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Source: *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, Vol. 228, No. 1175 (Mar. 22, 1955), pp. 477-490
Published by: The Royal Society
Stable URL: http://www.jstor.org/stable/99639
Accessed: 12/06/2013 23:02

Experimental investigations on electron interaction

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(*Communicated by M. S. W. Massey, F.R.S.—Received* 8 *October* 1954)

[Plate 5]

Certain observations in low-pressure gas discharges and in magnetrons appear to indicate an electron interaction effect several orders of magnitude in excess of the theoretical values based on binary encounters only. As the Coulomb interaction in low-pressure plasmas and in electron clouds usually extends over a range which contains at least several thousand electrons, it was not clear whether these observations indicated a breakdown of the theory, or some new effects, other than electron interaction. New experiments were therefore designed to establish an upper limit for the magnitude of the electron interaction effect. Both plasmas in thermal equilibrium and pure electronic space charges were investigated. The basic experimental method in each case was shooting a very carefully collimated electron beam through the charge cloud, and measuring the scattering by direct observation on a fluorescent screen. The apparatus was designed to resolve angles down to 10^{-4}. The density of the equilibrium plasma was inferred from capacity measurements on a thin wire probe in the plasma. The density of the electron cloud was determined by measuring the electron-optical effects produced. It is concluded that both for the plasma as for the electron cloud the scattering is less than five times the value predicted by the theories neglecting simultaneous multiple collisions. The interaction is therefore so small that it cannot be expected to account for the observed anomalies either in low-pressure gas discharges or in other electronic devices.

List of symbols

e	electronic charge
f_p	the 'plasma frequency'
I_b	beam current
J	current density
J_0	current density at the surface of the cathode
k	the Boltzmann constant
L	length of the charge cloud
m	mass of the electron
M	magnification produced by electron cloud
N	charge density measured in number of charges/unit volume
p	the collision parameter
s	the mean free path of an electron in a space-charge cloud
T	cathode temperature
ρ	space-charge density
ρ_c	space-charge density at the surface of the cathode
V	beam energy in volts
λ_D	Debye radius
θ	deflexion or scattering angle
ϕ	angular range of electrons at a focus in the electron beam

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1. Introduction

In the theoretical analysis of electronic devices, it is usual to discount the discrete nature of the charges, and the combined action of all other electrons on an individual electron is represented by an 'equivalent fluid', with a charge per unit volume, and a ratio of charge to mass identical with that for a single electron. This approach neglects collisions altogether. It appears reasonable to improve on it by taking into account collisions between pairs of electrons, but the improvement is somewhat doubtful. In the case of molecules, the repulsive forces fall off so rapidly with distance that a molecule may be considered as moving in straight lines between collisions; an idealization which gives rise to the concept of a 'mean free path'. In the case of electrons, the repulsive forces decrease only as the inverse square of the distance, so that the motion of an electron at any given time is influenced to a significant extent by a large number of other electrons.

The theory of Coulomb gases has been worked out by numerous authors, in particular by Landau (1936), Chapman & Cowling (1939), and Chandrasekhar (1942). The estimates of these authors for the suitably redefined mean free path agree fairly well between themselves, but they seem to be in flagrant disagreement with certain observations, in particular with the now thirty-year-old experiments of I. Langmuir (1925), in low-pressure mercury discharges. The almost perfect Maxwellian distribution of electron energies, and its stability against disturbances required for their explanation a mean free path of less than 1 cm in some cases, when the theory gave several methods. Some observations by Linder (1938) indicated the presence of similar inexplicable phenomena in magnetrons. In view of the observations, the possibility could not be dismissed that the theory was at fault, and a direct appeal to experiment was required.

A brief review of the theoretical calculations may first be given with the object of discovering in what respects they are incomplete or doubtful, and what experiments are needed to justify the assumptions that have to be made.

The deflexion θ suffered by an electron in an encounter with a second electron is given by

$$\sin\theta = (1+(mv^2p/2e)^2)^{-\frac{1}{2}}, \tag{1}$$

where p is the collision parameter.

If such an encounter takes place in the presence of a third electron, we have a three-body problem which is not in general soluble. Thus in considering the interaction of three electrons, the limits of rigorous analysis have already been reached. In the face of this difficulty, some simplifying assumptions must be made. The simplest, which was used by Jeans (1928) in a calculation of the gravitational interaction between stars, is to consider only those encounters for which the collision parameter p is less than $N^{-\frac{1}{3}}$, the mean distance between the particles in the cloud, distributed with a density N per unit volume. With this assumption the changes brought about by one encounter are largely complete before those due to the next become appreciable, and it is permissible to add the effects of consecutive encounters. This is certainly not the whole of the interaction, for although the encounters considered are the most violent, they are also the rarest, so that the combined effect of all the more distant charges might exceed that due to the close encounters. In a plasma it appears natural to take as the critical collision parameter some small multiple of the Debye radius

$$\lambda_D = (\boldsymbol{k}T/4\pi e^2 N)^{\frac{1}{2}}, \tag{2}$$

but a sphere with this radius contains, under conditions typical of a low-pressure discharge, of the order of 10^6 electrons. A number of attempts have been made to eliminate these difficulties by the assumption that the momentum and energy changes suffered by an electron A as a result of an encounter with a given electron B are entirely unaffected by the fact that both A and B are during their encounter 'colliding' with a large number of other electrons. It seems difficult to justify this procedure on any but intuitive grounds. Calculations of this type have been made, in addition to the authors previously mentioned, by Wilson (1923), Thomas (1928), Langmuir & Jones (1928) and Druyvesteyn (1938). In all these theories, the scattering due to the interaction becomes infinite if collisions with arbitrarily large values of p are included. This raises no serious difficulty, as in the result $p_{\text{max.}}$ appears only in the argument of a logarithm, so that the result is very insensitive to large changes in the choice of this parameter.

