PHYSICS OF THE THREE-ELECTRODE BULB.*

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INTRODUCTION.

PROBABLY the discovery and use of the three-electrode bulb mark the most important development in the art of wireless communication for, as sender or receiver, it is the "working" part of modern wireless sets. Its invention followed Edison's discovery of the "Edison" or "thermionic" effect, its study by Elster and Geitel, 1882-1890, and by Fleming, 1890-1896, and the development of the theory of the effect by Richardson since 1904. It is interesting to note, in passing, that the thermionic effect was discovered and studied by physicists of the seventeenth century, but the subject was dropped before significant results were obtained—to be revived and put to important use 200 years later.

The Edison effect can easily be demonstrated by wrapping tin-foil around the glass of an incandescent light bulb—taking care not to make contact with the screw base—and connecting a galvanometer in series with a battery between the tin-foil and one of the wires feeding the filament. If the battery is connected so as to make the tin-foil *negative* with respect to the filament, no deflection of the galvanometer is observed. If, however, the tin-foil is *positive*, the galvanometer indicates a current. This current comes as a stream of negative electrons from the hot filament, through the glass to the tin-foil, through the galvanometer and battery and back to the filament. No current flows in the above circuit until the glass inside the tin-foil becomes hot enough to be sufficiently conducting. This experiment may be performed with a tungsten filament lamp, but an old style carbon filament lamp gives a larger current unless the tungsten lamp is run over-voltage.

NATURE OF THERMIONIC EMISSION.

The principal investigations of the emission of electrons from

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hot bodies have dealt with the effects of the nature of the metal and its temperature on the number of electrons emitted per second and on the velocities with which they are emitted.

It is found that the electrons emitted from any pure metal at a given temperature emerge from it with all possible velocities between zero and a very high value, probably infinity, and that the relative numbers with various velocities are distributed according to Maxwell's probability law, with an average velocity which is proportional to the absolute temperature of the metal. In other

TABLE I.

Energy of Emission			
less than	at 1050° K. (volts)	at 3150° K. (volts)	Fraction
$\bar{V}$	0.27	0.80	0.392
2 $\bar{V}$	0.54	1.60	0.112
3 $\bar{V}$	0.80	2.40	0.032
4 $\bar{V}$	1.07	3.20	0.0086
5 $\bar{V}$	1.34	4.00	0.0019
6 $\bar{V}$	1.60	4.80	0.00042
7 $\bar{V}$	1.87	5.60	0.00011
8 $\bar{V}$	2.14	6.40	0.000027
9 $\bar{V}$	2.40	7.20	0.0000060
10 $\bar{V}$	2.67	8.00	0.0000014

words, the relative numbers with different velocities are the same as if the electrons were molecules of an ideal gas. It was first thought¹ that these velocities were the same as if the electrons were molecules of an ideal gas *at the temperature of the emitting metal*, but recent investigation has shown that their average kinetic energy is about twice this large, as if characteristic of about *twice the temperature of the metal*. An idea of the distribution of velocities among the emitted electrons may be gained from Table I, in which the velocities are expressed in terms of the equivalent number of volts V from the relation $\frac{1}{2} m v^2 = \frac{eV}{300}$.² The last column gives the fraction of all emitted electrons whose velocities

¹ Richardson and Brown, *Phil. Mag.*, 93, 1908; Richardson, "Emission of Electricity from Hot Bodies," Chap. V.

² e and m are the charge and mass of an electron and 300 is a factor to convert from electrostatic units of potential to volts. V is the number of volts of potential drop in which an electron would acquire a velocity v . $\bar{V}$ is the average energy, in volts.

exceed the value indicated in the other columns. For instance, at 1050° absolute, 0.0019 of the emitted electrons have energies exceeding five times the average energy, or possess sufficient kinetic energy to pass against a retarding field of 1.34 volts.

This type of velocity distribution is similar to that among the molecules of a vapor which have just escaped by evaporation from a liquid surface. It suggests that thermionic emission is really an evaporation of electrons from the surface of the hot metal.

