Some Contemporary Advances in Physics—VI
Electricity in Gases

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1. INTRODUCTION

THE physicists of a quarter of a century ago, who devoted themselves to the study of electricity in gases, were happily inspired; for among the myriad of intricate and obscure phenomena which they observed there are some few of an extreme simplicity, in which the qualities of the individual atoms of matter and electricity are manifest; in analyzing these they entered upon the path that led most directly to the deeper understanding of nature which is superseding the physics of the nineteenth century, and the physics of today is founded upon their efforts.   The electron was perceived for the first time in the course of observations on the electric discharge in rarefied gases, and other experiments in the same field established the atom in science as a real and definite object.   The discovery of the atom is commonly credited to the chemists; yet fifteen years have not passed since students of chemistry were being warned by a famous teacher that "atom" and "molecule" are figurative words, not on any account to be taken literally!   The laws of chemical combination were held insufficient to prove that atoms have any real existence; though elements may always combine with one another in unchanging proportions, this does not prove anything about the weights of the atoms, or their sizes, or their qualities, or even that all the atoms of an element have the same weight, or even that there are any atoms at all.   Now that we are past the necessity for this caution, and can count atoms, and measure their masses, and infer something about their structure, and estimate how close together they can approach, and know what happens to them when they strike one another or are struck by electrons; now that we can fill in the picture of the atom with so many and so diverse details, we are indebted for this progress chiefly to the men who gathered the data and made the theories concerning the conduction of electricity in gases.   Many will remember how in the years before the great war this field of research seemed the most vital part of physics, the most inspired with a sense of new life and swift advance; now others share with it the centre of the stage, but they won their places chiefly because of the light it shed upon them.

It seems strange that the flow of electricity in gases should have proved easier to interpret than the flow of electricity in metals, which in appearance is certainly by far the simpler.   One applies the terminals

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of a battery to the ends of a wire, and promptly the electric potential distributes itself with a uniform gradient along the wire and a current flows steadily down it. So rigorously is the current proportional to the voltage between the ends of the wire, over very wide ranges of voltage and current, that we regard the ratio as an essential constant of the wire; and we regard the ratio of potential-gradient (electric field) to current density as an essential characteristic of the metal, and give it a name—resistivity or specific resistance—and refer to theories of conduction in metals as theories of metallic resistance. It all seems exceedingly simple, and yet in the foregoing article of this series I have shown how all the attempts to interpret it have gone in vain. Much more complex in appearance is the discharge through a gas. One applies the terminals of a battery to a pair of electrodes facing one another in the open air, and perhaps nothing happens, or so minute a current flows that the most delicate of instruments is demanded to detect it; and then when the battery-voltage is very slightly raised, there may be an explosion with a blaze of light, dissociating the gas and corroding the electrodes, and draining off the available electricity in a moment. Or if one of the electrodes is acutely pointed there may be glows and luminous sheaths around it or tentacles of bluish light ramifying from it far and wide through the air. Or the discharge may rise to the heat of incandescence, and the gas and the electrodes shine with a blinding radiance, the brightest light that can be kindled on the earth. Or if the electrodes are enclosed in a tube containing a rarefied gas or vapor, the gas flares up into an extraordinary pattern of light and shade, lucent vividly-colored clouds floating between regions glowing feebly or obscure; and as the gas is gradually pumped away, the pattern changes and fades, a straight beam of electrons manifests itself by a luminous column traversing the tube, the glass walls flash out in a green fluorescence, and finally all becomes extinct. As for that even gradient, and that constant proportion between current and field strength distinguishing the metals, we cannot find them here. There is no such thing as the resistance of a gas; we had better forget the word, we cannot attach any physical meaning to the ratio of current and voltage.

I must not give the impression that all these manifold forms of the electric discharge in gases are understood. Certain of the simplest of them have been clarified, and as a result still simpler ones have been realized and comprehended in their turns, and so on down to the simplest of all, which is the discharge across a vacuum. This sounds somewhat like a paradox and so it would have seemed thirty or forty years ago, when electricity was thought to be inseparable

from matter, and the only known discharges across gases were the discharges in which the gas plays an indispensable role. It is important to note the manner of this evolution, for much of the history of modern physics is dominated by it. We should not be nearly so far advanced as we are, had we not learned two things: how to reduce the amount of gas in a tube until an electron can fly clear across it with scarcely any chance of meeting an atom, and how to persuade an electron to emerge from a metal otherwise than by starting a discharge in a gas over its surface. We who are so familiar with the idea of electrons boiling out of a hot wire, or driven out of a cold metal plate by light shining upon it, or fired as projectiles out of exploding atoms, find it difficult to imagine the confusion which of necessity prevailed when all these processes were unknown. In the early stages of research into the discharge in gases, it was made clear that of each self-maintaining discharge a stream of electrons flowing out of the negative electrode is an essential part; the electron-stream maintains the gas-discharge, and reciprocally the gas-discharge maintains the electron-stream. The latest stage commenced when it was made possible to produce and maintain such an electron-stream independently of any gas-discharge, and deal with it at will.

Let me then begin the exposition with this idea, which so many years of research were required to render acceptable: the idea of a stream of electrons emerging from a metal wire or a metal plate, at a constant rate which is not influenced by the presence or absence of gas in the space surrounding the metal. The reader may think either of thermionic electrons flowing spontaneously out of a hot wire, or of photo-electrons flying out of a metal plate upon which ultra-violet light is shining.[1]

2. The Flow of Electrons Through a Very Rarefied Monatomic Gas, and Their Encounters with the Atoms

Conceive a source of electrons, a negative electrode or cathode, which is enclosed in a tube. If the tube is highly evacuated, the

[1] While forming one's ideas it is preferable to think of the photoelectric source, for a variety of reasons; the electron-stream is not very dense, the electrons emerge with kinetic energies never in excess of a certain sharply-marked limiting value, the metal is cold and not likely to react chemically with whatever gas surrounds it. Also several of the classical fundamental experiments were performed in the years from 1898 to 1906, when the photoelectric effect had become a reliable instrument of research and the thermionic effect had not. Nowadays it is sometimes used in the hope of surpassing the accuracy of earlier work, or in experiments on compound gases which the hot wire might decompose. Still the hot wire is so much easier to insert and handle, its emission so much more convenient and controllable, that it will no doubt be employed in the great majority of experiments in the future as in the past.

electrons enter the vacuum freely; electricity has no horror of a vacuum, any more than nature generally. Still there is something which suggests the *horror vacui* of the scientists before Galileo; for the electrons which are already partway across the vacuum tend, by their electrostatic repulsion, to push back their followers which are just emerging from the metal. This is the space-charge effect, which has become famous since the audion became almost as common an object as the incandescent lamp in the American home. I shall presently have to write down the equations describing this effect; for the time being we may ignore it, so long as the electron-stream is not more profuse than a photoelectric current generally is. The electrons of these scanty discharges enter into the vacuum and pass over without hindrance.

At this point it is advisable to say what is meant by a "vacuum." Scientists are growing more exigent year by year in their use of this term; thirty or forty years ago people spoke of "vacuum tubes" meaning tubes so full of gas that they would transmit a big current with a resplendent luminous display, but this self-contradicting usage has become quite intolerable. At the present day the least density of gas, or the highest vacuum, commonly attained corresponds to a gas-pressure about 10^{-11} as great as the pressure and density of the atmosphere. This means that there are about 10^{-8} molecules in a cubic centimetre of the "vacuum," which may make the name sound absurd. But the practical criterion for a vacuum is not whether the remaining atoms seem many or few, but whether they are numerous enough to affect the passage of a discharge; and as an electron shooting across a tube 10 cm. wide and evacuated to this degree has 999999 chances out of a million of getting clear across without encountering a molecule, the tube is vacuous enough for any sensible definition.

Next we will imagine that a gas is introduced into the tube, in quantity sufficient so that each electron going from cathode toward anode will collide on the average with one or possibly two atoms on its way. It is best to begin by thinking of one of the noble gases, of which helium, argon and neon are the ones in common use; or of the vapour of a metal, mercury vapour being much the easiest of these to work with; for their atoms behave in a simpler and clearer manner toward the electrons than do the molecules of the commonest gases, particularly the oxygen molecules which are so numerous in air. In fact the practice of using the noble gases and the metal vapours—that is to say, the *monatomic* gases—wherever possible in these researches ought really to be regarded as one of the great advances of the last few years; our predecessors would certainly have learned more about the dis-

charge in gases than they ever did, if they had not studied it in air ninety times out of a hundred, and in other diatomic gases most of the other ten.

Let us suppose that the tube contains helium of the extremely small density I have just defined. Then so long as the kinetic energy of an electron does not exceed 19.75 volts, it will rebound from any helium atom which it strikes, like a very small perfectly elastic ball rebounding from a very large one. We might conceive the contents of the tube (for this purpose and only for this purpose!) as a flock of immense ivory pushballs floating languidly about, with a blizzard of equally elastic golfballs or marbles darting through the interspaces and occasionally striking and bouncing off from one of the pushballs. If the collisions between electrons and atoms are perfectly elastic, as I have said without giving evidence, the electron will lose an extremely small part of its kinetic energy at each collision, owing to the great disparity in masses—a fraction varying from zero up to not more than .000537 depending on the direction of rebound.

This was verified in a pretty experiment by K. T. Compton and J. M. Benade, who utilized a certain effect[2] which electrons produce when they have kinetic energy exceeding 19.75 volts at the moment of a collision with a helium atom. For example, when the pressure of helium was 4.34 mm. and the electrons were drawn from a cathode to an anode 0.265 cm. away, a voltage-difference of 20.25 (plus an unknown correction) was required to produce this effect; when the anode was 0.90 cm. from the cathode the required voltage-difference was 23.45 (plus the same correction). The extra volts were spent in replacing the energy lost by the electrons in the collisions with helium atoms over the extra 6.3 mm.; they amounted to an average of .0003 of the electron's energy lost in each collision, excellently in agreement with the assumption.

Now as for the transit of the electron-stream from cathode to anode, the helium atoms will simply thin it down by intercepting some of the electrons and turning their courses backwards or aside. The greater the number of atoms in the path, the greater the proportion of electrons intercepted; it can easily be seen that, so long as the gas is not denser than I have specified, this proportion increases as an exponential function of the number of atoms between cathode and anode,[3] whether this number be increased by introducing more gas or by moving the anode farther away from the cathode. If

[2] Incipient ionization, as described below.

[3] The proportion increases more slowly when there are already so many atoms between anode and cathode that an electron is likely to strike two or more on its way across.

the anode and the cathode are two parallel plates d centimetres apart, and there are P helium atoms in a cubic centimetre of the gas between, and N_0 electrons start out in a second directly towards the anode from any area of the cathode, the proportion $\Delta N/N_0$ of electrons which are intercepted before they reach the anode is

$$\Delta N/N_0 = 1 - e^{-APd} \tag{1}$$

and the number of electrons reaching the corresponding area on the anode in a second, $N_0 - \Delta N$, conforms to the equation:

$$\log_e (N_0 - \Delta N) = -APd + \text{const.} \tag{2}$$

The coefficient A is a constant to be interpreted as the effective cross-sectional area of the helium atom relatively to an oncoming electron— that is, the atom behaves towards the electron like an obstacle presenting the impenetrable area A to it.