In the calculations of Langmuir, Thomas and Druyvesteyn the scattering is calculated by a summation of the effects of binary encounters, with a random distribution of collision parameters. Landau achieved essentially the same object in an approach based on the Boltzmann transfer equation. In each case, the mean free path s, defined as the mean distance in which an electron is scattered by unit angle, is reduced to an expression of the form

$$s = \text{const.}\,(\boldsymbol{k}T)^2/e^4 N. \tag{3}$$

This value for s would lead to the conclusion that electron interaction effects could not be responsible for the apparently short mean free paths observed in gas-discharge plasmas.

These theories, in which the field of a charge is assumed to be substantially neutralized at some small multiple of the Debye radius, cannot be applied to cases where charges of only one sign are present, or for that matter to the gravitational problem of a cloud of stars, although it may turn out that the error in most cases is not one involving orders of magnitude.

The theoretical calculations so far discussed disregard the possibility of any degree of coherent action of the scattering electrons. The plasma is known to possess medium-like properties in a limited frequency range (Bohm & Gross 1949). It is conceivable that 'collective oscillations' could have a considerable effect on the mean free paths of the electrons in the plasma. It was realized by Langmuir that this might represent a possibility of accounting for the observed phenomena in terms of electron interaction. But the effect of random, thermally excited oscillations on the mean free paths has recently been calculated by one of us (Gabor 1952), and the result is that the scattering is even smaller than that due to collisions with a parameter less than λ_D. Thus unorganized plasma oscillations cannot materially affect the mean free path of the electrons.

It may be concluded that the energy and momentum changes brought about by the encounters with a collision parameter less than $N^{-\frac{1}{3}}$, as well as those brought about by the coherent interaction with electrons at distances greater than about $3\lambda_D$ can be calculated with fair accuracy. Incoherent interaction with electrons at distances greater than $N^{-\frac{1}{3}}$ can be taken into account only by the use of some simplifying assumptions. Although the error thus incurred cannot be accurately estimated, it would seem unlikely that it should explain the factor of several orders of magnitude by which the electron interaction so calculated fails to account for the phenomena observed by Langmuir. The purpose of the experimental investigation is to test this assumption.

2. Experimental method

The experimental method was to shoot a well-collimated electron beam through a charge cloud, and measure the scattering of the beam by direct observation on a fluorescent screen. The basic arrangement is shown in figure 1. The interacting medium is introduced between the lens and the screen, and the scattering is revealed by an increase in the diameter of the focused spot.

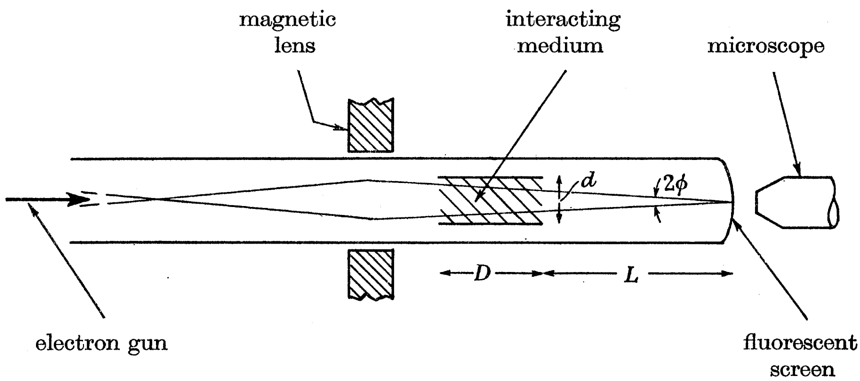

Figure 1. The basic experimental arrangement.

The theories based on binary encounters agree in predicting a mean free path given by equation (3). A form more directly applicable to our experiments derived by Thomas (1928) gives the root-mean-square angle through which an electron is scattered in traversing a charge cloud of density N and length L:

$$(\overline{\theta^2})^{\frac{1}{2}} = \frac{e}{V}(\pi NL \ln(Vp_{\max.}/e))^{\frac{1}{2}}, \tag{4}$$

where eV is the energy of the electron. Considering an example typical of some of our experiments, $N = 10^{10}$ electrons/cm^3, $L = 3$ cm, and $V = 1kV$, this is approximately 10^{-4}. Thus an experiment designed to confirm the order of magnitude of this effect must be capable of detecting very small scattering angles, and the beam-forming system must be designed to achieve the smallest possible spot diameter. The minimum spot diameter attainable is limited by the random thermal motion of the beam electrons. This limiting condition, first derived by D. B. Langmuir (1937), may be written in the form

$$J \leqslant J_0 \frac{eV}{kT} \sin^2 \phi, \tag{5}$$

or, in terms of the effective spot diameter, d,

$$d \geqslant \frac{1}{\sin \phi} \left(\frac{4 I_b kT}{\pi e V J_0}\right)^{\frac{1}{2}}. \tag{6}$$

