
<td>17.75</td>
<td>0.73</td>
<td>5.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.6</td>
<td>1.025</td>
<td>10.6</td>
<td>0.385</td>
<td>2.43</td>
<td>0.385</td>
<td>2.43</td>
<td>1.13</td>
<td>13.5</td>
<td>0.63</td>
<td>4.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3.2</td>
<td>1.035</td>
<td>10.8</td>
<td>0.34</td>
<td>2.19</td>
<td>0.34</td>
<td>2.19</td>
<td>1.08</td>
<td>12.0</td>
<td>0.61</td>
<td>4.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4.8</td>
<td>1.125</td>
<td>13.3</td>
<td>0.40</td>
<td>2.51</td>
<td>0.42</td>
<td>2.63</td>
<td>1.115</td>
<td>13.0</td>
<td>0.66</td>
<td>4.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>1.40</td>
<td>25</td>
<td>0.585</td>
<td>3.84</td>
<td>0.605</td>
<td>4.13</td>
<td>1.30</td>
<td>19.8</td>
<td>0.015</td>
<td>1.02</td>
<td>0.785</td>
<td>6.10</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>2.1</td>
<td>126</td>
<td>0.875</td>
<td>7.50</td>
<td>0.95</td>
<td>8.93</td>
<td>1.75</td>
<td>55</td>
<td>0.245</td>
<td>1.755</td>
<td>1.15</td>
<td>14.2</td>
</tr>
<tr>
<td>7</td>
<td>12.7</td>
<td>2.05</td>
<td>102</td>
<td>0.75</td>
<td>5.10</td>
<td>0.88</td>
<td>6.9</td>
<td>1.70</td>
<td>49.5</td>
<td>0.19</td>
<td>1.4</td>
<td>0.935</td>
<td>7.8</td>
</tr>
<tr>
<td>8</td>
<td>20.1</td>
<td>1.23</td>
<td>17.1</td>
<td>0.16</td>
<td>1.45</td>
<td>0.22</td>
<td>1.7</td>
<td>0.95</td>
<td>8.9</td>
<td>0.015</td>
<td>1.02</td>
<td>0.34</td>
<td>2.19</td>
</tr>
<tr>
<td>9</td>
<td>25.4</td>
<td>1.105</td>
<td>12.8</td>
<td>0.115</td>
<td>1.30</td>
<td>0.145</td>
<td>1.395</td>
<td>0.83</td>
<td>6.8</td>
<td>0.21</td>
<td>1.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>31.8</td>
<td>1.06</td>
<td>11.6</td>
<td>0.105</td>
<td>1.27</td>
<td>0.14</td>
<td>1.38</td>
<td>0.80</td>
<td>6.3</td>
<td>0.18</td>
<td>1.51</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The density and corresponding intensity values for the 2 hours exposure in (a) the negative glow and (b) the cathode dark space.

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Density (microphotometer rdg.)</th>
<th>(a) Relative Intensity(I)</th>
<th>(b) Relative Intensity(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.7</td>
<td>0.18</td>
<td>1.514</td>
</tr>
<tr>
<td>2</td>
<td>15.4</td>
<td>0.73</td>
<td>5.37</td>
</tr>
<tr>
<td>3</td>
<td>4.45</td>
<td>1.75</td>
<td>56.23</td>
</tr>
<tr>
<td>4</td>
<td>0.40</td>
<td>1.17</td>
<td>14.79</td>
</tr>
<tr>
<td>5</td>
<td>1.30</td>
<td>0.77</td>
<td>5.89</td>
</tr>
<tr>
<td>6</td>
<td>1.20</td>
<td>0.75</td>
<td>5.623</td>
</tr>
<tr>
<td>7</td>
<td>14.20</td>
<td>46.5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>20.9</td>
<td>2.0</td>
<td>3.02</td>
</tr>
<tr>
<td>9</td>
<td>0.80</td>
<td>1.4</td>
<td>25.12</td>
</tr>
<tr>
<td>10</td>
<td>8.30</td>
<td>0.41</td>
<td>2.57</td>
</tr>
<tr>
<td>11</td>
<td>9.70</td>
<td>0.32</td>
<td>2.09</td>
</tr>
<tr>
<td>12</td>
<td>2.95</td>
<td>0.89</td>
<td>7.76</td>
</tr>
</tbody>
</table>