In the experiments performed to verify these assertions and determine the value of A, the simple geometrical arrangement which I have described is generally modified in one way or another for greater accuracy or convenience. Mayer approached most nearly to the simple arrangement; in his apparatus (Fig. 1) the electrons
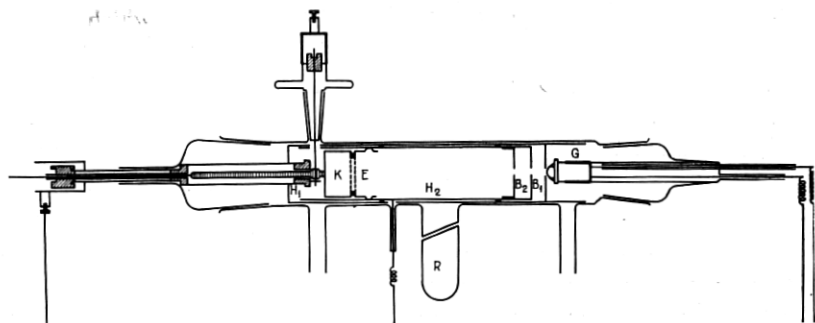

Fig. 1—Apparatus for determining the percentage of electrons which go across a gas of variable thickness without interception.   (Mayer, *Annalen der Physik*)

which emerge from the hot filament at G, pass through the two slits in front of it, and then go down the long tube to the anode K, which is drawn backward step by step.   The logarithmic curves of current versus distance for various pressures of nitrogen (Fig. 2) are straight. Unfortunately the current also diminishes as the distance is increased when the nitrogen is pumped out altogether; this is attributed partly

to residual vapors and partly to the electrons striking the walls of the
tube.   The other curves are corrected for this effect, and then A is
calculated.   For helium it is 25.10^{-16} cm²; the values obtained by
modifications of the method agree well.[4]

The helium atoms therefore behave as so many minute and yet
appreciable obstacles to the passage of the electron-stream, so long
as the electrons are not moving so rapidly that their energies of motion
do not surpass 19.75 volts.   Electrons as slow as these bounce off
from the atoms which they strike.   When, however, an electron pos-
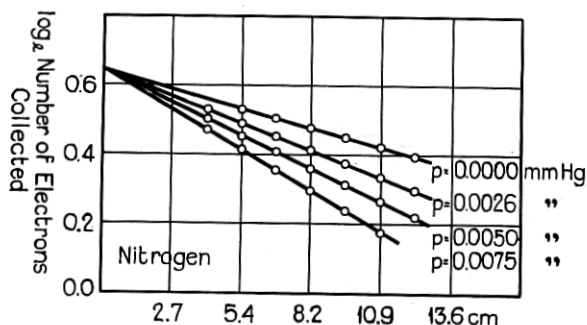sessing kinetic energy greater than 19.75 volts strikes a helium atom,

Fig. 2—Curves illustrating the interception of electrons by nitrogen molecules which
they strike.   (Mayer, *Annalen der Physik*)

it is liable to lose 19.75 volts of its energy to the atom, retaining only
the remainder.   This energy does not become kinetic energy of the
atom, a process which would be incompatible with conservation of
momentum; neither is the atom broken up; it receives the quota of
energy into its internal economy, where some kind of a domestic
change occurs with which we are not concerned for the moment,
except in that it furnishes an exceedingly accurate indirect way of
calculating the exact amount of energy taken from the electron.   The
atom is said to be put into an "excited" or sometimes into a "meta-

[4] The modified methods are generally more accurate.   Ramsauer's device, which
I described in the first article of this series, is probably the best.   By a magnetic
field he swung a stream of electrons around through a narrow curving channel, and
those which were deviated even through a few degrees struck the limiting partitions
and were lost from the beam; he varied the number of atoms in the channel by
varying the gas-pressure.   In this way he discovered that A for argon atoms differs
very greatly for different speeds of the electrons; it was later found that other kinds
of atoms have a variable A, although happily the variations are not great.   This
seems strange at first,[1] but it is probably stranger that A should have nearly the same
value for different speeds of the oncoming electrons, as for many atoms it does; and
stranger yet that it should have the same value for an oncoming atom as for an
oncoming electron, as is often tacitly assumed, and not too incorrectly.

stable" state, and the energy which it takes up, measured in volts, is called its *resonance-potential*. The electron is left with only the difference between its initial energy and the 19.75 volts which it surrendered.

This loss of energy in a so-called "inelastic" collision can be dem-
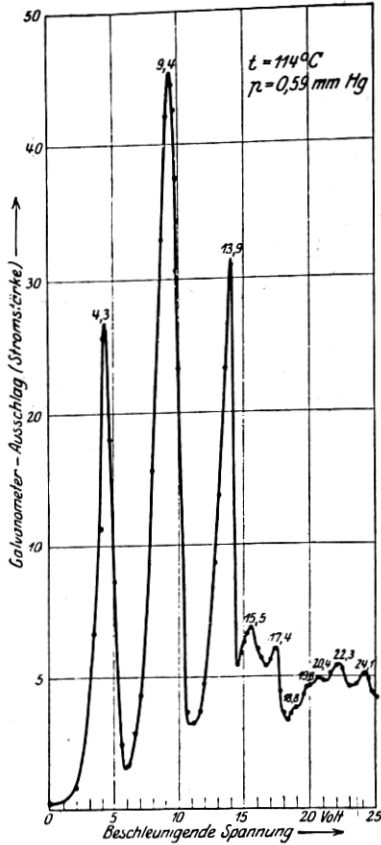

Fig. 3—Curve displaying resonance-potentials of mercury.
(Einsporn, *ZS. f. Physik*)

onstrated by inserting a third electrode into the path of the electrons, charged negatively to just such a degree that an electron retaining its full initial speed can overcome the repulsion of the electrode and win through to it, while an electron which has lost a quantity of its kinetic energy in an inelastic collision cannot quite "make the grade." When the energy of the electrons streaming into the helium

is raised just past 19.75 volts there is a sudden falling-off in the number of electrons arriving at the third electrode. The curve in Fig. 3, obtained by Einsporn, shows the current into such an electrode in mercury-vapor rising and falling again and again as the voltage passes through the values which are integer multiples of 4.9 volts, the least resonance-potential of mercury. Helium has a second resonance-potential, at 20.45 volts; neon has two, at 16.65 and 18.45 volts respectively; argon three, at 11.55, 13.0 and 14.0 volts;[5] mercury two, at 4.9 and 6.7 volts. It is almost certain that in each case these are only the most conspicuous among many, but the lowest mentioned is the lowest of all.

Up to this point we find the gas acting as a mere inert obstruction to the discharge; every collision of an electron with an atom interrupts the progress of the electron toward the anode and to that extent impedes the discharge. Past the resonance-potential the same action continues, although the interruption is doubtless less severe when the electron is deprived of part of its energy of forward motion than when it is flung backward with its motion reversed in direction and its energy intact. At the resonance-potential, the gas does begin to assist the discharge in an indirect way. Atoms which are put into an "excited state" by a blow from an electron revert of themselves to the normal state, some time later; in so doing they emit radiation, some of which falls upon the cathode; some of this is absorbed in the cathode metal, and expels electrons which go along with the maintained electron-stream as extra members of it. Thus the gas helps in increasing and maintaining the discharge; this effect is of great theoretical importance, and I will return to it later; but in these actual circumstances it is not very prominent.

The really powerful cooperation of the gas in the discharge commences when the electrons are given so great an energy that they disrupt the atoms which they strike, tearing off an electron from each and leaving a positively-charged residue, an *ion* which wanders back towards the cathode while the newly-freed electron and its liberator go on ahead towards the anode. The onset of this ionization may be detected by inserting a third electrode into the gas, it being charged negatively to such a degree that no electrons can reach it, but only positive ions; or by the increase in the current between cathode and anode, for the current increases very suddenly and very rapidly when the energy of the primary electrons is raised past the threshold-value, the *ionizing-potential* of the gas; 24.5 volts for helium, 21.5 for neon, 15.3 for argon, 10.4 for mercury. Consider for example the

[5] I take the values for neon and argon from Hertz' latest publication.

precipitate upward rush of the current-voltage curve in Fig. 4, from the work of Davis and Goucher.[6]

At this point I will digress to speak very briefly of the succession of events which occurs when the electron-stream is much denser than
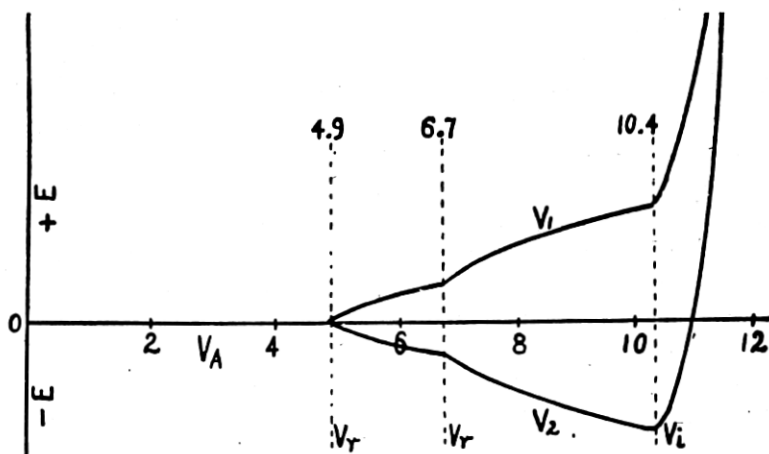

Fig. 4—Onset of ionization in mercury vapor at 10.4 volts (preceded by subsidiary effects at 4.9 volts and 6.7 volts; see footnote[6]).   (Davis and Goucher)

we have hitherto imagined.   So long as the energy of the electrons does not attain the resonance-potential of the gas, there is no reason to expect any novel effects; the collisions will be perfectly elastic, just as when the electrons were few.   But when the atoms are thrown into the "excited state" by impacts, there will be occasional cases of an atom being struck twice by electrons in such quick succession that at the moment of the second blow, it is still in the excited state provoked by the first.   Now, much less energy is required to ionize an atom when it is in the excited state than when it is normal; consequently when the electrons are so abundant that these pairs of

[6] The sudden upturn at 10.4 volts is the swift rise of current at the onset of ionization.   The much less violent upturns at 4.9 and 6.7 volts are due to the electrons expelled from the metal parts of the apparatus by the radiation from the excited atoms.   In the lower curve, by modifying the apparatus, the latter upturns are translated into downturns to distinguish them from the upturn which denotes ionization.   This distinction was not realized until 1917, and in articles published between 1913 and 1917 the lowest resonance-potentials of gases are given as their ionizing potentials.   Enormous improvements in the methods and technique of measuring these critical potentials, and recognizing of which kind they are, have been effected since then.

nearly-simultaneous collisions happen often, ionization will begin at the resonance-potential. *In a profuse electron-stream, the threshold potential for ionization is the lowest resonance-potential.* Another feature of the profuse discharge is, that when ionization does commence the current leaps up much more suddenly and violently than it does in the scanty discharge. This is because the electron-current is depressed at first by the space-charge effect, the repellence which the electrons crossing the gap exert against the electrons which are on the verge of starting; when positive ions first appear in the gap, they cancel the action of a great number of the traversing electrons, and the flow of electrons from the cathode to anode is immensely increased. I shall speak of this more extensively further on.