Thus, one requirement is to use the smallest beam current which just allows observation on a fluorescent screen, at the same time retaining a high current density at the cathode. Also, the angle of convergence of the beam at the screen (ϕ) must be

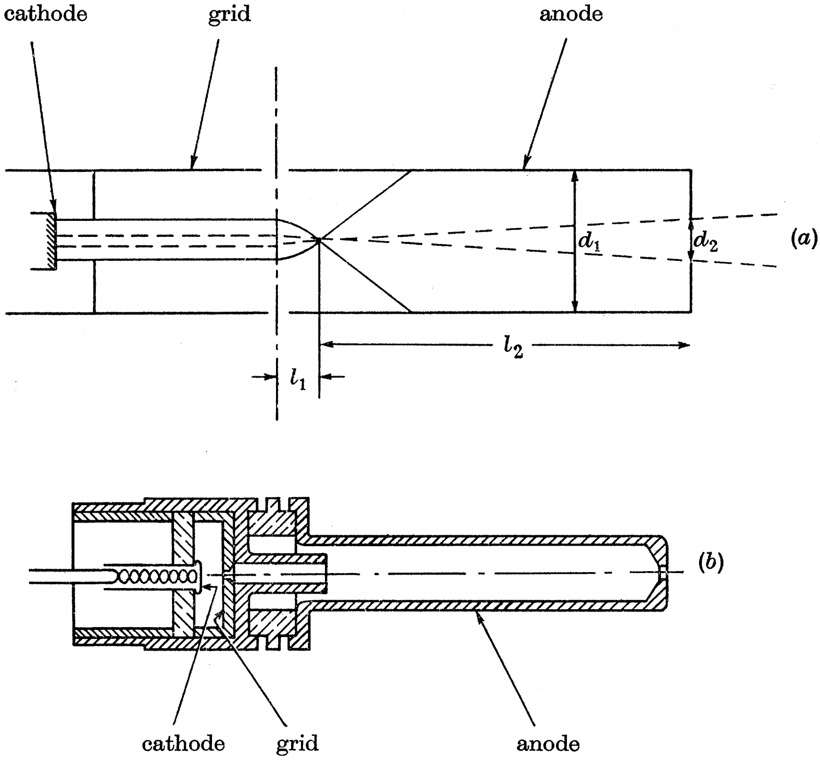

FIGURE 2. (*a*) Ray diagram of electron gun used in interaction experiments. (*b*) Section of electron gun used.

kept as large as permitted by the available aperture of the charge cloud. The present problem, in contrast to that usually encountered in the design of electron guns, requires the disposal of all but a very small fraction of the large current which must be drawn from the cathode. These considerations led to the design of the gun, shown in diagrammatic form in figure 2*a*. The cathode is placed inside a grid, to which is applied a positive potential such as to draw a large current from the cathode. The grid and anode constitute a very strong electrostatic lens, so that a cross-over is formed with a large angle of convergence, a short distance inside the anode. Most of the current is then allowed to flow to the anode, and only a small fraction emerges as the beam. This beam current can be approximately calculated from a knowledge of the focal length of two-tube lenses (e.g. Spangenberg 1948)

$$I_b \simeq J_0 \frac{\pi}{4}\left(\frac{d_1 d_2}{l_2}\right)^2. \tag{7}$$

The spherical aberration of the electric lens is negligible for the comparatively small angular aperture of the emerging beam.

A practical realization of this design is shown in figure 2*b*. In this case, only about 1/5000 of tbe cathode current is ultimately used in the beam. In special tubes built to test this design, it was found that spot diameters only 30 % larger than the theoretical optimum could be obtained. Two essentials in achieving this performance were very careful electric and magnetic shielding, and the compensation of the astigmatism of the magnetic lens.

3. Experiments with a plasma

The main problem in the investigation was the formation of a stable charge cloud. A high-density plasma is most easily produced in a gas discharge, but since the discharge plasma is not in equilibrium, it is not suitable as a test medium. Experiments on gas-discharge plasmas will form the subject of a separate paper.

An attempt was made to produce an electron cloud inside a tubular cathode, coated on the inside, and heated from the outside. Laue (1918) has calculated the space-charge density ρ which should be obtained on the axis of such a cathode:

$$\rho = 8\boldsymbol{k}T/er_c^2, \tag{8}$$

where r_c is the radius of the cathode. For an oxide cathode with a radius of 1 mm, this gives a value of about 6×10^8 electrons/cm³. It was hoped to measure this density by the effect of the macroscopic field of the charge cloud on the exploring beam. This effect would be that of a divergent lens (Gabor 1944), and with densities as small as 5×10^7 electrons/cm³, the divergence of the beam would have been observable. When the experiment was performed, no divergence could be detected. Later it was found that this behaviour could be attributed to neutralization of the space charge by positive ions; these ions appeared to come from the oxide cathode itself. It should be noted that since there is a tendency for ions to be trapped in the potential minimum formed by an electronic space charge, a very small rate of ion emission could account for these phenomena. The emission of positive ions from an oxide cathode, with current densities of the order of 10^{-10} A/cm², could be demonstrated by direct experiment. Thus a neutral plasma was obtained, which was of the very type needed for the electron interaction experiments. It is truly isothermal, with both electrons and ions in equilibrium with the cathode temperature. Moreover, very large electron densities can be obtained under these conditions. According to the Boltzmann distribution law, the density will be uniform over the cross-section of the tube, and consequently equal to that obtained at the surface of the cathode,

ρ_c. This is a function only of the saturation current density and the temperature of the cathode (Langmuir 1933).

$$\rho_c = J_0(2\pi m/kT)^{\frac{1}{2}}. \tag{9}$$

For an oxide cathode, ρ_c is of the order of 10^{11} electrons/cm^3.

