THE EMISSION OF ELECTRONS BY A METAL WHEN BOMBARDED BY POSITIVE IONS IN A VACUUM.

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IN the following paper, experiments are described which were undertaken with the object of ascertaining how the number of negative electrons emitted by a metal when bombarded by positive ions in a vacuum depends on the number, the velocity, and the nature of the positive ions.

It is well known that when a metal is bombarded by positive ions of sufficiently high velocity it emits negative electrons.[1] One of the first to show this was Villard,[2] who found that cathode rays are formed by positive ions impinging upon the cathode. He placed near the cathode a diaphragm having two small holes. As the tube was gradually exhausted, so long as the dark space did not extend to the diaphragm, the current flowed uniformly from the whole surface of the cathode. But after the dark space extended beyond the diaphragm the emission from the diaphragm became concentrated at two points opposite the holes in the diaphragm. In a high vacuum, two narrow rays passed from the cathode through the holes and produced a shadow of the diaphragm on the walls of the tube near the anode, showing that electrons were formed only when the positive ions hit the cathode.

J. J. Thomson[3] was the first to observe that when alpha rays from polonium bombard a metal, many slow speed electrons are emitted. Thomson named these negative electrons "delta rays," and concluded that their velocity was about that acquired in falling though a few volts only.

Füchtbauer has[4] shown that negative rays are given off when a metal is hit by canal rays, and that the velocity of the negative rays is independent of the velocities of the canal rays. He has further shown that some metals also reflect canal rays. When the velocity of the canal rays are due to a P.D. of 30,000 volts he found that all metals give off electrons for each canal ray particle in the same order as Volta's series; platinum giving least, and aluminum four electrons for each canal-ray particle.

[1] Townsend, Electricity in Gases (1915).
[2] Villard, Journal de Physique (3), 8, p. 1 (1899).
[3] J. J. Thomson, Proc. Cam. Phil. Soc., 13, p. 49 (1904).
[4] C. Füchtbauer, Phys. Zeit., Vol. 7, pp. 153–157 and pp. 748–750 (1906).

Campbell[1] found the speed of the delta rays to be independent of the speed of the alpha rays by which they were excited, and independent of the material from which the rays are emitted.

Bumstead[2] has found evidence that in addition to delta rays, positive ions are also produced when alpha rays impinge upon a metal in a very high vacuum. These, however, appear to come from the layer of absorbed gas on the metal.

More recently, McLennan and Found[3] have investigated the problem by measuring the number of delta rays emitted from zinc when bombarded with alpha rays in a high vacuum. They found an emission of three electrons per alpha particle from freshly scraped zinc. This effect diminished with the lapse of time and ceased altogether for a while when the zinc was freshly coated in vacuo with a deposit from zinc vapor.

THE EXPERIMENTS.

The method employed in this investigation was to obtain positive ions by heating different salts, such as potassium sulphate, in a vacuum, on a strip of platinum, through which an alternating current was passed. A metal plate was placed near the strip and the positive ions made to bombard it by giving it a negative charge. The current between the strip and plate could be easily measured by a sensitive galvanometer.

The ratio of the negative electrons emitted by the plate to the positive ions striking it, could be found in the following manner. Let C_1 represent the thermionic current carried by positive ions and negative electrons, so that

$$C_1 = C_+ + C_-. \tag{1}$$

Now, if a transverse magnetic field be set up which will stop the electrons by causing them to curve back upon the metal plate but will not stop the positive ions,

$$C_2 = C_+. \tag{2}$$

Dividing (1) by (2)

$$\frac{C_1}{C_2} = 1 - \frac{C_-}{C_+}$$

or

$$\frac{C_-}{C_+} = \frac{C_1}{C_2} - 1. \tag{3}$$

Let N_+ be the number of positive ions striking the plate per second, and N_- be the number of negative electrons given off from the plate per

[1] Campbell, Phil. Mag., Vol. 22, p. 276 (1911), and Vol. 23, p. 46 (1912).

[2] Bumstead, Am. Journ. of Sci., Vol. 36, pp. 91–108 (1913).