Richardson first applied this conception to the theory of thermionic emission. Within the metal there are electrons with velocities distributed as if they are molecules of an ideal gas. Those which strike the surface will escape if their kinetic energy exceeds the work which they must do against the retaining forces at the surface. These retaining forces include the attraction exerted on the escaping electron by the positive charge induced by it on the surface, and the total work done against these forces is the "heat of evaporation" of the electrons. This work is often called the "work function" and written as $e\phi$, where ϕ is the equivalent potential difference. On this theory, Richardson showed that the thermionic current per square centimetre of emitting surface should be

$$i = N e \sqrt{\frac{k}{2\pi m}} T^{\frac{1}{2}} e^{-\frac{e\phi}{kT}}, \quad (1)$$

where N is the number of free electrons per unit volume in the metal, k is the Boltzmann gas constant in $p v = nkT$, and T is the absolute temperature.

The same theory, applied to the Thomson effect in metals, indicates that N is closely proportional to $T^{\frac{3}{2}}$ so that the true variation of thermionic current with temperature should be given by the equation

$$i = A T^2 e^{-\frac{e\phi}{kT}}, \quad (2)$$

in which A is a constant. The same equation was derived by Richardson on more general grounds, without postulating the existence of free electrons within the metal, and Dushman³ has recently given grounds for supposing that A has the same value for all metals, and has calculated its value. Thus

³ Paper at Washington Meeting of American Physical Society, April, 1922.

the thermionic properties of metals seem to be determined entirely by the temperature T and the work function, or "latent heat of evaporation of an electron," ϕ . To obtain large thermionic currents it is necessary to use a substance with a small value of ϕ and with a high enough melting point to permit its use at a high temperature.

Equation 2 has been tested over an enormous range, with sufficient temperature variation to produce a variation of ten million million fold, or 10^{13} fold, in the thermionic current, without detecting any inaccuracy in equation 2.⁴ Table II gives some actual

TABLE II.

Temperature	Thermionic Current
1050°K.	0.000000235 microamps.
1200	0.000169 per sq. cm.
1350	0.0282
1500	1.70
1650	49.0
1800	809.
1950	8730.
2100	67000.
2250	394000. etc.

currents from a tungsten wire. Currents as large as 8 amperes per square centimetre of emitting surface have been obtained. A convenient method of testing equation 2 is illustrated by Fig. 1, in which the equation is plotted in its logarithmic form. In this form, the graph of the observed values of i and T should give a straight line, such as BC .

THE "WORK FUNCTION" ϕ .

The slope of the curve, as plotted in Fig. 1, gives the value of the work function ϕ characteristic of the metal from which the plotted values were obtained. This value, and the intercept $\overline{OA}$, determine the other constant A .

Since the work function ϕ is of the nature of a heat of evaporation, we should expect a metal to be cooled by its thermionic emission just as a liquid is cooled by evaporation. This was found by Cooke and Richardson⁵ to be the case. They used a metal fila-

⁴ K. K. Smith, *Phil. Mag.*, 1915.

⁵ *Phil. Mag.*, 20, p. 173, 1910; 25, p. 624, 1913.

ment as one arm of a sensitive Wheatstone's bridge, which provided its heating current and measured its resistance. The filament was surrounded by a coaxial electrode which could be charged negatively or positively with respect to the filament so as to prevent or permit the emission of a thermionic current from the filament. When this emission was permitted, the temperature

FIG. 1.

of the filament was observed to decrease. From the additional amount of energy of heating current required to bring the filament back to its original temperature, the total rate of loss of heat by evaporation of electrons was determined. From this the heat of evaporation per electron, ϕ , was calculated and found to agree with the value obtained as in Fig. 1.

A third method of measuring ϕ is to consider it as a "heat of condensation." That is, heat should be developed in a metal when electrons pass into it through its surface. This was also proved and ϕ measured by Richardson and Cooke,⁶ who observed the increase in temperature of a thin metal strip, which formed one arm of a Wheatstone's bridge, when electrons passed into it from a neighboring hot filament.

⁶ *Phil. Mag.*, 20, p. 173, 1910; 21, p. 404, 1911.