The main difficulty is in measuring this density. Langmuir probe techniques used in gas-discharge work cannot be applied, because the plasma is dependent on a very limited ion supply, so that ions absorbed by the probe cause large variations in the plasma density as its potential is varied. Also, since the electron temperature is so low that the mean energy is of the order of 0·1 V, the Langmuir technique would involve the measurement of potentials considerably smaller than the contact potentials, which are never stable under these conditions. A further practical drawback is that it is very difficult to prevent some electronic emission from the probe, which reaches a temperature very little below that of the cathode which surrounds it.

Using a different technique, it was possible to determine a lower limit for the plasma density. A thin wire probe was stretched longitudinally inside the cathode structure (figure 3*a*) and its capacity to the cathode was measured. In the absence of ions, this capacity would show only small changes as the cathode was heated, provided that the frequency of measurement was sufficiently below the plasma frequency to make the polarization negligible. If there are enough ions present to allow the formation of a plasma, and of a sheath around the probe, the capacity change would be large. The conductivity of the plasma is high compared with that of the sheath, so that the probe-cathode impedance is almost entirely determined by the probe-plasma impedance. This depends only on the dimensions of the sheath. Thus the formation of the plasma effectively decreases the spacing between probe and cathode to tbe sheath thickness. The formation of a plasma would then be revealed by a large increase in the measured capacity when the cathode was heated. Such increases were in fact found, and of such a magnitude (20-fold increases) as to rule out the possibility of stray effects. These capacity changes are plotted in figure 3*b* as a function of the probe voltage relative to its floating potential, for three different cathode temperatures, indicated by the heater voltage. (The construction did not allow direct measurement of the temperature.) The measurements were carried out at a frequency of 1 Mc/s, but almost identical results were obtained at all other frequencies in the range of the test equipment used (500 kc/s to 2 Mc/s). It is seen that as the probe voltage is made negative, there is at first a very rapid rise of capacity, followed by a much slower decrease as the negative probe voltage is further increased. The maximum value of the capacity-increase ratio rises rapidly with the cathode temperature, a behaviour in complete accord with equation (9), since J_0 is itself a critical function of the cathode temperature. One notable feature of the results is the double peak found for the highest value of the cathode temperature. This is attributed to the ionization of barium atoms (ionization potential 5·2 V), yielding an additional supply of ions. This phenomenon was again encountered in the course of experiments with a pure electronic space charge, to be described. The eventual decrease of the capacity ratio at large negative voltages is due to the increasing number of ions absorbed by the probe, resulting in the collapse of the plasma.

These results undoubtedly prove the existence of a plasma, but it is not easy to relate them quantitatively to the plasma density. Some deductions can, however, be made. The sheath thickness cannot be less than the Debye length, for it is in effect the distance in which the surface charges on the probe are shielded from the plasma; the Debye distance can be regarded as the 'sheath thickness' for a single charge. It is apparent that the corresponding distance for a concentration of charges, all of the same sign, cannot be less than this. In the case of a typical low-density

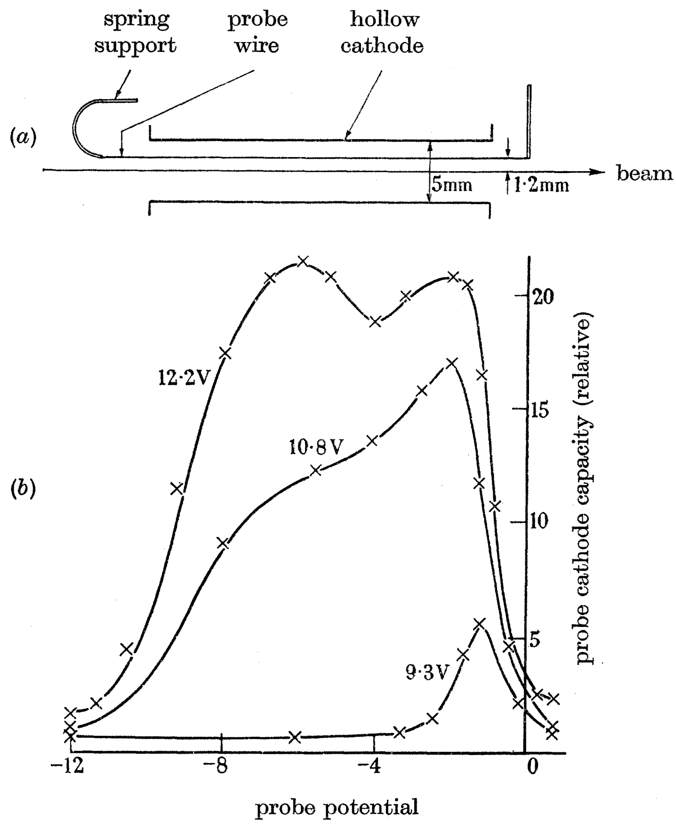

FIGURE 3. (a) Hollow cathode structure incorporating longitudinal probe wire. (b) Relative increase of probe cathode capacity on heating cathode, as a function of probe potential.

gas-discharge plasma it is usually of the order of $10\lambda_D$. If then the plasma density is calculated on the assumption that the measured capacity is due to a sheath thickness of λ_D, it can be assumed that the true density will exceed this value, and in all probability by a considerable factor. In this way, the lower limit for the density, obtained at the highest cathode temperature, was found to be $1{\cdot}9 \times 10^{10}$ electrons/cm^3. Although it cannot be said with any confidence by how much the actual density exceeds this figure, it can be accepted as a reliable lower limit. It should be added that the curves of figure 3*b* were stable, and repeatable with considerable accuracy after long time intervals.