We return to the case of the feeble electron-stream. We have considered various things which an electron may do to a helium atom which it strikes—bouncing off harmlessly, or putting the atom into an excited state, or ionizing it; we have mentioned that each of the two latter actions commences at a critical value of energy, at the so-called *resonance* or *ionizing* potential, respectively; we have considered the effect of each of these actions upon the discharge. Have we listed all the possible interactions between atoms of matter and atoms of electricity, when electrons flow across helium? and if we knew all the resonance potentials and all the ionizing potentials [7] of helium, could we predict all the features of all electrical discharges in pure helium, whether in rarefied gas or in dense, whether the electron-stream be scanty or profuse? This is the general belief; whether justified, it is impossible to say. We evidently need another Maxwell or another Boltzmann, somebody exceedingly skilful in statistical reasoning, able to take the information we can provide about the possibility or the probability of various kinds of impacts, and deduce the state of affairs in the mixture of atoms, ions and electrons without getting hopelessly entangled in the frightful maze of equations into which his very first steps would certainly lead him. While awaiting him we have to content ourselves with our successes in interpreting the flow of electrons through very rarefied helium and the other noble gases and the metal vapors; and as for the discharges in denser gases

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[7] I have simplified this passage somewhat so as not to retard the exposition. We know that an electron may "excite" a helium atom if its energy exceeds 19.75 volts, but this does not prove that it *must* do so; it is more reasonable to suppose that it has a certain chance of exciting the atom, zero when its energy is less than 19.75 volts, but greater than zero, and a certain function of its energy, when the latter exceeds 19.75 volts. We should know these functions for all the resonance-potentials and for the ionizing-potential; independent experiments to determine them have been performed, and no doubt will be multiplied.

we have to take the experimental data as we find them, and analyze them as best we may, not with too great an expectation of penetrating to the properties of the ultimate atoms; and yet, as we shall see, the analysis does in certain cases penetrate unexpectedly far.

3. THE FLOW OF ELECTRONS ACROSS DENSE AIR, NITROGEN, HYDROGEN AND SIMILAR GASES

The celebrated series of researches by Professor Townsend of Oxford and by his pupils, commenced in 1902 and continuing through the present, relate chiefly to such gases as hydrogen, nitrogen, oxygen and the familiar mixture of the last two which we breathe; and chiefly to these gases at densities much greater than we have hitherto considered—densities corresponding to such pressures as a thousandth or a hundredth of an atmosphere, therefore so great that an electron crossing over from a cathode to an anode a few centimetres away must collide with scores or hundreds of atoms. If a stream of electrons is poured into perfectly pure helium of such a density, we must not look for a sudden onset of ionization when the voltage between cathode and anode is raised just past 24.5, for the reason illustrated by those experiments of Compton and Benade—the electrons lose energy in all of their collisions, even the elastic ones, and arrive at the anode not with the full energy corresponding to its potential but with this energy diminished by what they lost on the way. In the familiar diatomic gases, the electrons lose much more energy in their ordinary collisions. I did not speak of these gases in the foregoing section, because experiments of the very same type as those which show the sharp distinction between elastic impacts and inelastic impacts in the noble gases and give the sharply-defined values of the resonance-potentials of these gases, yield comparatively vague and ill-defined data, when they are performed on hydrogen or air. In these gases, above all in active gases like oxygen or iodine, it is unlikely that any of the impacts, whether the electrons be moving rapidly or slowly, are truly elastic.[8]

[8] However, Foote and Mohler have obtained quite undeniable evidence of critical potentials, at which the loss of energy by the impinging electron is much greater than it is just below these potentials. The electron can transfer energy to (and receive energy from) a molecule in more different ways than to (from) an atom; such as by setting the molecule into rotation, or putting its constituent atoms into vibration relatively to one another. There is also the mysterious fact of "electron affinity"—an electron may adhere firmly to a non-ionized molecule. Numerous measurements of the rate at which electrons progress through a gas (a field of research which I have not space to consider here) indicate that at field strengths such as prevail in these experiments, adhesion of electrons to molecules is rare and transient.

Now if an electron on its way through the electric field from cathode to anode strikes atoms so often that it rarely has a chance to acquire more than say half a volt of energy from the field between one impact and the next, and if in each impact it loses most of the energy it has just acquired—if this condition prevails, we need not wonder that the voltage between the electrodes must be raised far beyond the ionizing-potential of the gas before there is the least sign of intensification of current.

In interpreting the experiments upon such gases and at such pressures as these last, it has been customary to make a more drastic assumption, the opposite extreme from the one which justified itself in dealing with rarefied helium; it is assumed that the electron surrenders at every impact all the energy which it has derived from the field since its last preceding impact. One may be inclined to make mental reservations in accepting so extreme an assumption, and it could almost certainly be advantageously modified; but as a tentative assumption it is successful enough to be legitimate. If it is true the electron can never build up a capital of energy step by step along its path; the only chances it will have to ionize will come at the ends of unusually long free flights.

Let us imagine a specific case *pour fixer les idées*: supposing the anode and the cathode to be parallel plates d apart, and representing the potential-difference between them by V and the field strength between them by X $(X = V/d)$, we will set $d = 6$ cm., $V = 300$ volts, $X = 50$ volts/cm.; we will imagine that the interspace is filled with a gas having an ionizing-potential equal to 15 volts, and so dense that the average free path of an electron between collisions is one millimetre. I say that the *average* free path is 1 mm. long; if all the sixty free paths which the electron traverses in going from cathode to anode were equal, it would never acquire more than 5 volts of energy, and could never ionize an atom; but owing to the statistical distribution of free paths about the mean value, there will be a certain number out of the sixty which will be longer than three millimetres, and long enough, therefore, for the electron to acquire the 15 volts of energy which are necessary to ionize. In this case there will be $60/\epsilon^2$, about eight, of these long free paths. In each centimetre there will be $10/\epsilon^2$ of them. I will use the letter α' to designate this latter number, which is the number of atoms struck by the electron in each centimetre of its path, at moments at which it has energy enough to ionize an atom; α' is therefore the *number of chances to ionize* which the electron has *per centimetre*. The formula for α' is:

$$\alpha' = \frac{1}{\lambda}\epsilon^{-V_0/X\lambda} = C\epsilon^{-CV_0/X} = Bp\epsilon^{-BpV_0/X}, \tag{3}$$

in which V_0 represents the ionizing-potential of the gas; λ represents the mean free path of the electron; C, its reciprocal, is the number of collisions suffered by the electron in each centimetre of the path; and, since C is proportional to the pressure of the gas, it is replaced by Bp in the final formulation.[9]

It is already clear that the new assumption leads to a theory which requires a different language and a different set of ideas from those of the foregoing section. Not the ionizing-potential, but the number of ionizations performed by an electron in a centimetre of its path, is the quantity to be measured by experimental devices; not the voltage between the electrodes, but the field strength in the gas, is the factor which controls the phenomena.[10] In dealing with gases which are expected to conform to the theory, the appropriate procedure is to measure the number of molecules which an electron ionizes in a centimetre of its path, for all practical values of the field strength X and the density of the gas (or its pressure p) as independent variables. I will designate this number, following the usual practice, by α; if the theory is true it cannot be greater than α', it may be less. These quantities α and α' are statistical quantities, not like the ionizing-potential qualities of the individual atom or molecule, and this is a misfortune and disadvantage of the theory and of the experiments which it interprets; we are not, so to speak, in the presence of the ultimate atoms as before, we are one step removed from them, and this step a difficult one to take.

The measurement of α is effected by varying the distance d between anode and cathode, and determining the current as function of d. If N_0 electrons flow out of the cathode in a second, the ionization commences at the distance $d_0 = V/X$ from the cathode, and from that

[9] Since the number of free paths, out of a total number N_0, which exceed L in length is equal to $N_0 \exp(-L/\lambda)$; and since the potential-difference between the beginning and the end of the path of length L, if parallel to the field, is XL. It may be objected that the electrons bounce in all directions from their impacts, while the language of this paragraph implies that they are always moving exactly in the direction of the field. The rebuttal is, that if they do lose almost all of their energy in an impact, or all but an amount not much greater than the mean speed of thermal agitation, they will soon be swerved around completely into the direction of the field no matter in what direction they start out.

[10] The ionizing-potential determines the distance from the cathode at which ionization commences; this is equal to $d_0 = V_0/X$, and within this distance from the cathode there is no ionization and the theory does not apply; beyond this distance the ionization is controlled entirely by the field strength and by the number of inflowing electrons and the voltage between cathode and anode affects it only insofar as it affects these.

point onward the electron-stream increases exponentially, so that the current Ne arriving at the anode is

$$Ne = N_0 e \exp \alpha \, (d - d_0) \tag{4}$$

In Townsend's experiments the cathode was a zinc plate, the anode a film of silver spread upon a quartz plate; through little windows in the silver film a beam of ultraviolet light entered in from behind, crossed over the interspace and fell normally upon the zinc plate, and drove electrons out of it. The zinc plate was raised and lowered by a screw; the voltage-difference between it and the silver film was altered *pari passu* so that the field strength in the gas remained always the same. The current rose exponentially as the distance between the plates was increased, and thus α was determined. A typical set of data (relating to air at 4 mm. pressure, with a field strength of 700 volts/cm.) is plotted logarithmically in Fig. 5, the logarithm of the current as ordinate and the distance from anode to cathode as abscissa. The first few points lie close to a straight line, corresponding to an exponential curve such as equation (4) requires; the value deduced for α is 8.16. (The distance d_0 is about .35 mm. and has been ignored.) Of the divergence of the later points from the straight line I will speak further on.