The functions obtained for the light intensity of the two lines 3888.6 Å and 4471.5 Å by combining J.H. Lees's data with the screened probe data are given below. The distances quoted are measured from the C.D.S. edge into the negative glow.
<table>
<thead>
<tr>
<th>E (Volts)</th>
<th>0</th>
<th>2mm.</th>
<th>3mm.</th>
<th>5mm.</th>
<th>9mm.</th>
<th>17mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>23.3</td>
<td>56.1</td>
<td>62.6</td>
<td>43.1</td>
<td>26.3</td>
<td>9.2</td>
</tr>
<tr>
<td>27</td>
<td>63.4</td>
<td>152.4</td>
<td>162.6</td>
<td>111.5</td>
<td>62.6</td>
<td>23.7</td>
</tr>
<tr>
<td>30</td>
<td>71.9</td>
<td>166.4</td>
<td>167.9</td>
<td>95.5</td>
<td>51.1</td>
<td>19.9</td>
</tr>
<tr>
<td>35</td>
<td>50.1</td>
<td>102.1</td>
<td>86.1</td>
<td>41.9</td>
<td>21.3</td>
<td>10.4</td>
</tr>
<tr>
<td>40</td>
<td>29.2</td>
<td>50</td>
<td>35.9</td>
<td>18.1</td>
<td>11.9</td>
<td>3</td>
</tr>
<tr>
<td>45</td>
<td>19.4</td>
<td>25.7</td>
<td>17.4</td>
<td>9.1</td>
<td>5</td>
<td>3.5</td>
</tr>
<tr>
<td>50</td>
<td>13.3</td>
<td>14.5</td>
<td>8.7</td>
<td>5</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>7.3</td>
<td>4.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>E (Volts)</th>
<th>0</th>
<th>2mm.</th>
<th>3mm.</th>
<th>5mm.</th>
<th>9mm.</th>
<th>17mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>2.34</td>
<td>5.62</td>
<td>6.29</td>
<td>4.27</td>
<td>2.61</td>
<td>0.92</td>
</tr>
<tr>
<td>27</td>
<td>6.36</td>
<td>15.24</td>
<td>16.3</td>
<td>10.85</td>
<td>6.27</td>
<td>2.37</td>
</tr>
<tr>
<td>30</td>
<td>10.8</td>
<td>25.3</td>
<td>25.5</td>
<td>14.2</td>
<td>7.52</td>
<td>2.80</td>
</tr>
<tr>
<td>35</td>
<td>8.23</td>
<td>16.85</td>
<td>14.31</td>
<td>6.69</td>
<td>3.52</td>
<td>1.71</td>
</tr>
<tr>
<td>40</td>
<td>5.05</td>
<td>8.5</td>
<td>6.25</td>
<td>2.84</td>
<td>1.76</td>
<td>1.00</td>
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<td>45</td>
<td>3.83</td>
<td>5.0</td>
<td>3.5</td>
<td>1.57</td>
<td>1.00</td>
<td>0.62</td>
</tr>
<tr>
<td>50</td>
<td>2.9</td>
<td>3.06</td>
<td>1.9</td>
<td>0.80</td>
<td>0.70</td>
<td>0.25</td>
</tr>
<tr>
<td>60</td>
<td>1.94</td>
<td>1.26</td>
<td>0.8</td>
<td></td>
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<tr>
<td>80</td>
<td>0.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1.
Normalised probability distribution of electron energies.

\[ X_p = 3 \text{ volts/cm/mm. for Druyvesteyn, Smit & Holstein distributions.} \]
\[ kT = 6 \text{eV for Maxwellian distribution.} \]

- Maxwellian distribution.
- Druyvesteyn distribution.
- Smit distribution.
- Holstein distribution.
FIG. 2.

FREQUENCY SHIFT & ELECTRON DENSITY FROM CAVITY MEASUREMENTS.

SILICA DISCHARGE TUBE.