[3] McLennan and Found, Phil. Mag., Vol. 30, p. 491 (1915).

second. Then $C_+ = N_+e_+$ and $C_- = N_-e_-$ where e_+ and e_- are the charges on the positive and negative ions respectively. But since $e_+ = e_-$, we have the desired relation,

$$\frac{N_-}{N_+} = \frac{C_-}{C_+}. \tag{4}$$

The procedure was to observe, for a given P.D., first C_1 (directly with the galvanometer), then C_2, then C_2 with the magnetic field reversed, and finally C_1, again. This was done to obviate any fluctuations arising from a change of heating current. In most cases, however, this was really unnecessary, for the initial and final values of C_1 did not differ appreciably. From the means of C_1 and C_2, C_-/C_+ was calculated. Representative values to illustrate this are incorporated in Table I.

Table I.

Pt Cathode, K + ions.

P. D. Volts.	Galv. Deflections in Mm. (1.65×10^{-10} Amp.).						C_1/C_2.	C_-/C_+.
	C_1.	C_2.	C_2 (*H* Reversed.)	C_1.	C_1 Mean.	C_2 Mean.		
146	131	130	130	130	130.5	130	1.004	.004
190	147	146	146	147	147	146	1.006	.006
250	154	152	156	158	156	154	1.012	.012
280	160	157	157	159	159.5	157	1.015	.015
350	166	163	163	166	166	163	1.018	.018
400	166	162	162	165	165.5	162	1.021	.021
475	172	168	168	172	172	168	1.023	.023
525	168	164	164	169	168.5	164	1.025	.025
560	152	148	148	152	152	148	1.025	.025

The magnitude of H (the magnetic field), necessary to stop the negative ions without stopping the positive, could be calculated from a formula given by J. J. Thomson[1] for determining e/m when using a magnetic field to stop ions passing between parallel plates; viz.,

$$\frac{e}{m} = \frac{2V}{H^2d^2},$$

where e/m is the ratio of the charge in the ion to its mass, V the potential difference between the plates, H the magnetic field, and d the distance between the plates.

Calculations according to this formula are exhibited in the following table.

[1] J. J. Thomson, Conduction of Electricity through Gases (1906), p. 219.

TABLE II.

Nature of Ions.	Electrons.	K + Ions.	Li + Ions.	Pb + Ions.
e/m.	1.7×10^7 E.M.U.	$10^4/39$ E.M.U.	$10^4/7$ E.M.U.	$10^4/85$ E.M.U.
H(calculated) necessary to just stop ions at 100 volts (10^{10} E.M.U.)	50	9,000	4,000	13,000
H(calculated) necessary to just stop ions at 600 volts (6×10^{10} E.M.U.)	110	21,000	9,000	32,000
H employed in the experiment	..	400	400	400

The effect produced by H was further tested by choosing a definite P.D. and varying H over a considerable range (100–1,000). As no change occurred in the diminution of the leak it was concluded that even with as high a value of H as 1,000 units positive ions were not being deflected unless it were at very low potentials, such as 10–50 volts. No observations of C_-/C_+ were made at these low P.D.s, the reason being that any diminution of current caused by H was too small to be detected or did not exist at all. In nearly all the observations here recorded H was 400 units.

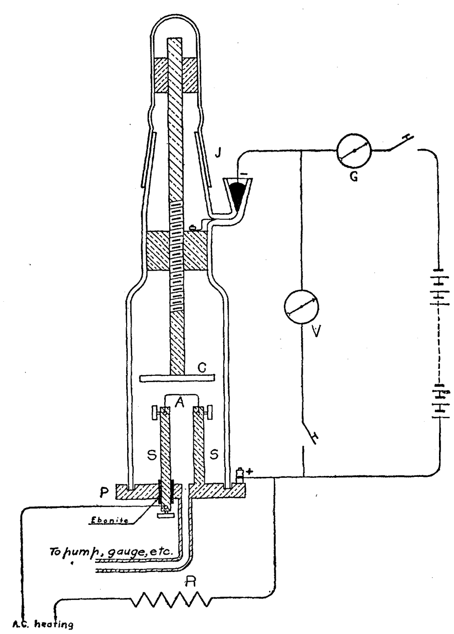

Fig. 1.