Such an experiment shows that there *is* an α—that the theory is not at any rate in discord with the first obvious physical facts—and it gives the value of α for the existing values of X and p. Townsend performed many such measurements with different field strangths and different pressures, and so accumulated a large experimental material for determining α as function of the two variables p and X. To interpret these we will begin by making the tentative and temporary assumption that whenever a molecule is struck by an electron having energy enough to ionize it, it *is* ionized—that is, $\alpha' = \alpha$. Rewriting the equation (3) which expresses α' as function of p and X, we see that

$$\alpha'/p = B \exp \, (-B V_0 p / X) = f \, (X/p). \tag{5}$$

Therefore, if $\alpha' = \alpha$, the quotient of α by p is a function of X and p only in the combination X/p; or, whenever the pressure and the field strength are varied in the same proportion, the number of molecules ionized by an electron in a centimetre of its path varies proportionally with the pressure. I leave it to the reader to invent other ways of expressing (5) in words which illuminate various aspects of its physical meaning.
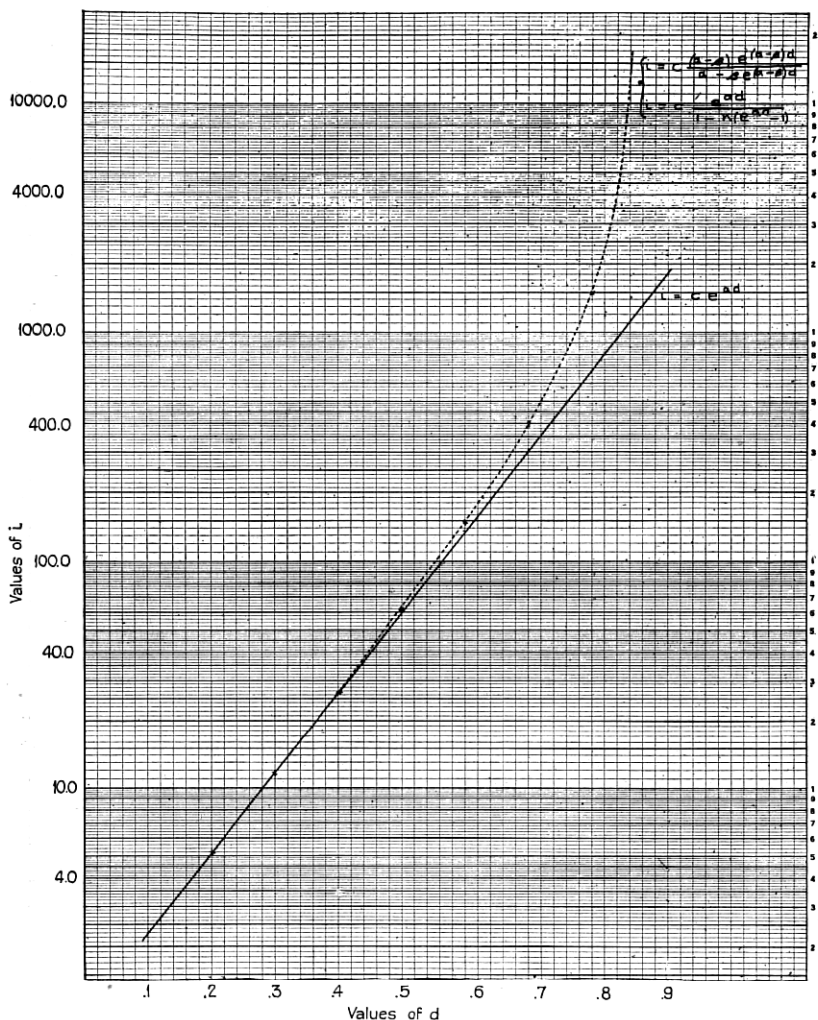
Fig. 5—Logarithmic plot of the currents across a gas (air) in which ionization by collision is occurring, for a constant field strength and various thicknesses of gas
(Data from Townsend)

Experimentally, the test of (5) is made by dividing each one of Townsend's values of α by the pressure at which it was determined, and then plotting all these values of α/p versus the corresponding values of X/p. All the points for any one gas should lie on or close to a single curve, and within certain ranges of pressure and field strength they do; so far, good. The curve should be an exponential

one, and within certain ranges of field strength and pressure it is; again, good. The next step is to calculate the values of B and V_0 which the curve imposes on the gas to which it relates. I quote the values of V_0, the ionizing-potential, which Townsend presents:

Air	N_2	H_2	CO_2	HCl	H_2O	A	He
25	27.6	26	23.3	16.5	22.4	17.3	12.3

When the first of these values were determined, no more direct way of measuring ionizing-potentials was known. Now that we have some values obtained by the direct methods sketched a few pages back, and fortified by indirect but very forcible evidence from spectroscopy, it is possible and quite important to test some of these. The values for argon and helium, although of the proper order of magnitude, are certainly too low. This is not in the least surprising, considering how many of the collisions between electrons and atoms must be perfectly elastic. It seems indeed rather mysterious that the current-voltage relation in either of these gases should have conformed closely enough to (4) to make it possible to define and measure α; but the electrons no doubt entered into many of the collisions with energy enough to put the atoms into excited states, if not to ionize them; and it is nearly always possible to take refuge in the assertion that the impurities may have been sufficient to distort the phenomena. As for the other gases in the list, all of them diatomic or triatomic, Townsend's values are too high—not very much too high, however; usually a matter of one-third to two-thirds.[11]

It appears therefore that the theory I have just developed is too simple, and must be amended. It seems natural to begin by dropping the tentative assumption that a molecule is ionized whenever it is hit by an electron having as much or more energy than is required to ionize it, and adopt instead the idea once already suggested in these pages, that it is sometimes but not always ionized by such a blow; that there is a certain *probability* of ionization by a blow from an electron having energy U, a probability which is zero when $U < V$ and is some yet-to-be-determined function of U when $U > V$. This would leave intact the conclusion that α/p should be a function of X/p, a conclusion which we have already found to be verified by experiment; but it would relieve us of the necessity of assuming that

[11] Townsend's values of B likewise correspond to values of the effective cross-section of the molecule, the quantity A of equation (2), which are of the same order of magnitude as the directly determined values of A.

that function is precisely the exponential function appearing in (5). Essentially the theory is reduced to this postulate: the number of molecules ionized by an electron in a centimetre of its path depends only upon the energy it acquires from the field in its free flight from one collision to the next. If in this form the theory still cannot give satisfaction, the next step will be to alter the original assumption that the electron comes practically to a dead stop in every collision. In dealing with the noble gases and the metal vapours, the facts about elastic collisions which I have already outlined prove that this assumption should not be made at all. It is clear that this is another problem for the future Boltzmann!

Meanwhile, one of the cardinal features of the Townsend experiments is the fact that they display the gradual advent of the transformation of the maintained currents which we have hitherto considered, into the self-maintaining discharges which are the familiar and the spectacular ones; and we now have to examine the agencies of this transformation.

4. THE DISCHARGE BEGINS TO CONTRIBUTE TO THE ELECTRON-STREAM WHICH MAINTAINS IT

Greatly though the current of primary electrons from the cathode to the anode may be amplified by the repeated ionizations which I have described, there is nothing in this process which suggests how the discharge may eventually be transformed into a self-maintaining one like the glow or the arc. The free electrons may ionize ever so abundantly, but as soon as the supply from the cathode is suspended by cutting off the heat or the light, the last electrons to be emitted will migrate off towards the anode, and whatever electrons they liberate will go along with them, leaving a stratum of gas devoid of electrons in their wake; and this stratum will widen outwards and keep on widening until it reaches the anode, and then the discharge will be ended. Something further must happen continually in the gas through which the electrons are flowing, something which continually supplies new free electrons to replace, not merely to supplement, the old ones which are absorbed into the anode and vanish from the scene.

We have already noticed one sort of event continually happening in such a gas as helium traversed by not-too-slow electrons, which might conceivably develop into a mechanism for maintaining the discharge; for, when an atom of the gas is put into the "excited state" by a blow from an electron, it later returns into its normal state, and

in so returning it emits a quantum of radiant energy which may strike the cathode, and be absorbed by it, and cause another electron to leap out of the cathode and follow the first one. There are two other conceivable processes, which have the merit that they can not only be conceived but also witnessed in operation by themselves when the right conditions are provided. Positive ions flung violently against a metal plate drive electrons out of it, as can be shown by putting a positively-charged collector near the bombarded plate and noticing the current of negative charge which flows into it; and positive ions flowing rapidly across a gas ionize some of the atoms in it, as may be shown by sending a beam of such ions across the interspace between two metal plates, with a gentle crosswise field between them which sucks the freed electrons into the positive plate. The mechanism of the first process is not understood, except when the positive ions are so many and so swift that they make the metal hot enough to emit thermionic electrons, which does not happen in the cases we are now considering. The mechanism of the second process is only dimly understood, but it is clear enough that a positive ion driven against an atom is much less likely to ionize it, than an electron of equal energy would be.[12] Either of these two processes is very inefficient, at least at the comparatively low speeds with which positive ions move under the circumstances of these experiments; but they are probably efficient enough to do what is required of them. No doubt all three of them contribute to the discharge; but the relative proportions in which they act certainly differ very much from one sort of discharge to another, and will furnish research problems for years to come.

Returning to Fig. 5, we note once more that as the electrodes are moved farther and farther apart while the density of the gas and the field strength are held constant, the current at first rises exponentially (linearly in the logarithmic plot) as it should if the free electrons and only the free electrons ionize; but eventually it rises more rapidly and seems to be headed for an uncontrollable upward sweep. Townsend attributed this uprush to the tardy but potent participation of the positive ions, either ionizing the molecules of the gas by impact after the fashion of the negative ions, or driving electrons out of the cathode when they strike it, or both. Either assumption leads to

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[12] If momentum is conserved in the impact between ion and atom, the ion must retain a large part of its kinetic energy after the collision, or else the struck atom must take a large part of it as kinetic energy of its own motion; it is not possible for the striking particle to spend nearly its entire energy merely in liberating an electron from the struck one. Conservation of momentum perhaps does not prevail on the atomic scale; but of all the principles of classical dynamics, it is the one which the reformers of physics most hesitate to lay violent hands upon.

an equation expressing the data equally well. If we adopt the former, and designate by β the number of molecules ionized by a positive ion in a centimetre of its path, and by N_0 the number of electrons supplied per second at the cathode, we get

$$N = \frac{N_0(\alpha - \beta)e^{(\alpha - \beta)d}}{\alpha - \beta e^{(\alpha - \beta)d}}. \tag{6}$$

Of course, β must be much smaller than α, or the positive ions would have made themselves felt earlier. Or if we adopt the latter idea, and designate by k the number of electrons expelled from the cathode (on the average) by each positive ion striking it, we arrive at the formula

$$N = \frac{N_0 e^{\alpha d}}{1 - k(e^{\alpha d} - 1)}. \tag{7}$$

Naturally k must be much smaller than unity for the same reason. In Fig. 5 the broken curve represents (6), with the values 8.16 and .0067 assigned to α and β; it also represents (7), with the values 8.16 and .00082 assigned to α and k.[13] (It was expected that the curves representing the two equations would be perceptibly apart on the scale of Fig. 5; but they were found to fall indistinguishably together.)