Finally, there is a relation between the values of ϕ and the contact difference of potential of metals which is useful in estimating or predicting values of ϕ for metals which have not been accurately investigated by the preceding methods. Consider two metals (1) and (2), connected at the junction J and placed in an enclosure at constant temperature. Calculate the work done in the processes involved in taking an electron around a cycle as follows: Starting in (1), take it out through the surface of the metal, doing work $e\phi_1$ on it. Then take it to a point just outside the surface of (2), doing work $e(V_2 - V_1)$ against the contact

TABLE III.

Metal	ϕ (in volts)
Pt	5.3
W	4.4
Mo	4.04
Ca	3.04
Na	2.65
BaO	3.65
CaO	3.48

difference of potential between the metals. Then take it through the surface into (2), in which process it does work $e\phi_2$. Finally, take it around through the metals, across the junction J to the starting point, doing work at the junction equal to eP , where P is the Peltier coefficient for the metals. The work done against metallic resistance may be neglected, since this depends on the square of the current and we may imagine the process to be performed as slowly as we please. The total work done must be zero, since it is a reversible cycle at constant temperature. Therefore,

$$V_1 - V_2 = \phi_1 - \phi_2 + P. \quad (3)$$

P is so small as to be practically negligible, whence we see that the difference between the work functions of two metals equals their contact difference of potential. A very electropositive metal has a small value of ϕ . Equation 3 has been verified by direct experiment with only moderate accuracy, since the values of V are very difficult to determine free from spurious effects. Indirect verification of the equation has, however, been quite convincing.

Table III gives a few typical values of ϕ . Expressed in equivalent volts, the average kinetic energy of a gas molecule is 0.13 volt at 1000° K., 1.3 volts at 10,000° K., and 6.5 volts at

50,000° K. We see that ordinary temperatures are sufficiently low to keep electrons from rushing freely out of metals, only a minute fraction of them having sufficient energy to escape.

It is desirable, in a three-electrode bulb, that the thermionic emission from the filament be large, homogeneous as regards velocity distribution, obtained with a minimum expenditure of battery power, and absolutely constant under constant external conditions. Large currents are obtained with large area of emitting surface, high temperature and small ϕ . Tungsten is there-

FIG. 2.

$$V_1 - V_2 = \phi_1 - \phi_2 + P$$

fore superior to platinum, for it combines a smaller value of ϕ with a much higher melting point. Homogeneity of velocities demands low temperatures, which, in turn, necessitate a substance with a small value of ϕ . For this reason, platinum strips coated with the oxides of the electropositive and fairly non-volatile alkaline earths are advantageous. These are also advantageous because of their operation with minimum expenditure of battery power, since they give good emission at a dull red heat, whereas tungsten must be heated to bright incandescence. Pure metals are probably preferable to oxide coated filaments as regards constancy, although the constancy of the present commercial bulbs with oxide-coated filaments is remarkable.

A very recent development which may be important was reported by Langmuir.⁷ Thoriated tungsten filaments, given proper heat treatment, become coated with a surface layer of thorium which is very stable unless the temperature is excessive. The filament then has the properties of a thorium filament and com-

⁷ *Proc. Am. Phys. Soc.*, Washington meeting, April, 1922.

bines very advantageously a relatively low value of ϕ with ability to operate at a moderately high temperature.

If the prime requirement is a maximum emission, nothing equal to tungsten is known.

FIG. 3.

EFFECT OF SPACE CHARGE.

Although equation 2 gives the total rate of emission of electricity from a metallic surface, the actual thermionic current is often less than this because some of the emitted electrons return to the emitting metal, being forced back by the repulsion of other electrons which have been emitted just ahead of them. The region surrounding the emitting metal contains electrons and thus has a "space charge" which tends to prevent the emission of additional electrons. On the other hand, an electric field may be applied to aid the escape of emitted electrons. The current, therefore, adjusts itself to such a value that the accelerating effect of the applied

electric field is just balanced by the retarding effect of the space charge, so that the resulting electric field just outside the surface of the metal is zero.

Actually, due to their initial velocities, electrons will be able to escape against a small opposing field, so that the current is really a little larger than that which would just give the balance suggested above. The emitting surface is surrounded by a region of opposing field which reaches zero at a surface of minimum potential at some point outside the metal. Here the field changes direction and is an accelerating field in the remaining interval to the anode.