The apparatus is shown diagrammatically in Fig. 1. It consisted of a glass tube about 4 cm. in diameter cemented to a brass plate P with sealing wax, and supported between the poles of a large electromagnet. SS were two brass rods, supporting the narrow strip of platinum, A. One of the rods passed through an ebonite plug and was thus insulated from P. The strip of platinum could be heated to any desired temperature by passing a 60-cycle alternating current through it. It could be made the anode by connecting to the positive terminal of a battery of "Tungsten Ever-Ready" cells (capable of giving nearly 600 volts), while C, the metal plate, was made the cathode. C was carried by a micrometer screw and could be moved up and down by turning the ground joint J, so that the distance AC could be varied as desired. Some observations made by moving C up and down and noting the current showed that the leak across the gap AC decreased slightly as the distance AC was increased. This is shown in the following table.

Table III.

Dist. Between Electrodes (Mm.).	Current × (1.65 × 10⁻¹⁰ Amperes) (P.D. = 146 Volts).						
1............	160	160	150	134	127	180	210
2............	160	158	—	132	125	178	208
4............	154	156	—	—	—	—	202
5............	150	155	140	127	120	170	200
6............	150	154	138	127	118	168	—
8............	145	148	—	—	—	166	198
10...........	142	145	134	126	112	165	196

In the subsequent observations the distance between the platinum strip and the metal plate was kept at about one centimeter.

The potential difference between A and C was measured by a Kelvin Electrostatic Voltmeter, and the thermionic current was measured by a Leeds and Northrup sensitive galvanometer (sensibility $= 1.65 \times 10^{-10}$ ampere per mm. deflection).

The greatest difficulty throughout the experiment was the securing of a good vacuum. A Gaede rotary mercury pump was used in series with a box pump. When a sensitive McCleod Gauge indicated no gas pressure, the vacuum was put to further test by means of an induction coil whose terminals were placed across the gap AC and the pump kept running

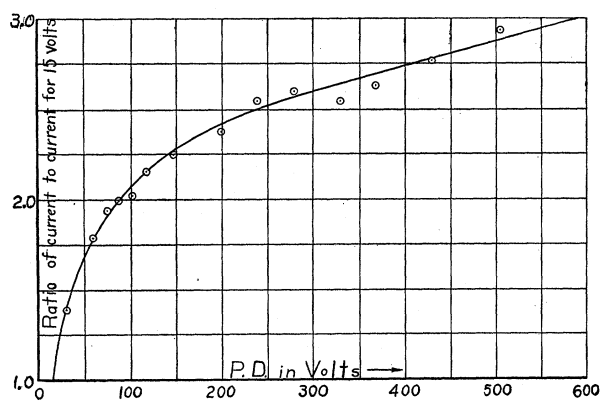

Fig. 2.

until no fluorescence appeared in the tube and the spark preferred to pass through the air outside. The mercury or oil vapors which might have been in the apparatus were frozen out by means of CO_2 snow. Finally, the pump was kept running throughout a series of observations. The apparatus was kept dry by means of P_2O_5, and the vacuum was washed out from time to time with a little dry air.

To test the variation of the thermionic current with the change of potential difference, a double throw switch was placed in the circuit so that the leak for any P.D. could be compared quickly with the leak for 15 volts. This is illustrated in Fig. 2, in which the P.D.s are plotted as abscissæ and the ratios of the leak for given P.D.'s to the leak for 15 volts as ordinates. It is worthy of note that with low potential differences the leak rose rapidly with the increase of P.D. until about 150 volts where it approached saturation.

To find C_-/C_+, observations were made with aluminium and platinum as cathodes and K_2SO_4, Li_2SO_4, and Rb_2SO_4 respectively on the hot platinum strip A, as a source of positive ions. For each particular salt and metal, a great many observations were made. Table IV. shows representative values for a number of observations in a particular case,

TABLE IV.

Pt Cathode, K + Ions.