Evidently, therefore, the positive ions, weak and lethargic as they are in liberating electrons (one has only to compare β with α, or look at the value assigned to k in the last sentence!), can produce a notable addition to the current when the electrodes are far enough apart; and more than a notable addition, for when the distance d is raised to the value which makes the denominator of (6)—or of (7), whichever equation we are using—equal to zero, the value of N is infinite! Per-

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[13] The derivations of (6) and (7) are as follows. Represent by $M(x)$ the number of electrons crossing the plane at x in unit time (the cathode being at $x = o$ and the anode at $x = d$); by $P(x)$ the number of positive ions crossing the plane at x in unit time; by N_9, the number of electrons *independently* supplied at the cathode per unit time, which is not necessarily equal to the value of M at $x = o$ (hence the notation); by i the current, or rather the current-density, as all these reasonings refer to a current-flow across unit area. We have

$$Me + Pe = i, \text{ hence}$$

making the assumption which leads to (6) we have

$$dM/dx = aM + \beta P = (a - \beta)M + \beta i/e$$

The boundary conditions are: $M = N_0$ at $x = o$ and $M = i/e$ at $x = d$. Integrating the equation and inserting these we get (6). Making the assumption which leads to (7) we have

$$dM/dx = aM$$

The boundary conditions are: $M = N_0 + k(i/e - M)$ or $(1 + k)M = N_0 + ki/e$ at $x = o$, and $M = i/e$ at $x = d$. Integrating the equation and inserting these we arrive at (7).

haps the best way to conceive of this is, that as the distance between the plates is increased toward that critical value of d, the value of N_0—which is the rate at which we have to supply electrons at the cathode, in order to keep a preassigned current flowing—diminishes continuously and approaches zero; so that eventually the current will keep itself going (and actually start itself) with the assistance of the occasional ions which are always appearing spontaneously in every gas, even though it be encased in an armor-plated shield. Of course, it is rather risky to predict just what is going to happen, when an equation which has been fixed up to represent a finite physical phenomenon over a certain range exhibits an infinite discontinuity at a point outside of that range. Usually, of course, the infinite value which the equation requires is modified into a finite one by the influence of some factor which was neglected when the equation was devised. In this case, however, the infinite discontinuity corresponds to a sudden catastrophic change. If an electrometer is shunted across the interspace between anode and cathode, its needle is forcibly jerked; if a telephone-receiver is connected in series with the interspace, it makes a clicking or a banging sound; if the gap is wide, so that the voltage just before the disruption is high, there is a brilliant flash, which may bear an uncomfortably strong resemblance to the lightning-bolt which is the cosmical prototype of all electric sparks.

What goes on after the critical moment of transition or transformation depends on many things; and not only on obvious features of the spark-gap, such as the kind and density of gas and the shape and size and material of the electrodes, but also on such things as the resistances and the inductances in series with the discharge, and the qualities of the source of electromotive force and its ability to satisfy the demands for current and voltage which the new discharge may make. Sometimes these demands are too extravagant for most laboratory sources or perhaps for any source to meet; probably this is why the spark between extended plane surfaces in dense air is as ephemeral as it is violent. But this does not always happen; in a sufficiently rarefied gas, the self-maintaining discharge which sets in after the transformation requires only a modest current and a practicable voltage, and supports itself with a few thousand volts applied across its terminals. The same thing occurs in a dense gas, if either of the electrodes is pointed or sharply curved, like a needle or a wire; the condition, more exactly, is that the radius of curvature of either electrode should be distinctly less than the least distance between the two. The transformation, however, is always very sudden, whether the new discharge be transient or permanent; and there are also sudden transi-

tions from one sort of self-maintaining discharge to another, *e.g.*, from glow to arc or from one kind of glow to another when certain critical conditions are transgressed (critical conditions which may themselves depend on the battery and the circuit as well as the con- stants of the spark-gap). There are discontinuities of current and discontinuities of voltage at these transitions, and abrupt changes in the visible appearance in the discharge; and at each transforma- tion there is a rearrangement of the distribution of space-charge in the gas. Hitherto we have encountered space-charge only in one or two of its simplest manifestations, retarding the flow of an electron- stream across a vacuum, and suddenly annulled when positive ions are mingled with the stream. Now we have to consider much subtler and more complicated cases, in which the space-charge varies rapidly in density and even in sign from one part of the gas to another, and the field and potential distributions are utterly distorted by it; and these distortions are essential to the life of the discharge. This distribution of space-charge is indeed dominant; and so I will write down some formulae which may be used to describe it.

5. DIGRESSION TO WRITE DOWN SOME SPACE-CHARGE EQUATIONS

The fundamental equation of the electrostatic field, known as Poisson's equation, is

$$\nabla^2 V = \frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} + \frac{d^2V}{dz^2} = -4\pi\rho \tag{8}$$

in which V represents the electrostatic potential, and ρ the volume- density of electric charge.

We consider only the mathematically simplest case in which all variables are constant over each plane perpendicular to the x-axis, and so depend only on the coordinate x; as for example near the middle of an exceedingly wide tube with the x-axis lying along its axis. In this case Poisson's equation is

$$\frac{d^2V}{dx^2} = \frac{dX}{dx} = -4\pi\rho \tag{9}$$

in which X represents the potential-gradient, or field strength with sign reversed.[14] The value of X is determined at all points when the

[14] Field-gradient is therefore, proportional to space-charge with sign reversed, and *vice versa*. Positive field-gradient implies negative space-charge; negative field-

value of X at any one point and the values of ρ at all intermediate points are preassigned.   Thus let X_0 represent the preassigned value of X at $x=0$, and X_d represent the value of X at $x=d$; we have

$$X_d = -4\pi \int_0^d \rho\, dx + X_0. \tag{10}$$

Consequently the P.D. between any two points is also determined; that between $x=0$ and $x=d$ is

$$V_d - V_0 = -4\pi \int_0^d dx \int_0^x \rho\, dx + X_0 d. \tag{11}$$

Now we introduce the further assumption that the electric charge is concentrated upon corpuscles (electrons or charged atoms) of one kind, of equal charge E and mass m, of which there are ndv in a very small volume dv at x; n is a function of x.   Then

$$nE = \rho. \tag{12}$$

Assume finally that the corpuscles are moving with speed u, identical for all corpuscles having the same x-coordinate, but depending on x; represent the current-density by i; we have

$$nEu = i \tag{13}$$

and consequently

$$\rho = i/u. \tag{14}$$

Now consider the flow of current between two parallel planes, from one electrode at $x=0$ to the other at $x=d$.   If the current is borne by corpuscles of one kind, and the assumption last made is true; and if we know the speed of the corpuscles at every point between the plates, and the field strength at some one point; then we can calculate the field strength everywhere between the plates, and the potential-difference between them.

The customary convention about the field strength is to assume it to be zero at the electrode from which the corpuscles start, so that $X_0 = 0$ in (11).   Rewriting (11) to take account of (14), we have

$$V_d - V_0 = -4\pi i \int_0^d dx \int_0^x dx/u \tag{15}$$

as the general equation.

gradient implies positive space-charge; uniform field implies zero space-charge. It is instructive to examine mappings of field-distribution with this principle in mind; such mappings, for example, as those in Fig. 9.   The uniform field in a current-carrying wire means that positive and negative charges are distributed everywhere in the metal with equal density—a conclusion one might forget, but for these more general cases.

If we suppose that the corpuscles acquire their speed u at the distance x in free flight from the electrode where they start, we have $\frac{1}{2}mu^2 = eV$, and

$$(V_d - V_0)^{3/2} = \frac{9\pi}{\sqrt{2}}\sqrt{\frac{m}{E}}\,id^2. \tag{16}$$

This is the equation adapted to electrons or other ions flowing across otherwise empty space.

If we suppose that the corpuscles have at each point a speed proportional to the field strength at that point, we have $u = \pm k\,dV/dx$, and

$$V_d - V_0 = \frac{2}{3}\sqrt{\frac{8\pi i\,d^3}{k}}. \tag{17}$$

This equation would be adapted to ions drifting in so dense a gas, or so weak a field, that they acquire *very little* energy from the field (in comparison with their average energy of thermal agitation in the gas) between one collision and the next, and lose it all at the next.[15]

If we conceive of ions which acquire *much* energy from the field between one collision and the next (much, that is, in comparison with their average energy of thermal agitation) and lose it all at the next collision, we have $u^2 = (\pi el/2m)\,dV/dx$ and

$$(V_d - V_0)^{3/2} = Cid^{5/2} \tag{18}$$

the constant C being equal to $\sqrt{m/El}$ multiplied by a certain numerical factor, and l standing for the mean distance traveled by the ion between one collision and the next.

The theory just given is too simple; it is an essential fact of the actual physical case that the ions emerge, at the surface of the electrode whence they start, with forward velocities which are distributed in some way or other about a mean value. These initial forward velocities, though often small compared with the velocities which the ions may acquire as they cross to the other electrode, are large enough so that all of the ions would shoot across the gap if the field strength were really zero at the emitting electrode and assisted them everywhere beyond it. In fact the space-charge creates a retarding field at the surface of the emitting electrode, and a potential minimum (if the ions are negative; a potential maximum, if the ions are positive) at a certain distance in front of it. Here, and not at the emitting electrode as we previously assumed, the field strength is zero. Equation (16) is often valid in practice, because this locus of zero field-strength is often very close to the emitting electrode. In fact, by

[15] As in electrical conduction in solid metals (cf. my preceding article).

raising the P.D. between the plates sufficiently, the locus of zero field can be driven back into coincidence with the emitting plate; beyond which stage, the "limitation of current by space-charge" ceases. But if the P.D. is sufficiently low the potential minimum (or maximum) is prominent and is remote from the electrode, and in these cases the equations we have just deduced are inapplicable.

It thus may readily happen that when we apply a certain potential to one electrode and a certain other potential to another electrode separated from the first one by gas or vacuum, we may find points between them where the potential is *not intermediate* between the potentials of the electrodes. This is a queer conclusion, to anybody accustomed to the flow of electricity in wires. But it is true, and must be kept in mind.

6. The Self-Maintaining Discharges

The *Arc* ought to be the easiest to understand among the self-maintaining discharges, in one respect at least; for it keeps its own cathode so intensely hot that thermionic electrons are supplied continuously in great abundance at the negative end of the discharge, and the theorist can begin his labors by trying to explain how and why this high temperature is maintained. Anything which tends to lower the temperature of the cathode, for instance by draining heat away from it, is very perilous to the arc. Stark uses various schemes for preventing the cathode from growing very hot, and they all killed the arc. This also explains why the arc is most difficult to kindle and most inclined to flicker out when formed between electrodes of a metal which conducts heat exceptionally well, and most durable when formed between electrodes of carbon, which is a comparatively poor conductor for heat. It probably explains why the arc has a harder time to keep itself alive in hydrogen, a gas of high thermal conductivity, than in air. While the gas in which the arc has its being and the anode to which it extends both influence the discharge, the high temperature of the cathode is cardinal.

The cathode is presumably kept hot by the rain of positive ions upon it, striking it with violence and yielding up their energy of motion to it; at least this is the obvious and plausible explanation. Now the arc is commonly and easily maintained in fairly dense gases, with a comparatively small potential-difference between widely-separated electrodes; and the energy which an ion can acquire from the field strength prevailing in it, in the short interval between two collisions with molecules, is so small that it cannot be made to account

for the furious heat developed at the cathode when the ions finally strike it. Just before the ions arrive at the cathode they must be endowed with a kinetic energy which is very unusual (to say the least) in the middle of the discharge; and it is in fact observed that just in front of the cathode there is a sharp and sudden potential-fall, corresponding to a strong field extending but a little way outward from the electrode and then dying down into the weak field prevailing through the rest of the arc. This strong field picks up the ions which have meandered to its outward edge from the body of the discharge and hurls them against the cathode—not very forcibly, for the energy they receive from that potential-fall is not a great amount by ordinary standards, and most of the ions probably lose some of it in collisions on the way; but with much more energy than they would be likely to possess anywhere else in the arc.