Fig. 3 illustrates the effect of space charge in limiting the thermionic current. The heavy curve gives the maximum current possible at each temperature and agrees with equation 2. To obtain such currents, a sufficiently large accelerating electric field must be used to completely offset the effect of the space charge. The effect of using smaller accelerating fields is shown by the broken curves, which give experimental results for 60, 120 and 240 volts, respectively. For a low voltage, the experimental curve departs from the theoretical curve at small currents, whereas the curves at higher voltages agree with the theoretical curve to much larger currents. It is seen that, for 60 volts, the maximum possible current is given at 2050° K., and further increase in the temperature of the filament does not increase the current. Similar maximum currents are characteristic of each other voltage.

For a hot filament, the actual current is seen to depend on the applied voltage, as long as the current is less than that given by equation 2. These currents I_{60} , I_{120} , etc., are found to be proportional to the $3/2$ power of the corresponding voltages. Langmuir has shown ⁸ that the above considerations lead to a relation between the current density i and the voltage V , for values of i considerably less than those given by equation 2, of the form

$$i = 2.33 (10)^{-6} d^{-2} V^{3/2} \text{ amps. per sq. cm.} \quad (4)$$

if the electrodes are parallel plates distant d apart, and

$$i = 14.65 (10)^{-6} r^{-1} V^{3/2} \text{ amps. per sq. cm.} \quad (5)$$

for a small straight filament surrounded by a coaxial cylinder of radius r .

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⁸ *Phys. Rev.*, **2**, p. 450, 1913.

The actual relation between filament current and voltage is shown by Fig. 4, which was calculated for the case of a cylindrical anode of unit radius. The solid curve represents equation 5. At any temperature the currents depart from this curve as the saturation value given for that temperature by equation 2 is approached.

FIG. 4.

Note that for 20 volts, for instance, it is impossible to obtain a current greater than 1.3 m.a., no difference how hot the filament is. But a greater current could be obtained at 20 volts and high temperatures if the distance r between the electrodes were diminished (or, as we shall see later, if positive gas ions are present to neutralize the negative space charge. The above conclusions regarding the effect of space charge apply only to the case of electrodes in a high vacuum).

ELECTRON ATMOSPHERES.

Let me now call attention to a necessary consequence of the facts of thermionic emission, *i.e.*, to the existence of an electron atmosphere at the surface of every metal and extending out with diminishing density to greater distances from its surface. We may picture to ourselves the cause of this atmosphere in the following way. Electrons within the metal continually reach its surface with sufficient kinetic energy to carry them a greater or less distance out, against the attractive forces (which give rise to the work function) which tend to draw them back into the metal. Some few have sufficient energy to escape. The rest are drawn back into the metal, after a short-lived freedom. Thus, at any given distance from the surface, there is a certain average number of electrons per unit volume, or electron density, which remains constant although the particular electrons in this group are continually changing. At higher temperatures this electron atmosphere is denser and extends farther from the surface, owing to the greater kinetic energy of the electrons. Electrons in this atmosphere will collide with each other and behave as molecules of a gas in a field of force.

This force of attraction back toward the metal may arise jointly from several causes, but, unless the atmosphere is very dense, the principal cause is probably the attraction due to the equal positive charge induced by each escaping electron on the surface of the metal. If we assume, as a first approximation, that this is the *only* cause, and that the surface of the metal may be considered as perfectly continuous, instead of being composed of discrete atoms with intervening gaps, we may draw conclusions regarding the electron atmosphere as follows:

Let AB be the surface of the metal and an electron be distant r from it. The electric field due to the induced positive charge on the surface is the same as if due to the positive "mirror image" of the electron at a depth r within the metal. The force of attraction of the electron toward the surface is, therefore $F = e^2/4r^2$. The work done by an electron which escapes from the surface is thus

$$W = e\phi = \int_a^\infty \frac{e^2}{4r^2} dr = \frac{e^2}{4a}, \quad (6)$$

where a is the distance from which the electron started, so that $2a$ is the initial distance between the electron and its accompanying positive charge.