REGION. EXTENT.
1. POSITIVE COLUMN. 15 MM.
2. FARADAY DARK SPACE. 30 MM.
3. NEGATIVE GLOW. 5 MM.
4. CATHODE DARK SPACE. 2.5 MM.
FIG. 3

VACUUM SYSTEM

PORTABLE VACUUM SYSTEM
(SIDE VIEW B)

1. THERMOCOUPLE
2. NEEDLE VALVE
3. MERCURY MANOMETER
4. M'LECO GAUGE

1. OVEN
2. DISCHARGE TUBE
3. CAPACITY BRIDGE
4. DIFFUSION PUMP BYPASS VALVE
5. DIFFUSION PUMP
6. LIQUID AIR TRAP
7. P₂O₅ DRYING BOTTLE
8. GAS BOTTLE
A COPPER CUP. (HIGH VAC SIDE)
B HARDENED STEEL RING.
C COPPER CUP (MANOMETER SIDE)
D DIAPHRAGM.
E STEEL STOP PLATE.

FIG. 4.
MANOMETER CONSTRUCTION.

A COPPER CUP (HIGH VAC SIDE)
B HARDENED STEEL RING.
C COPPER CUP (MANOMETER SIDE)
D DIAPHRAGM.
E STEEL STOP PLATE.

DETAIL OF VACUUM SEAL.
KOVAR LEAD I SILLIM SLEE GLASS SHE GRID

FIG. 7.
SCREENED PROBE ASSEMBLY

KOVAR WIRE LEAD TO CONNECTOR
SILLIMANITE SLEEVING
GGLASS SHEATHING
GRID APERTURE
GRID SUPPORT CAP

ENLARGED VIEW OF CIRCLE SECTION 'A'
SCALE: -10/1

ENLARGED SIDE VIEW OF MAGNETIC SLUG IN ARROW DIRECTION
SCALE: -5/1
FIG. 8
LANGMUIR PROBE
ASSEMBLY

GLASS TO METAL SEAL

MAGNETIC SLUG

BERYLLIUM COPPER
SPRING

WALL OF DISCHARGE
TUBE

TUNGSTEN WIRE
FIG. 9. PROBE CIRCUIT.

[Diagram of probe circuit with labels: ANODE, GRID, COLLECTOR VOLTS, B.F.O., C.R.O., V.V., COLLECTOR CURRENT, ZERO SET, SENS, 10K, 2-2K, 100K, GRID VOLTS, STABILISED POWER UNIT, CATHODE.]
FIG. 10.
TYPICAL SEMI-LOG PLOT OF ELECTRON CURRENT TO COLLECTOR VS. GRID VOLTS.

ELECTRON CURRENT (μA)

GRID VOLTS WITH RESPECT TO ANODE.
FIG. 11. ELECTRON GROUPS IN 600 μA. DISCHARGE IN 0.58 MM HELIUM.
FIG. 12.

SPACE POTENTIAL & SECONDARY GRID EMISSION AS FUNCTIONS OF POSITION IN NEGATIVE GLOW.

(PROBE FACING CATHODE IN TUBE A.)
FIG. 13. ELECTRON GROUPS IN 600 μA DISCHARGE IN 0.58MM HELIUM PROBE FACING ANODE IN NEGATIVE GLOW; TUBE A.

DISTANCE FROM C.D.S. EDGE (MMS)
FIG. 14. HIGH ENERGY REGION OF SCREENED PROBE CHARACTERISTIC IN 600 µA. DISCHARGE IN 0.58 MM. HELIUM.

(TUBE A 6 MM. FROM C.D.S. EDGE.)
FIG. 15. ACCURATE MEASUREMENT OF PRIMARY GROUP CONTRIBUTION.

TUBE A.
0.5 MMS. HELIUM.
600 µA, 900VOLTS.
PROBE FACING CATHODE, 7 MMS.
FROM EDGE.
FIG. 16.

RADIAL ELECTRON DISTRIBUTION.