In a particular tube, the measured spot diameter was 0·75 mm in the absence of the plasma at a beam voltage of 1 kV. When the cathode was heated to the highest temperature (figure, 3*b*) an increase by 0·06 mm was observed. This corresponded to a mean-square scattering angle of $5 \times 10^{-4} \pm 50\%$. According to equation (4), this angle of scattering would be produced by a plasma of density 5×10^{10} electrons/cm^3. The actual density deduced from the capacity measurements was $1{\cdot}9 \times 10^{10}$ electrons/cm^3, a figure which, as has been pointed out, may be an underestimate by a considerable factor. Thus the observed diffusion must be attributed to electron interaction. Making allowance for the maximum possible errors in the density measurement, and in the measurement of the scattering, it can be concluded that the electron interaction under these conditions does not exceed the value predicted by equation (4) by a factor greater than 5. It is probable that the agreement is in fact much closer.

4. Experiments with a pure electronic space charge

The microfield in an electronic space charge can differ from that in a neutral plasma only to the extent that charges outside the Debye sphere have a significant effect. These charges would not be expected to make a contribution to the scattering comparable with that due to the nearer electrons, unless their action is coherent. As has already been stated, this coherence has been shown to be entirely negligible in

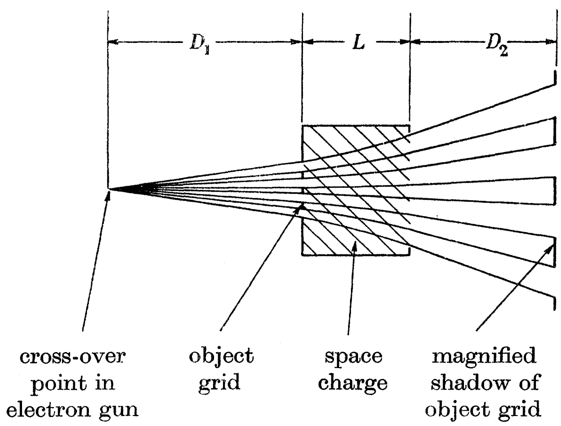

Figure 4. Experiments with an electronic space charge.

this problem. One would therefore expect little difference in the microfield inside a pure electron cloud as compared with that in a plasma. The main reason for undertaking the experiments to be described was to confirm the results obtained for the plasma by an essentially different method, which would allow an accurate determination of the electron density. The experiments were also of interest on account of possible applications for the use of space-charge clouds in electron optics (Gabor 1944).

The chief features of the experimental arrangement are shown in figure 4. The main departure from the previous method is in the absence of a magnetic lens. The beam cross-over is used as a point source to illuminate an object grid placed immediately in front of the space-charge cloud, which acts on the beam as a divergent lens. In this way a magnified shadow of the object grid is obtained on the fluorescent screen. The focal length of this lens as well as the magnification M which it produces can be derived from Poisson's equation and the equation of motion:

$$M = (\cosh PL + PD_2 \sinh PL) + 1/PD_1(\sinh PL + PD_2 \cosh PL), \tag{10}$$

where $$P^2 = \pi\rho/V.$$

M is shown as a function of ρ in figure 5 for the particular geometry used in the experiments. Thus the space-charge density is directly related to the magnification, and can be determined by a simple measurement with a microscope.

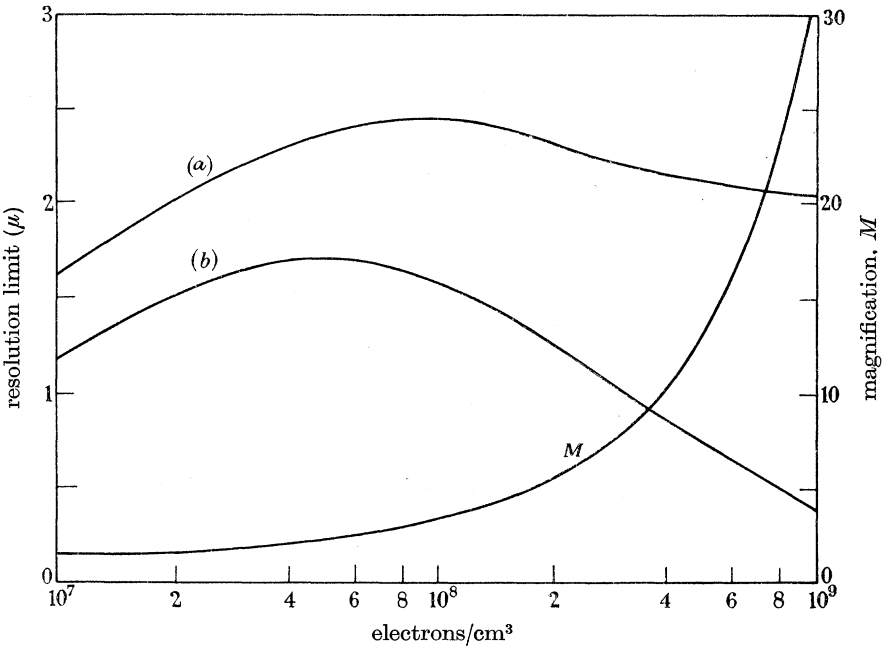

FIGURE 5. Magnification and resolution limit for the geometry used in the interaction experiments.