This potential-fall immediately in front of the negative electrode, the *cathode-fall* of the arc, is measured by thrusting a probe or sounding-wire into the discharge as close as possible to the cathode (generally about a millimetre away), and determining the *P.D.* between it and the cathode. The probe is regarded with some distrust, as it raises in an acute form the old question as to how far the phenomena we observe in nature are distorted by the fact that we are observing them; the wire may alter the potential of the point where it is placed, or it may assume a potential entirely different from that of the environing gas; but the general tendency nowadays, I believe, is to accept its potential as a moderately reliable index of the potential which would exist at the point where it stands if it were not there.[16] The cathode-fall, as so measured, depends unfortunately on quite a number of things; the material of the cathode, the gas, the current. The gas is always mixed with a vapour of the electrode-material, particularly in the vicinity of the electrode; the only way to have a single pure gas is to enclose the whole system in a tube, evacuate the tube to the highest possible degree, and then heat it until the vapor-tension of the metal of which the cathode is made rises high enough for the vapor to sustain the arc. This is practicable with the more fusible metals; and with mercury, the arc generates heat enough to maintain the vapor-tension sufficiently high. In pure mercury-

[16] On this matter the experiments of Langmuir and Schottky, mentioned further along in this article, promise new knowledge. The probe automatically assumes such a potential that the net current-flow into it is nil; for example, if it is immersed in an ionized gas in which electrons and ionized atoms are roaming about, its eventual potential is such that equal numbers of particles of the two kinds strike and are absorbed in it per unit time. If the electrons are much more numerous or have a much higher average energy, or both, this potential may be several volts more negative than the potential at the same point before the probe was put in. The same may be said about the wall of the tube.

vapor, the cathode-fall assumes the value 4.9 volts which is the first resonance-potential of the mercury atom and therefore, as we have seen, is effectively the ionizing-potential of the free mercury atom when the electron-stream is as dense as it is in the arc. This suggests a delightfully simple theory of the whole process: the electrons stream from the cathode, they acquire 4.9 volts of energy from the cathode-fall, they ionize mercury atoms at the outward edge of the region of high field strength, the positive ions so created fall backward across the cathode-fall and strike the cathode, surrender their energy to it and so keep it hot, more electrons pour out, and so forth *ad infinitum*. It remains to be seen whether so simple a theory can be modified, by statistical considerations or otherwise, to explain the values of the cathode-fall in mixed and diatomic gases.

We do not know *a priori* what is the ratio of the number of electrons flowing outward across the cathode-fall in a second to the number of ions flowing inward. It might, however, be very great, and still the number of ions within the region of the cathode-fall at any instant could far surpass the number of electrons within it—the electron moves so much more rapidly than the ion, and has so much better a chance of crossing the region in one free flight without a collision. Even in hydrogen, in which the ions are the lightest of all ions, the electron current would have to be 350 times as great as the ion-current if the electrons just balanced the ions in unit volume. It is therefore legitimate to try out the assumption that the region of cathode-fall is a region of purely positive space-charge, in which some such equation as (16), (17), or (18) gives the current of positive ions as a function of the cathode-fall and the width of the region. K. T. Compton selected (18). Unfortunately the width of the cathode-fall region has not been measured, but he assumed it equal to the mean free path of an electron in the gas. The value which he thus calculated for the current of positive ions was about 1% of the observed total current; the remaining 99% consists of the electrons.

From the cathode region onward to the anode, the gas traversed by the arc is dazzlingly brilliant. In the long cylindrical tubes which enclose the mercury arcs so commonly seen in laboratories and studios, the vapor shines everywhere except near the ends with a cold and rather ghastly white light tinged with bluish-green. This is the positive column of the mercury arc. The potential-gradient along it is uniform, suggesting the flow of electricity down a wire; but here the resemblance stops, for when the current-density goes up the potential-gradient goes down. The curve of voltage versus current, which for a solid metal is as we all know an upward-slanting straight

line, is for the arc a downward-slanting curve (Fig. 6). Such a curve
is called a *characteristic*, and the arc is said to have a *negative character-
istic*. Ionization goes on continually within the positive column,
and ions of both signs can be drawn out by a crosswise field; but
recombination of ions, a process which we have not considered, also
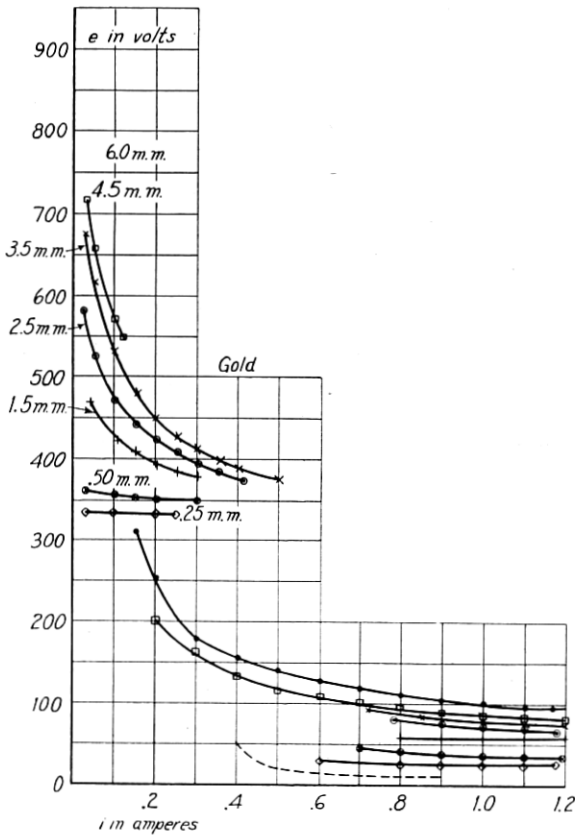goes on continually and maintains an equilibrium. Presumably it

Fig. 6—Voltage-current curves or "characteristics," for arc discharges (below) and
glow discharges (above) in air, between gold electrodes. The different curves corre-
spond to different anode-cathode distances. (Ives, *Journal of the Franklin Institute*)

is the effect of the field strength on this equilibrium which causes
the current-voltage curve to slant in what most people instinctively
feel is the wrong way; but the theory of the equilibrium is not yet
far advanced.

Langmuir and Schottky, working independently in Schenectady
and in Germany, performed some very pretty experiments by thrust-

ing negatively-charged wires or plates into the positive column. These wires and plates surrounded themselves with dark sheaths, the thickness of which increased as the potential of the metal was made more and more highly negative. The explanation is, that the electrons in the positive column cannot approach the intruded wire, being driven back by the adverse field; the dark sheath is the region from which they are excluded, and across it the positive ions advance to the wire through a field controlled by their space-charge. The equation selected by Langmuir to represent the relation between the thickness of the sheath, the voltage across it, and the current of positive ions into it, is (16). As the sheath is visible and its thickness can be measured, as well as the other quantities, the relation can be tested. This was done by Schottky; the result was satisfactory. When the intruded electrode is a wire, the sheath is cylindrical, and expands as the voltage of the wire is made more negative. As the area of the outer boundary of the sheath is increased by this expansion, more ions from the positive column touch it and are sucked in, and the density of flow of positive ions in the column can be determined. By lowering the potential of the wire gradually so that the electrons can reach it, first the fastest and then the slower ones, the velocity-distribution of the electrons in the column can be ascertained. Their average energy depends on the density of the mercury vapour, and may amount to several volts.

Beyond the positive column lies the anode, itself preceded by a sharp and sudden potential rise. The electrons are flung against it with some force, and it grows and remains very hot; usually, in fact, hotter than the cathode. This high temperature does not seem to be essential to the continuance of the discharge, for the anode can be cooled without killing the arc; yet it seems strange that a quality so regularly found should be without influence upon the discharge. One must beware of underestimating the influence of the anode; when an arc is formed in air between two electrodes of different materials, it behaves like an arc formed between two electrodes of the same material as the anode, *not* the cathode!

The so-called *low-voltage arc*, although not a self-maintaining discharge, merits at least a paragraph. A dense electron-stream poured into a monatomic gas from an independently-heated wire, and accelerated by a P.D. surpassing the resonance-potential of the gas, may ionize it so intensely that there is a sudden transformation into a luminous arc-like discharge. This is a sort of "assisted" arc, its cathode being kept warm for its benefit by outside agencies. Its history is a long and interesting chapter of contemporary physics, whereof the end is not yet. The most remarkable feature of this arc
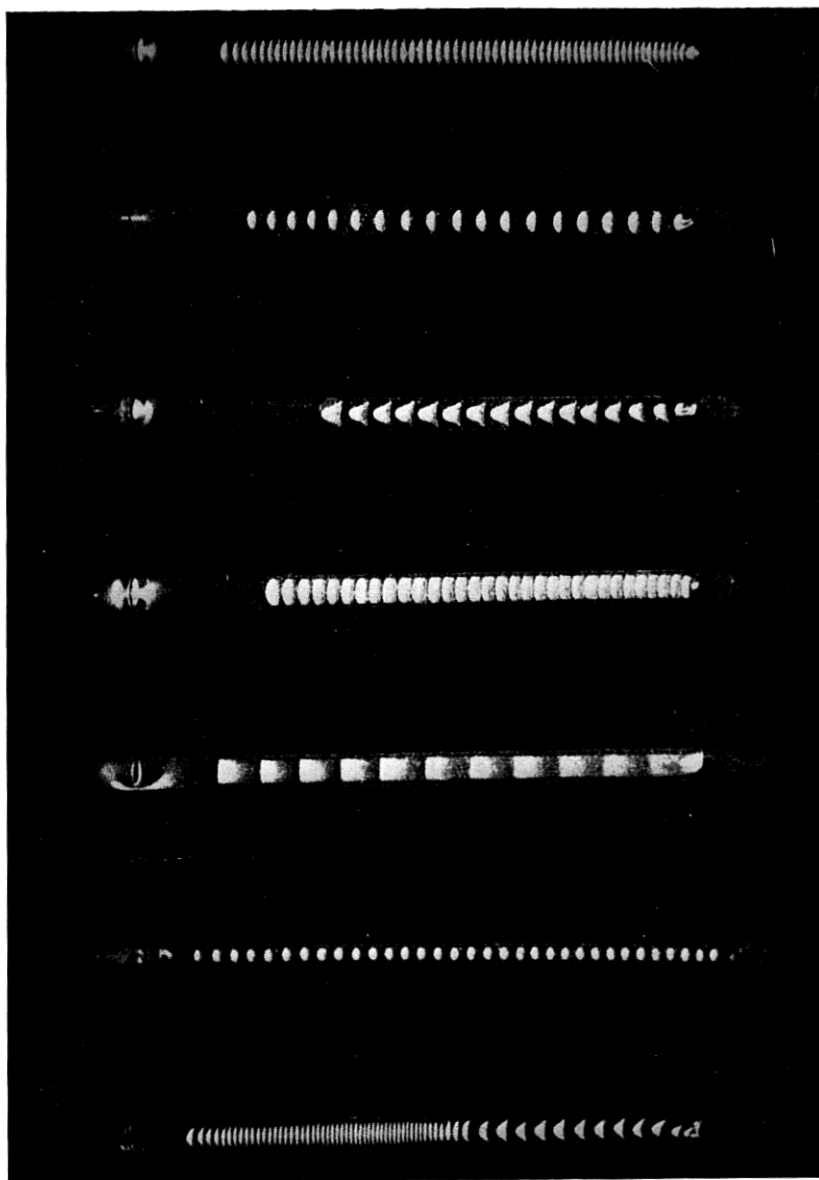
Fig. 7—Photographs of the glow-discharge in a long narrow cylinder, showing chiefly the subdivision of the positive column into striations. (De la Rue and Muller, *Philosophical Transactions of the Royal Society*)

is that it can survive even if the voltage between anode and cathode is far below the resonance-potential of the atoms of the gas, which seems impossible. A year ago it seemed that this effect could always be ascribed to high-voltage high-frequency oscillations generated in the arc. This explanation was presently confirmed in some cases and disqualified in others, and now it appears that when there are no oscillations an astonishingly strong potential-maximum develops within the ionized gas. Potential-maximum and oscillations alike are probably to be regarded as manifestations of space-charge.