According to a well-known theorem of statistical mechanics, the numbers of electrons n_1 and n_2 at any two different positions

FIG. 5.

in a field of force depends on the work ${}_2W_1$ required to take an electron from the second to the first position according to the equation

$$\frac{n_1}{n_2} = \epsilon^{-\frac{{}_2W_1}{kT}} \quad (7)$$

where ϵ is the base of the Napierian logarithms and T is the absolute temperature. If the second position is the initial position at a distance a , so that $n_2 = n_a$, and if the first position is any position distant r , we have the number of electrons per unit volume at distance r given by equations 7 and 6 as

$$n = n_a \epsilon^{\frac{e^2}{4kT} \left(\frac{1}{r} - \frac{1}{a} \right)} \quad (8)$$

To determine n_a we notice that the saturation value of the thermionic current, as given by equation 2, must depend on the den-

sity n_{∞} at relatively great distances $r = \infty$ from the metal in a way which is easily shown by kinetic theory to be

$$i_{\max.} = n_{\infty} e \sqrt{\frac{k T}{2 \pi m}} . \quad (9)$$

This gives the value of n for $r = \infty$, and hence enables the constant n_a in equation 8 to be determined.

From these equations, I have calculated the electron densities given in Table IV at various distances from the surface for the case of tungsten, $\phi = 4.4$ volts and $i_{\max.} = 8$ amperes per square centimetre at 3000° K., whence $2a = 1.6(10)^{-8}$ cm.

TABLE IV.

d (cm.)	n (300° K.)	n (1000° K.)	n (3000° K.)
0.8 (10) ⁻⁸	3.0 (10) ²⁰	3.0 (10) ²⁰	3.0 (10) ²⁰
1.0 (10) ⁻⁸	1.5 (10) ⁵	7.6 (10) ¹⁵	8.7 (10) ¹⁸
2.0 (10) ⁻⁸	1.9 (10) ⁻²⁶	4.3 (10) ⁶	7.1 (10) ¹⁵
4.0 (10) ⁻⁸	7.4 (10) ⁻⁴²	1.0 (10) ²	2.1 (10) ¹⁴
1.0 (10) ⁻⁷	4.4 (10) ⁻⁶¹	2.0 (10) ⁻¹	2.5 (10) ¹³
1.0 (10) ⁻⁶	1.0 (10) ⁻⁵⁶	3.6 (10) ⁻³	6.8 (10) ¹²
∞	3.0 (10) ⁻⁵⁷	3.0 (10) ⁻³	5.9 (10) ¹²

Evidently the electron atmosphere is extremely rare at appreciable distances from metals at ordinary temperatures. Experimental evidence regarding its detection at ordinary temperatures is conflicting. R. W. Wood⁹ reports currents of several milliamperes between optically flat plates of speculum metal, separated by fine quartz fibres, with application of only a few millivolts. On the other hand, Millikan and Shackelford were unable to draw electrons out of gas-free metals with potential gradients lower than about four million volts per centimetre, and suggest that such electron discharges previously reported are due, in some way, to surface impurities.¹⁰ However this may be, the fact of thermionic emission proves the existence of such atmospheres at higher temperatures, and there is no reason for doubting their existence at lower temperatures, although with lower density and extending not so far from the surface.

Recently, in our laboratory, a significant proof of electron

⁹ *Phil. Mag.*, **24**, 1912.

¹⁰ *Phys. Rev.*, **15**, 1920.

atmospheres at high temperatures was obtained. An incandescent tungsten wire was mounted close and parallel to a tungsten strip. The thermal expansion of the leads caused the wire slowly to approach the strip. The ammeter, in series with a battery and the gap between wire and strip, registered the normal thermionic current until the approach was very close, when the current began rapidly to increase with increasing proximity. Before actual contact was made, the thermionic current had risen to many times

FIG. 6.

its normal value. This must have been due to an approach within the region in which the electron atmosphere around the filament showed a noticeable increase in density.

It should be emphasized that the above calculation of densities is necessarily very rough. Actually the metal surface consists of discrete atoms, so that the law of force is more complicated than that underlying equation 6. Furthermore, the effect of the space charge will modify the force on an electron at any point, tending to spread the electron atmosphere to a greater distance from the metal, but with less density near the metal. Nevertheless it is probable that for points not too near the surface, the electron densities are somewhat as given in Table III.