The effect of the scattering produced by interaction will be to blur the outlines of the shadow of the object grid on the fluorescent screen. The detection limit will depend on the attainable resolution, which is limited by the random thermal velocities in the beam. Equation (6) can be applied to this case, if ϕ is now interpreted as the minimum angular range of the electrons reaching the point where the current density is J. With a gun of the type shown in figure 2, and a beam voltage of 1 kV, it is possible to reduce ϕ to about 10^{-4}. Reference to equation (4) shows that for an electron density of 10^9 electrons/cm³ (which could be achieved in these experiments), theory predicts a mean-square scattering angle of $0{\cdot}8 \times 10^{-4}$. Thus the random motion in the beam has been reduced to a level comparable with the additional disorder which, according to the theory, will be introduced by electron interaction. The scattering formulae are not exactly applicable to the case of a pure electron cloud, as the macroscopic field has a considerable effect on the random velocities introduced into the beam. In order to interpret the scattering observed in such a case, it would be necessary to consider the effect of the microfield and that of the macrofield simultaneously. This becomes clear when one considers that a deflexion suffered by an electron at the beginning of the electron cloud is magnified by the divergent lens action of the remainder of the cloud. To carry out this calculation in detail would be a formidable task, but fortunately it is unnecessary for the degree of accuracy here required. It can be assumed that the effect of the electron interaction on the observed shadow of the object grid will be within the limits of that which would be produced by the scattering assumed concentrated at the beginning of the cloud, and that which would be produced by the same amplitude of scattering concentrated at the end of the cloud. These cases can be calculated without difficulty, and the results have been presented in figure 5. The two cases are compared in terms of the resolution limit referred to the object grid as a function of the electron density. It can be concluded that in these experiments an observed limit of resolution on the screen can be related to the magnitude of the electron interaction with a probable error of $\pm 25\,\%$ due to this cause.

Realization of an electronic space charge

Figure 6*a* shows the essential features of the system for producing the electron cloud. A grid at a positive potential is placed inside and concentric with a hollow cylindrical cathode, so that the electrons are accelerated into the inside of the grid. Positive ions are not emitted, as the grid establishes a positive gradient at the surface of the cathode. The space-charge density obtained on the axis can be calculated from a knowledge of the current crossing the grid, the grid radius r_g, the grid voltage V_g, and the relation of the grid geometry to the grid-cathode spacing. Calculations have shown that this geometrical factor can result in a great variety of space-charge distributions, which can have a maximum or a minimum of density on the axis. For the particular geometry used in the experiment, the distribution was almost constant over the diameter. Calculation shows that in this case the space-charge density is given by

$$\rho = \frac{I_g}{2r_g}\left(\frac{m}{2eV_g}\right)^{\frac{1}{2}}, \tag{11}$$

with I_g the current per unit length crossing the grid from the outside to the inside. This relation is useful for design purposes; it was not required in the experiment, in which the space-charge density was derived directly from the observed magnification (figure 6*b*).

The construction of this device is shown in figure 6*b*. The main practical difficulty was the maintenance of the very close grid-cathode spacing (0·75 mm) necessary for the achievement of sufficiently high electron densities, under conditions when both the cathode and the grid were at a red heat, and subject to large expansions. The cathode (length 30 mm, internal diameter 4·7 mm) is supported inside an accurately machined pyrophyllite housing, which is held in position by two copper-nickel end-plates. The cathode is held rigidly at one end of the housing; at the other end it is centred by three molybdenum springs, welded to a flange on the cathode, which leaves it free to expand in axial direction. The grid (3·2 mm outside diameter) was made by spot-welding nickel gauze (mesh size 0·25 mm) round a copper mandrel. With sufficient care it was found possible to reduce the variation of diameter at the seam to 0·001 in. The transparency of the grid was subsequently increased from 40 to 75 % by electrolytic etching in sulphuric acid. The grid is supported rigidly at one end-plate, and on flexible metal tapes at the other. The whole structure is mounted on machined mica disks, which fit into a precision-bore Pyrex tube. An electron microscope object-supporting grid with a mesh size of 65 μ was used as the shadow-casting object, and was surrounded by a small fluorescent screen to assist in the location of the beam.