The *Glow in a rarefied gas* is a magnificent sight when the gas is rarefied to the proper degree, not too little and not too much; divided into luminous clouds of diverse brightnesses and diverse colors, recalling Tennyson's "fluid haze of light," yet almost rigidly fixed in their distances and their proportions, it is one of the most theatrical spectacles in the repertoire of the physical laboratory. The grand divisions of the completely-developed discharge are four in number, two relatively dim and two bright; beginning from the cathode end,
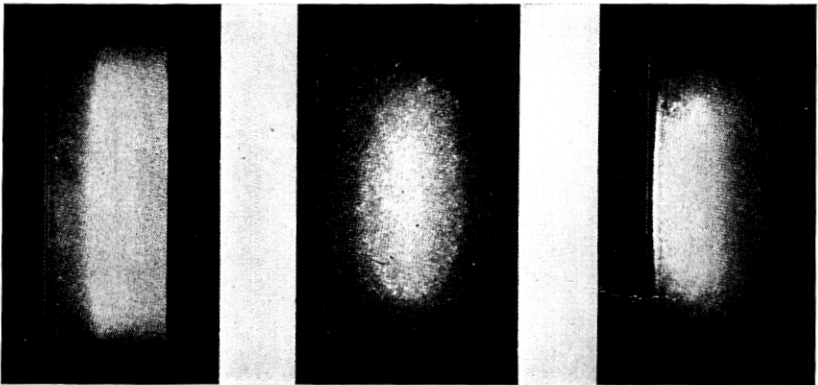

Fig. 8—The Crookes dark space between the cathode (thin line at left) and the negative glow. See footnote [12]. (Aston, *Proceedings of the Royal Society*)

they are the Crookes dark space, the negative glow, the Faraday dark space, and the positive column. Additional gradations of color and brightness can often be seen very close to the cathode and very close to the anode. Photographs of the glow which give anything approaching a true idea of its appearance to the eye are hard to find. I reproduce in Fig. 7 some photographs taken nearly fifty years ago by de la Rue, which have reappeared in many a text; they show chiefly the striking flocculent cloudlets into which the positive column sometimes divides itself. In Fig. 9 there are two sketches made by Graham.

The Crookes dark space (or cathode dark space, or Hittorf dark space as it is called in Germany) extends from the cathode to the boundary of the bright luminous cloud which is the negative glow. The boundary is generally so well-defined and distinct that an observer finds it easy to judge when a sounding-wire just touches it, or the cross-hair of a telescope coincides with its image; "in the case of oxygen," Aston said, "the sharpness was simply amazing; even with so large a dark space as 3 cm., the sighter could be set (to the boundary) as accurately as to the cathode itself, *i.e.*, to about 0.01 mm." I reproduce some of Aston's photographs in Figure 8, although he says that for reasons of perspective the boundary of the negative glow appears more diffuse than it really is.[17] The electric field strength within the Crookes dark space is greater, often very much greater, than in any of the other divisions of the discharge; almost the whole of the voltage-rise from cathode to anode is comprised within it, and the remainder, although spread across all the brilliant parts of the glow, is inconsiderable unless the tube is made unusually long. The behavior of the dark space when the current through the tube is varied (by varying a resistance in series with the tube) is curious and instructive. If the current is small and the cathode large (a wide metal plate) the negative glow overarches a small portion of the cathode surface, lying above it like a canopy with the thin dark sheath beneath it. When the current is increased the canopy spreads out, keeping its distance from the metal surface unaltered, but increasing its area proportionally to the current; the thickness of the Crookes dark space and the current-*density* across it remain unchanged. If the experimenter continues to increase the current after the cathode is completely overhung by the glow, the dark space thickens steadily, and the current-density across it rises.

The changes in the voltage across the Crookes dark space which accompany these changes in area and thickness are very important. The voltage is measured with a sounding-wire, like the cathode-fall in the arc; but since the boundary of the dark space is so sharply marked, the experimenter can set the sounding-wire accurately to it instead of merely as close as possible to the cathode. So long as the

[17] Adjacent to the cathode a thin perfectly dark stratum can be distinguished (especially in the picture on the right). The P.D. across this thin black space is, as nearly as it can be guessed from the width of the space, of about the magnitude of the ionizing-potential of the gas. In fact Aston estimated it for helium (to which the pictures refer) as 30 volts, a good anticipation of the value 24.5 assigned years later to the ionizing potential. It seems therefore that the outer edge of the very dark space is at the level where the electrons coming from the cathode first acquire energy enough to ionize.

negative glow does not overarch the whole cathode, and the thickness and current-density of the dark space keep their fixed minimum values, the voltage across it remains constant likewise. This is the *normal cathode-fall* of the glow. It is an even more thoroughgoing constant than the thickness or the current-density of the dark space, for these vary with the pressure of the gas (the dark space shrinks both in depth and in sidewise extension, if the current is kept constant while the gas is made denser) while the normal cathode-fall is immune to changes in pressure. It depends both on the gas and on the material of the cathode; the recorded values extend from about 60 volts (alkali-metal cathodes) to about 400 volts. Attempts have been made to correlate it with the thermionic work-function of the cathode metal, and there is no doubt that high values of the one tend to go with high values of the other, and low with low. When the cathode is entirely overspread by the negative glow and the dark space begins to thicken, the voltage across it rises rapidly; the cathode-fall is said to become *anomalous*, and may ascend to thousands of volts.

Almost the whole of the voltage-rise from cathode to anode, as I have stated, is generally comprised in the cathode-fall; the remainder, although spread over all of the brilliant divisions of the discharge, is inconsiderable unless the tube is unusually long. The field strength in the Crookes dark space is also much greater than anywhere else in the glow. This is illustrated by the two curves in Fig. 9, representing the field strength in the discharges sketched above them. (For the region of the Crookes dark space, however, the curves are defective.) In the luminous clouds the electric force is feeble, and they in fact are not essential to the current-flow; if the anode is pushed inwards towards the cathode, it simply swallows them up in succession without interfering with the current; but the moment it invades the Crookes dark space, the discharge ceases unless the electromotive force in the circuit is hastily pushed up. The mechanism which keeps the glow alive lies concealed in the dark space.

One naturally tries to invent a mechanism resembling the one suggested for the arc: the cathode-fall serves to give energy to the electrons emerging from the cathode, so that they ionize molecules at the edge of the negative glow; and the ions fall against the cathode with energy enough to drive out new electrons. But the details are more difficult to explain. The cathode-fall gives much more energy to the electrons than they need to ionize any known molecule, so that apparently its high value is what the ions require to give them enough energy to extract electrons from the cathode. We can hardly argue that the electrons are thermionic electrons; the cathode does not

grow hot enough; if it does, the cathode-fall suddenly collapses, and the glow is liable to turn into an arc. Expulsion of electrons from cold metals by ions striking them has been separately studied, but not sufficiently.

On the other hand, there is good evidence that the Crookes dark space, like those dark sheaths scooped out in the positive column
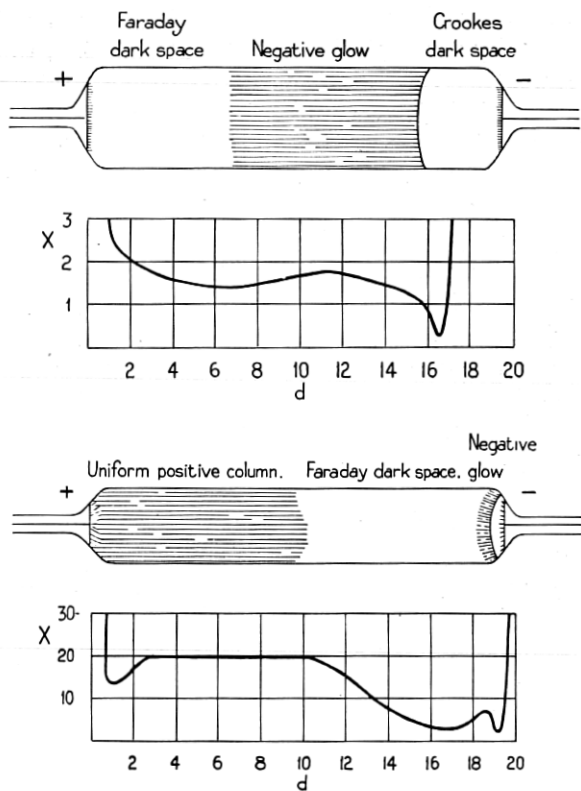

Fig. 9—Sketches of the glow in rarefied nitrogen at two pressures (the higher below) with curves showing the trend of field strength along the discharge. (Graham, *Wiedemanns Annalen*)

of the mercury arc by intruding a negatively-charged wire, is a region of predominantly positive space-charge, in which positive ions advance towards the cathode in a manner controlled by some such equation as (16) or (17). For example, Gunther-Schulze proposed (16) to describe the state of affairs in the Crookes dark space in the condition of normal cathode-fall; that is, he assumed that the ions fall unimpeded from the edge of the negative glow to the cathode surface. No

doubt this assumption is too extreme, yet it leads to unexpectedly good agreements with experiment. Thus when the thickness of the Crookes dark space is altered (by altering the pressure of the gas) leaving the voltage across it constant, the current-density varies inversely as the square of the thickness, as it should by (16). And when Gunther-Schulze calculated the thickness of the dark space from (16), using the observed values of cathode-fall and current for six gases and two kinds of metal, and substituting the mass of the molecule of the gas for the coefficient m in that equation, the values he obtained agreed fairly well (within 40%) with the observed thicknesses. Long before, J. J. Thomson had proposed (17), and Aston tested it by a series of experiments on four gases, in the condition of strong anomalous cathode-fall. As k of that equation should be inversely proportional to the pressure p of the gas, the product $id^3 V^{-2}$ (V standing for the cathode-fall) should be constant at constant pressure, and the product $id^3 V^{-2}p$ should be constant under all circumstances. These conclusions were fairly well confirmed for large current-densities.