ELECTRIC VALVES.

An electric valve is a device which permits the passage of an electric current in one direction only. It is evident that any

combination of two neighboring conductors not in contact, one of which is surrounded by an electron atmosphere, whereas the other is not, constitutes an electric valve. Electrons can pass continually from the one with the atmosphere to the other, but cannot pass in the reverse direction. Now a hot and a cold metal constitute such a combination. The hotter is the hot metal, the greater is

FIG. 7.

the current-carrying capacity of the valve; while the colder is the cold metal, the more perfect is the rectification. The "Kenetron" is an example of this type of thermionic rectifier. I have wondered if the action of crystal rectifiers may not be due to some peculiarity of distribution of electron atmospheres around the surfaces of crystals.

THE THREE-ELECTRODE VALVE.

Fig. 6 shows the elements of a three-electrode valve, and their simplest mode of connection. Electrons are emitted thermionically by the filament F and pass toward the perforated grid G if the field V_1 is in the appropriate direction. Since the grid has very large mesh, most of the electrons which reach it pass through the

openings and are attracted to the plate P . The ammeter A , or a telephone receiver or other detecting device, is operated by this plate current.

If V_1 is connected to a source of variable electromotive force, the field V_1 varies and consequently the current reaching and passing through the grid will vary. If the thermionic current is large, these variations in the plate current may be very large, even though the current applied to the grid is only large enough to produce the variations in its electrostatic potential, these variations being opposed, to a certain extent, by that portion of the electronic current, which actually reaches the grid instead of passing through. Thus this device is an *amplifier*.

The conditions necessary to secure large amplification and true reproduction of the variable electromotive force applied to the grid are illustrated in Fig. 7. The curve is of the type of Fig. 4. The current at a negative, or retarding, grid voltage is due to the fact that the electrons are emitted from the filament with initial velocities. If the grid is maintained, by a battery through a high resistance, at an average potential V_1 , and if a variable electromotive force dV from the antenna is superimposed, then the plate current is varied by an amount di .

To secure maximum amplification, V_1 must be chosen at the point of maximum steepness of the current-voltage curve, *i.e.*, at the point of inflection. If K is the slope of the curve, then

$$di = K dV. \quad (10)$$

Furthermore, for short distances on each side of this point of inflection the slope is practically constant, so that, if the variable e.m.f. to the grid is a simple harmonic function of the time,

$$dV = V_0 \cos wT,$$

then (11)

$$di = K V_0 \cos wT.$$

Thus the amplified current faithfully reproduces the current which is being amplified. If two-stage amplification is desired, the amplified current from the first-stage tube may be passed through the primary of a step-up transformer, whose secondary is connected to the grid of the second-stage tube.

GAS-FILLED TUBES. DETECTORS.

The preceding relations between voltage and thermionic current hold true only when the electrodes are in so good a vacuum

that effects of collisions of electrons with gas molecules are negligible. When even a minute amount of gas is present the results are very different. At low voltages the thermionic currents are much reduced by the presence of the gas, owing to the fact that electrons emitted by the filament are likely to collide and therefore escape from the region of negative space charge around the tube less quickly than if the gas were absent. If the gas is multi-atomic, the electrons start practically from rest after each collision, while, if the gas is monatomic, the electrons rebound elastically. The effect of a gas is, therefore, to increase the negative space charge around the filament and therefore to reduce the thermionic current. This decrease is greater in monatomic than in multi-atomic gases, since the zig-zag path of an electron through a monatomic gas causes it to remain longer in the immediate neighborhood of the filament.

If the voltage is high enough to cause electrons to ionize gas molecules, the situation is quite different. The positive gas ions, which are drawn toward the filament, neutralize more or less of the negative space charge around the filament and thus permit the escape of more electrons, some of which produce additional positive ions, and so on. Each positive ion neutralizes the space charge of a large number of electrons, since it remains longer in the region of the space charge because of its greater mass and consequent slower motion. If the amount of ionization in the gas is sufficient to permit, by neutralization of negative space charge, the escape of a number of electrons approaching that for maximum or saturation emission characteristic of the temperature of the filament, then the resultant space charge becomes less negative, with the result that the distribution of potential between the electrodes changes so as to give a greater fraction of the entire potential drop in the immediate neighborhood of the filament. This favors further ionization, with the result that the space charge becomes positive and the total current becomes equal to the saturation thermionic current characteristic of the filament temperature, plus a small additional current due to the gas ions.