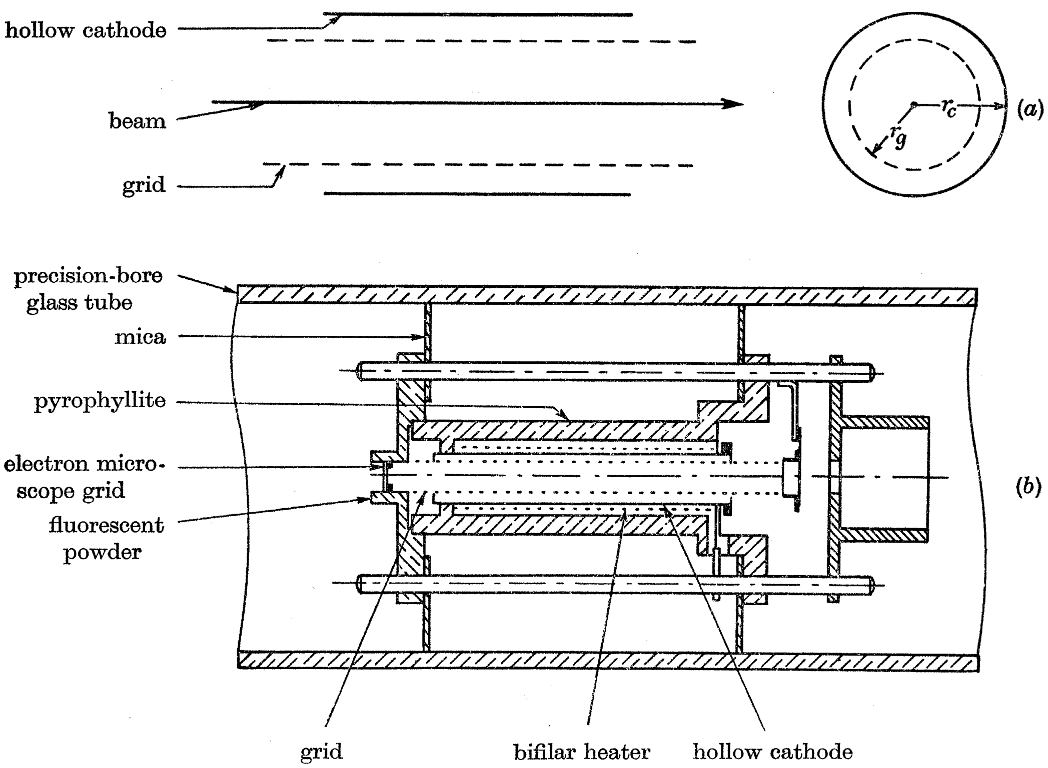

FIGURE 6. (a) Realization of an electronic space charge. (b) Section of interaction chamber used in electron cloud experiments.

Experimental results

Figures 7*a* to *d*, plate 5, show photographs of the shadow of the object grid on the fluorescent screen. (The irregular dark patches are caused by small particles of Willemite, inadvertently placed on the object grid.) Figure 7*a* was taken with zero voltage on the grid (i.e. $\rho = 0$) and the magnification is simply $(1+D_2/D_1)$. Figure 7*b* was obtained with a grid voltage of 4 V, and from the measured magnification the space-charge density is found to be 4×10^8 electrons/cm^3. As V_g was further increased, the magnification decreased, and the shadow was considerably distorted (figure 7*c*). This is attributed to the production of ions inside the grid, by the