TUBE B: 0.70MMS. HELIUM. 1mA; 450 VOLTS
PROBE FACING CATHODE, 23MM.
FROM EDGE.
(DISTANCES MARKED ARE MEASURED FROM CENTRE OF TUBE.)
FIG. 17. TEMPERATURE OF ULTIMATE GROUP

TUBE B
0.70MM. HELIUM
1MA 450 VOLTS
PROBE FACING CATHODE, 23MM. FROM EDGE.
DENSITY OF ULTIMATE GROUP.

\[ \eta = n_0 J_0 \left( \frac{2.405 \gamma}{R} \right) \]

EXPERIMENTAL CURVE.

CORRECTED EXPERIMENTAL CURVE FOR C.D.S. BOUNDARY CURVATURE.

PLASMA POTENTIAL.

\[ V_T - V_0 = \frac{kT}{e} \left( \log \frac{n}{n_0} \right) \]

EXPERIMENTAL CURVE.

CORRECTED EXPERIMENTAL CURVE FOR C.D.S. BOUNDARY CURVATURE.

FIG. 18. ULTIMATE GROUP DENSITY & PLASMA POTENTIAL AS FUNCTION OF RADIUS.

TUBE B:
0.70 MMS HELIUM.
1 mA. 450 VOLTS.
PROBE FACING CATHODE 23 MMS FROM EDGE.
FIG. 19.

TYPICAL LANGMUIR PLOT AT LOW PRESSURES.

PRESSURE 0.17MM HE LiUM.
DISCHARGE CURRENT 2mA.
SCREENED PROBE 25MM. FROM C.D.S. EDGE, FACING CATHODE.
FIG. 20.

LANGMUIR SEMI-LOGARITHMIC PLOT
FOR SCREENED PROBE.

(IDENTICAL CONDITIONS TO THOSE
FOR DRUYVESTEYN ANALYSIS.)
FIG. 21.

DRUYVESTEYN ANALYSIS.

TUBE A: 600 μA DISCHARGE IN 0.50MM HELIUM.
SCREENED PROBE FACING CATHODE, 5MM FROM EDGE.

--- THEORETICAL MAXWELLIAN DISTRIBUTION
WITH $kT = 0.34 \text{ V}; N_0 = 110 \times 10^7 \text{ cc}.$

--- DRUYVESTEYN ANALYSIS WITH AMPLITUDE OF
A.C. INPUT = 0.1 VOLT.

--- DRUYVESTEYN ANALYSIS WITH AMPLITUDE OF
A.C. INPUT = 0.3 VOLT.
FIG. 22

DENSITY — LOG INTENSITY CURVE FOR ZENITH PLATE.

LOGARITHM OF RELATIVE INTENSITY.
FIG. 23

INTENSITY VARIATION OF SPECTRAL LINES IN NEGATIVE GLOW AND CATHODE DARK SPACE.

FIG. 24

LONGER EXPOSURE OF SPECTRAL LINES IN NEGATIVE GLOW AND CATHODE DARK SPACE.
Figure 25. Excitation cross section in helium. (J.H. Lees)
FIG. 26. LIGHT INTENSITY-ENERGY CURVES FROM SCREENED PROBE DATA.

FOR $\lambda = 3888.6\text{Å} \quad (2^3S - 3^3P)$
FIG. 27.
LIGHT INTENSITY-ENERGY CURVES
FROM SCREENED PROBE DATA
FOR $\lambda = 4471.5\,\text{Å} \left(2^3\,P - 4^3\,D\right)$
\[ \lambda = 3888.6 \text{Å} \ (2^3 S - 3^3 P) \]

RELATIVE INTENSITY - DISTANCE IN GLOW.

- **X---X** EXPERIMENTAL SPECTROSCOPIC POINTS.
- **O---O** CALCULATED FROM SCREENED PROBE DATA & J.H.LEES FIGURES FOR EXCITATION PROBABILITIES.

POSITION OF VISUAL C.D.S. EDGE.
FIG. 29.

$\lambda = 4471.5^\circ \text{A} \ (2^3P - 4^3D)$.

RELATIVE INTENSITY – DISTANCE IN GLOW.

- **X**—**X**— EXPERIMENTAL SPECTROSCOPIC POINTS.
- **O**—**O**— CALCULATED FROM SCREENED PROBE DATA & J.H. LEES FIGURES FOR EXCITATION PROBABILITIES.

POSITION OF VISUAL C.D.S. EDGE.