P.D. (Volts).	C_-/C_+.												Mean C_-/C_+.
146	.005	.005	.007	.004	.002	.005	.005	.003	.005	.003	.003	.007	.0045
190	.005	.012	.012	.006	.008	.005	.007	.009	.006	.006	.009	.004	.007
250	.012	.012	.012	.012	.013	.012	.020	.012	.011	.011	.011	.011	.0125
280	.012	.015	.012	.015	.018	.018	.016	.015	.013	.012	.013	.013	.014
350	.018	.032	.018	.013	.012	.020	.012	.012	.016	.019	.013	.016	.017
400	.023	.014	.023	.021	.025	.018	.025	.015	.013	.021	.016	.020	.0195
475	.023	.020	.022	.018	.030	.024	.015	.022	.021	.017	.020	.016	.021
525	.020	.030	.025	.025	.026	.022	.022	.025	.028	.018	.028	.018	.024
560	.020	.026	.032	.025	.028	.028	.028	.031	.018	.018	.028	.029	.025

while Table V. gives the mean values for all the salts and metals used. By an inspection of Table V. and Fig. 3, it is seen that the largest effect occurs in the case of lithium and the smallest with rubidium, while that from potassium lies between the others; the values for all three being greater with aluminium than with platinum.

Some preliminary experiments showed that the effect decreased somewhat after the apparatus had stood evacuated for several days. Consequently, all the results recorded in Tables I., IV. and V. are those taken after the apparatus had been allowed to stand evacuated for several days. Some observations were made with Li_2SO_4 on the hot strip, and aluminium as cathode, after the apparatus had been standing for nearly a

TABLE V.

Mean Values of G/C_+.

P.D. Volts.	Al Cathode.			Pt Cathode.		
	K_+.	Li_+.	Rb_+.	K_+.	Li_+.	Rb_+.
74	.004	....	....	....	.006	....
115	....	....	....	....	....	.0016
125	.008	....	....	....	....	....
146	.011	....	....	.0045	.013	.002
177	....	.010	....	....	....	....
190	....	....	....	.007	.017	.003
215	.018	.020	....	....	....	....
235	....	....	....	....	....	.005
250	....	....	....	.0125	....	....
265	....	....	....	....	.019	....
275	.025	.058	.008	.014	.007	....
300	....	....	....	.024	....	....
340	.037	.093	.014	....	....	....
350	....	....	....	.017	....	.008
360	....	....	....	....	.026	....
375	.047	....	....	....	....	....
390	....	....	....	....	.030	....
400	....	....	....	.0195	....	.009
450	.067	.138	.022	....	....	....
475	.080	....	....	.0207	.036	....
535	....	.214	.036	....	....	....
560	.092	....	....	.025	.043	.012

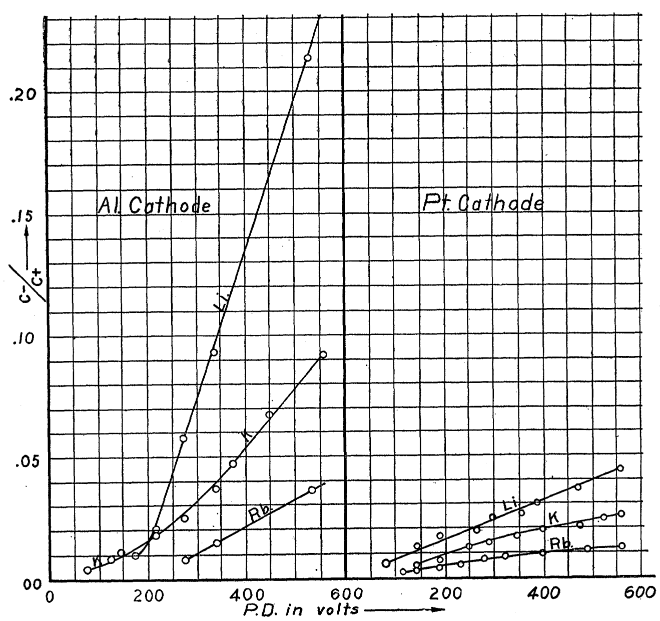

Fig. 3.

month. Comparing the results with those obtained after a week's time a slight decrease is noticeable (Fig. 4).