These stages in the current-voltage curve, in the presence of a gas, are illustrated by Fig. 8, for the case of a tube filled with helium at the indicated pressures.

Curve (a) is at a pressure and thermionic current density too low to give an arc. Indication of ionization is given by a "break" in the curve at 20 volts. Curve (b) shows an arc pro-

FIG. 8.

duced by emission from a relatively cool filament. Not sufficient ionization to produce the arc was obtained until a voltage of

28 volts was applied. With decreasing voltage, however, the arc was maintained at a lower voltage. Curve (c) is a case of a hotter filament, where the arc still strikes at a voltage higher than 20 but breaks definitely at this voltage. With the hottest filaments, the arc both strikes and breaks at the definite minimum of 20 volts, although it may be maintained at a lower voltage, curve (d).

The relative increase in current when the arc strikes may be enormous, amounting to as much as 50,000 fold with scarcely noticeable change in voltage at 20 volts. A two- or three-electrode tube could therefore be used as a *detector* of very great sensitive-

FIG. 9.

ness by adjusting the voltage to a value just less than the striking voltage, so that the increased voltage impressed by the incoming signal causes the arc to strike. Almost infinite amplification may be thus secured. Even if the arc is not used, the gas pressure or filament temperature being too low to produce it, very great amplification may be obtained because of the steepness of the current voltage curve beyond the ionizing point.

Unfortunately, however, the use of ionized gases to increase amplification is attended with complications which probably render such methods of little value except for very special work. Chief among these difficulties are non-reversibility and lag effects, which produce serious distortion. Fig. 8 illustrates that, except under special conditions, the course of the current-voltage curve depends upon whether the voltage is increasing or decreasing. This is due to a difference in the distribution of potential in the space between the electrodes in the two cases.

Lag effects, as illustrated in Fig. 9, are due to the time required for the recombination of ions and for abnormal, or partially ionized, molecules to return to their normal stable conditions. These curves are approximate reproductions of some very interesting unpublished results obtained by Mr. Kannenstine, at the

University of Chicago. They represent oscillograph records of the variation of the current, due to thermionic emission from a filament in an atmosphere of helium gas, as the voltage between the electrodes is varied. Curve (a) represents a stage intermediate between curves (a) and (b), Fig. 8, when the voltage is varied slowly. Curve (b) is taken under similar conditions with the voltage varied more rapidly, as by a 60-cycle e.m.f. Curve (c) shows the results with an e.m.f. of still higher frequency. In curve (b) on the return curve, some of the helium molecules have persisted in an abnormal state which renders them ionizable at voltages down to about four volts. In curve (c) this effect is more pronounced, since the time is shorter. Not all the ions have recombined or have been drawn to the electrodes in the period of the cycle, as is evident from the reverse current during the negative cycle. And some abnormal molecules are still present when the positive part of the cycle is again reached as is shown by the increased current at about four volts.

Consideration of the operation of a three-electrode bulb, as presented in Fig. 7 and its discussion, makes it evident that gas-filled bulbs with characteristics, as shown in Figs. 8 and 9, will not function satisfactorily as amplifiers for ordinary high-frequency transmission. As detectors, valves, keys, etc., they may be of considerable advantage.

CONCLUSION.

It is evident to you that I have kept closely to my subject, The *Physics* of the Three-electrode Bulb, and have attempted to give a survey, necessarily incomplete, of some of the physical phenomena which have become of great practical importance in their applications and which have also had very important bearing on our ideas regarding the nature and structure of matter and electricity. I have not attempted to discuss details of practical operation of three-electrode bulbs, for two sufficient reasons: Time did not permit discussion of both aspects of the subject, and I am not a practical expert in the use of three-electrode bulbs.

For any who are interested in practical uses of the three-electrode bulb, the following books are suggested: "Radio-Communication," Mills; "Thermionic Vacuum Tube and its Applications," Van der Bijl; "Vacuum Tubes in Wireless Communication," Bucher.