Several attempts to test the theory by actually determining the potential-distribution in the Crookes dark space were made with sounding-wires and by other methods; but they have all been superseded, wherever possible, by the beautiful method founded on the discovery that certain spectrum lines are split into components when the molecule emitting them is floating in an intense electric field, and the separation of the components is proportional to the strength of the field. This was established by Stark who applied a strong controllable electric field to radiating atoms, and by LoSurdo who examined the lines emitted by molecules rushing through the strong field in the Crookes dark space, in the condition of anomalous cathode-fall. Now that the effect has been thoroughly studied it is legitimate to turn the experiments around and use the appearance of the split lines as an index of the field strength in the place where they are emitted. Brose in Germany and Foster at Yale did this. In the photographs (Fig. 10, 11) we see the components merged together at the top, which is at the edge of the negative glow, where the field is very small; thence they diverge to a maximum separation, and finally approach one another very slightly before reaching the bottom, which is at the cathode surface.[18] This shows that the net space-charge in the Crooke

[18] The displacements of certain components are not rigorously proportional to the field, and sometimes entirely new lines make their appearance at hitherto unoccupied places when a strong field is applied. Both of these anomalies can be detected in the pictures. For the original plate from which Fig. 11 was made I am indebted to Dr. Foster.
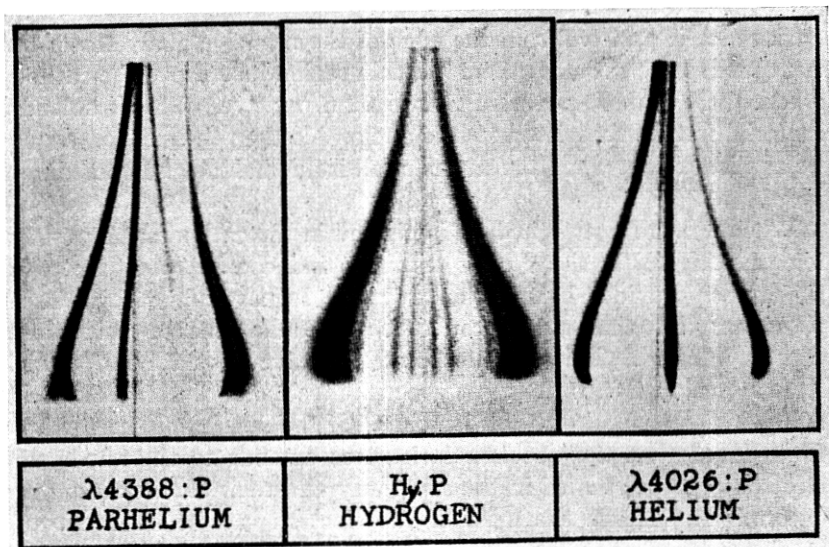
| λ4388:P PARHELIUM | Hγ P HYDROGEN | λ4026:P HELIUM |

Fig. 10—Spectrum lines subdivided and spread out in the Crookes dark space by the strong and variable field. See footnote [18]. (J. S. Foster, *Physical Review*)
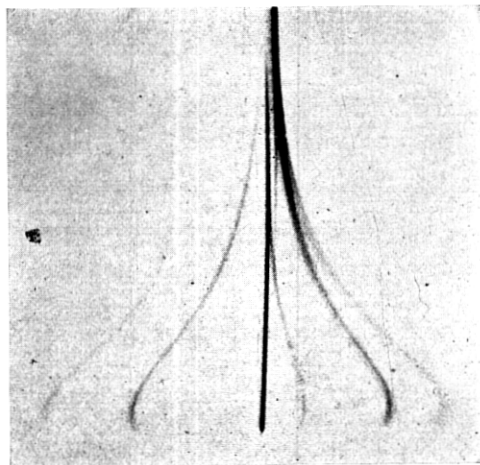

Fig. 11—A group of lines near λ4388 (parhelium spectrum) resolved and spread out in the Crookes dark space. See footnote [18].

dark space is positive from the edge of the negative glow almost but not quite to the cathode; there is a thin region just above the cathode where there is more negative charge than positive. This is splendid material for the theorist, and it is deplorable that the method cannot be applied except when the cathode-fall is anomalous and exceedingly large.

When a narrow straight hole is pierced in the cathode, the positive ions making for it shoot clear through, and can be manipulated in a chamber provided behind the cathode. In particular the ratios of their charges to their masses can be measured, and thence their masses can be inferred. This is Thomson's "positive-ray analysis," which Aston developed into the most generally available of all methods for analyzing elements into their isotopes. If the density of the gas is so far reduced that the Crookes dark space extends to the anode, the electrons can be studied in the same way and their charge-mass ratio determined. Hence the mass of the electron can be deduced, and its dependence upon the speed of the electron ascertained, yielding precious evidence in support of the special or restricted theory of relativity. These are among the simple phenomena which I mentioned at the beginning of this article, in which the properties of the ultimate atoms of electricity and matter are revealed.

The positive column, which is the brilliant, colorful and conspicuous part of the glow, resembles in some ways the positive column of the mercury arc. In it the potential-gradient decreases with increasing current, and the characteristic of the glow is negative (Fig. 6). Often the positive column subdivides itself into a regular procession of cloudlets or *striations*, all just alike and equally spaced (Fig. 7). The potential-difference between two consecutive striations has the same value all along the procession, and everyone feels instinctively that it ought to be the ionizing-potential or the resonance-potential of the gas; but this is evidently too simple an interpretation for the general case, although striations at potential-intervals of 4.9 volts have been realized in mercury vapor. Generally, if not always, the striations appear when the gas is contaminated with a small admixture of another. In this fact the key to the problem of their origin probably lies.

The *Glow in a dense gas* (as dense as the atmosphere, or more so) is visible only when the surface of either or both electrodes is curved, with a radius of curvature smaller than the minimum distance between the two. In these circumstances the field strength varies very greatly from one point to another of the interspace, at least before the space-charges begin to distort the field, and presumably afterwards as well;

it attains values just in front of the curved electrode (or electrodes, if both are curved) so great that if they prevailed over an equal inter-space between flat electrodes they would instantly provoke an explosive spark. In some cases the glow in a dense gas resembles a very con-
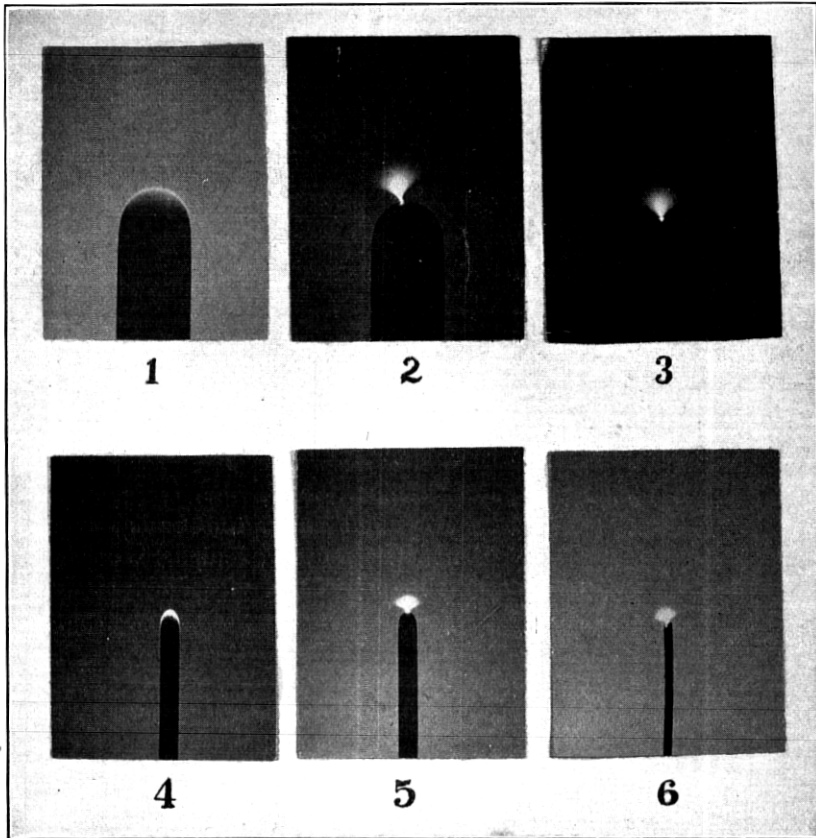

Fig. 12—The glow in air at atmospheric pressures, near a curved electrode (the other electrode is a plate beyond the top of the picture). In 1, 4 the curved electrode is the anode; in 2, 3, 5, 6 it is the cathode. (J. Zeleny, *Physical Review*)

tracted and reduced copy of portions of the glow in a rarefied gas. Thus in the photographs (Figs. 12, 13) of the luminosity surrounding a very curved cathode, it is possible to discern two dark spaces and two bright ones, the first dark space lying just outside the cathode, the last bright region fading off into the darkness which extends away towards the flat anode (far above and out of the picture). In the pictures of the glow surrounding a very curved anode, we see only a luminous sheath

spread over the metal surface (Fig. 12).[19]   Mathematically the simplest
case (at least before the space-charge begins to affect the field) is
realized by a slender cylindrical wire stretched along the axis of a

Fig. 13—Magnification of one of the pictures in Fig. 11.   (The lowest bright spot
is a reflection in the cathode surface)

much wider hollow cylinder, the wall of which may be imagined
to recede to infinity in the limiting case.   In this case the glow bears
the euphonious name of *corona*, and has been intensively studied
because it wastes the power transmitted over high-tension lines.

[19] I am indebted to Professor J. Zeleny for plates from which these figures were
made.

Often there is a luminous cylindrical sheath encasing the wire, and from the boundary of the sheath outwards to the outer cylinder the gas is dark. It is customary to assume that the dark region, like the other dark spaces we have considered, is traversed by a procession of ions of one sign, positive or negative as the case may be, moving at a speed proportional to the field and controlled by their own space-charge according to the equation in cylindrical coordinates corresponding to (17); and the experiments support this assumption to a certain extent.

I must use my last paragraph to erase the impression—inevitably to be given by an account so short as this, in which the understood phenomena must be stressed and the mysterious ones passed over—that the flow of electricity through gases is to be set down in minds and books as a perfected science, organized, interpreted and finished. Quite the contrary! there are as many obscure and mysterious things in this field of physics as there are in any other which has been explored with as much diligence. Its remarkable feature is not that most or many of the phenomena in it have been perfectly explained; but rather, that for those few which have been explained, the explanations are very simple and elegant; they are based on a few fundamental assumptions about atoms and electrons which are not difficult to adopt, for they are not merely plausible but actually *demonstrable*. Perhaps as time goes on all the phenomena will be explained from these same assumptions. There will be experimenters who modify the apparatus and the circumstances of past experiments so that all of the avoidable complications are avoided and the phenomena are simplified into lucid illustrations of the fundamental principles; and there will be theorists, who take the complicated phenomena as they are delivered over to us, and extend the power of mathematical analysis until it overcomes them. They may find it necessary to make other and further assumptions, beyond those we have introduced; at present it is commonly felt that ours may be sufficient. Whether posterity will agree with us in this, must be left for posterity to decide.