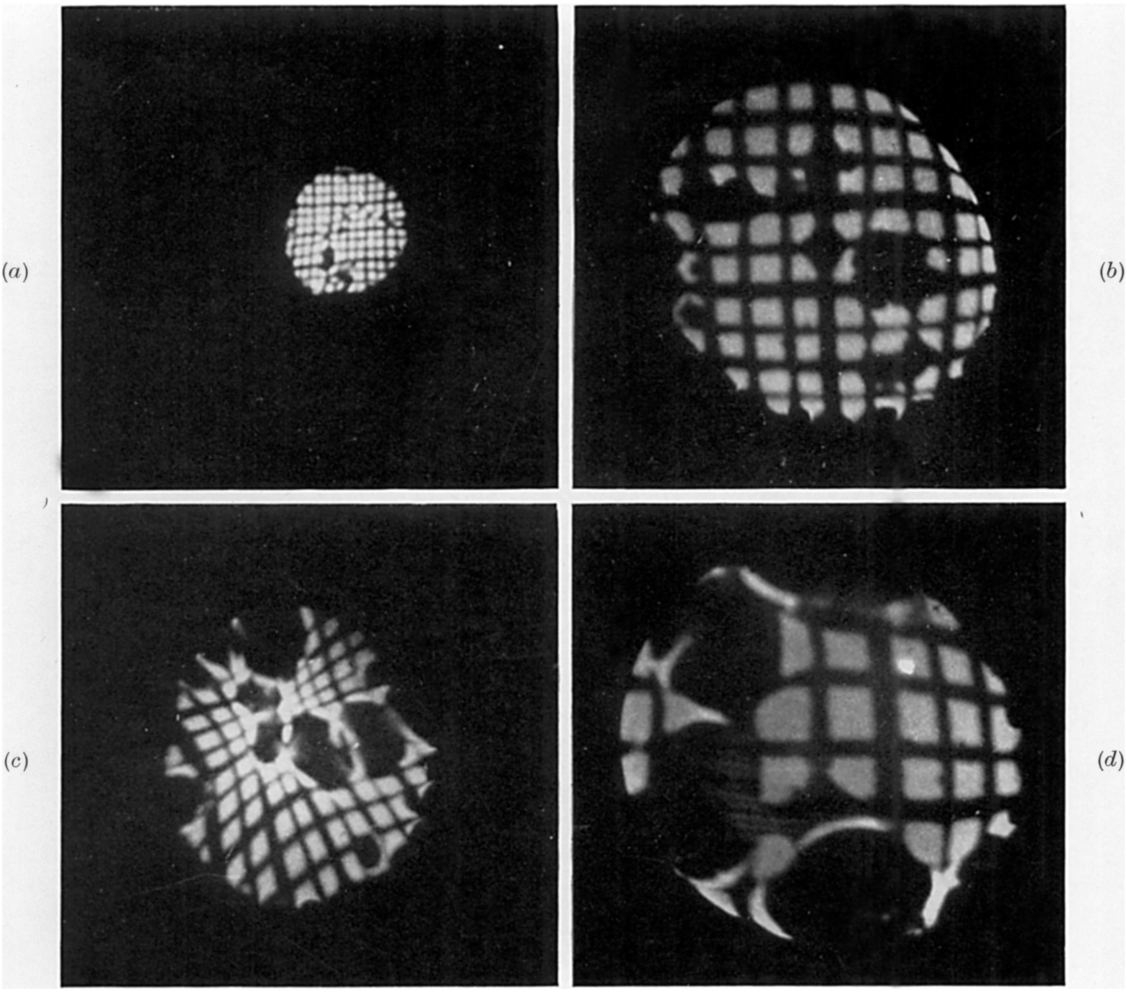

FIGURE 7. Shadow photographs of an electron microscope object grid, 65μ mesh size, through a space-charge lens. (*a*) Zero voltage on grid, zero space charge. (*b*) Grid voltage 4 V., electron density $4 \times 10^8/\text{cm}^3$. (*c*) With further increase of the grid voltage barium atoms evaporated from the cathode are ionized, and the space charge collapses in an irregular manner. (*d*) Barium ions eliminated by periodic sharp negative pulses on grid, electron density about $8 \times 10^8/\text{cm}^3$.

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ionization of barium vapour from the oxide cathode, an effect which was noted in the previous experiments with a neutral plasma. This phenomenon shows in a striking manner how a small rate of ion production is sufficient to neutralize the electron cloud. With careful adjustment of the grid voltage to just above the critical value, the neutralization of the space charge took place so slowly that the decreasing magnification of the shadow on the screen could actually be observed, and took as long as 30 s to reach equilibrium. It was possible to eliminate the disturbance due to the ions by applying a succession of short negative pulses to the grid. During the period when the grid is negative, the ions which have been trapped inside the space charge are free to move in a random manner determined only by their thermal velocities, and will in time be absorbed by the grid. With a pulse width of $50\,\mu$s, and a repetition time of 1 ms, the electron cloud could be kept entirely free from ions (figure 7*d*).

Owing to the need for making the beam current as small as possible, in order to reduce the lateral thermal velocities of the electrons in the beam, the exposure times for these photographs were very long (up to 15 min); although the supplies were stabilized, there was some consequent loss of resolution. The estimates of the highest achieved resolutions are therefore based on visual observations with a measuring microscope. It is a matter of some difficulty to determine the least resolved distance with precision, but small irregularities on the wires of the object grid, about one-tenth of the mesh size ($65\,\mu$), could be distinguished, with a magnification corresponding to a density of 6×10^8 electrons/cm^3. Reference to figure 5 shows that under these conditions, the electron interaction, calculated on the basis of Thomas's results (equation (4)), would limit the resolution to $1{\cdot}5 \pm 0{\cdot}3\,\mu$ corresponding to one-fortieth of the mesh size.

It can be concluded that under the conditions of the experiment, the electron interaction is not more than five times that predicted by equation (4). Thus the conclusions reached in the experiments with a plasma are confirmed, and, by means of an experiment, which although giving a negative result, involves the measurement of positive effects only.

5. Conclusions

The experiments have shown that the electron interaction effect in an equilibrium plasma, and in an electron cloud, does not exceed the value calculated from an exclusive consideration of binary encounters by a factor greater than five. Thus the experiments justify, at least in order of magnitude, the theories based on the summation of the effects of large numbers of binary encounters, and neglecting multiple collisions.

It may be concluded that electron interaction effects are not responsible for the short mean free paths observed in gas discharges, and it is very unlikely that they ever play a significant part in determining the characteristics of devices such as the magnetron. If nevertheless electron interaction should influence the behaviour of some system, the order of magnitude of this influence can be predicted with confidence, by applying the theories based on binary collisions.

This investigation, carried out in the Electrical Engineering Department of the Imperial College, London, formed part of the Ph.D work of one of us (E. A. A.), who is indebted to the Institution of Electrical Engineers for the award of the Oliver Lodge Scholarship (1950 to 1952).

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Surface tension in ionic crystals

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(*Communicated by E. C. Stoner, F.R.S.—Received* 13 *October* 1954)

In communicating this paper Professor Stoner explains that it was found among the manuscripts of the late Dr M. M. Nicolson by his widow, Dr Phyllis Nicolson. The main part of the work on which the paper is based was carried out at the Cavendish Laboratory, University of Cambridge, between 1945 *and* 1948. *The paper was written later, while Dr Nicolson was a member of the staff of the Physics Department of the University of Leeds from* 1948 *until his death in a train accident in December* 1951. *For an obituary notice see* Proc. Phys. Soc. A, **65**, 1065 (1952).

The calculation of surface tensions in crystals of NaCl type is described, with particular reference to the (100) planes. In the cases investigated, the surface tension was greater than the corresponding surface energy by a factor of about 5.

An account is given of experimental work carried out to confirm the presence of these surface forces. The basis of the method used was the measurement of the unit-cell dimensions of small crystals compared with those of normal size. As the particle size is diminished, surface forces of the order of those calculated should cause a gradual change in the unit-cell