It seems quite likely, therefore, that part of the effect, at least, is due to gas absorbed by the metal. However, some tests were made with

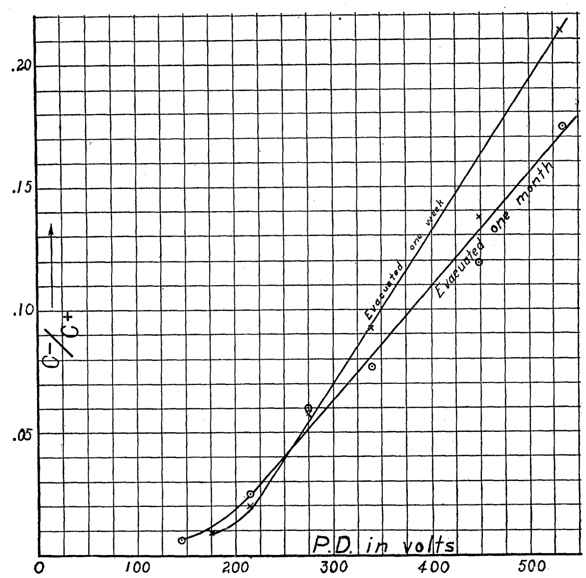

Fig. 4.

platinum cathode and rubidium, after heating the metal plate for several hours in air at a low pressure by bringing it in contact with the hot platinum strip. The results obtained (Table VI.), although somewhat erratic,

TABLE VI.

Showing the Effect of Gas. (Pt Cathode, Rb^+ Ions.)

P.D. (Volts).	C_-/C_+.		
	As in Table V.	After Heating in Air.	After Heating in Hydrogen.
115	.0016	....	....
146	.002	.000	.0025
190	.003	.004	.005
235	.005	.0065	.0085
265	....	.007	....
275	.007	....	.009
350	.008	.008	.010
390	....	.009	....
400	.009	.009	.012
485	.011	.0095	.014
560	.012	.010	.017

approximate to those obtained prior to the test with air. A similar test was made using hydrogen instead of air. This time the values of C_-/C_+ were slightly greater than previously, indicating that the platinum had possibly soaked up some of the hydrogen. These values, however, are not as greatly in excess as one might expect, so it appears that the gas was only slightly absorbed.

Application to Discharge in Gases.

Consider the dark space in a discharge of electricity through a gas at low pressure and suppose no positive ions striking the cathode during a particular time interval. Some of these positive ions striking the cathode will set free electrons but only those which have fallen through a long enough free path to acquire sufficient velocity. Let the *mean* free path be represented by λ. Let n be the number during this time interval which have free paths greater than a length x. Then $dn = -\beta n dx$, where β represents the number of collisions a positive ion makes in going one centimeter.[1] Therefore, on integrating, $n = n_0\epsilon^{-\beta x} = n_0\epsilon^{-x/\lambda}$. The number having free paths between x and $x + dx$ is therefore given by

$$dn = \frac{n_0}{\lambda}\epsilon^{-x/\lambda}dx.$$

Let γ be the ratio of the number of electrons emitted from the cathode to the number of positive ions producing them. γ is a function of the velocity of the positive ions as has been found in the experiments described above. $\bar{\gamma}$, the average value of γ, is given by the expression

$$\bar{\gamma} = \frac{1}{n_0}\int dn\gamma = \frac{1}{n_0}\int_{x_1}^{x_2}\left(\frac{n_0}{\lambda}\epsilon^{-x/\lambda}\right)\gamma dx. \tag{5}$$

By considering Fig. 3, it can be seen that the curve representing the values of $\gamma(= C_-/C_+)$ is practically a straight line and can be expressed analytically by

$$\gamma = aV - b, \tag{6}$$

where V is the potential difference, a the slope of the curve and b a constant. Equation (6), however, holds only for positive values of γ.

If we assume, on the basis of Aston's experiments,[2] that there is no appreciable difference of potential between the cathode and the adjacent gas, we may write

$$V = \int_0^x X dx,$$

[1] Townsend, loc. cit.

[2] F. W. Aston, Proc. Roy. Soc., *A*, 84, p. 526, 1911.

where X is the electric force. In the dark space X varies uniformly, being a maximum at the cathode and a minimum at the negative glow, so that $X = A - Bx$, where A and B are constants. At the negative glow $X = 0$, and $A = BD$, where D is the length of the dark space. Hence

$$V = B\int_0^x (D - x)dx = B\left(Dx - \frac{x^2}{2}\right). \tag{7}$$

When $\gamma = 0$, $V = b/a$. Call this particular value of V, V'. Then

$$V' = B\int_0^{x'} (D - x)dx = BDx' - \frac{Bx'^2}{2}, \tag{8}$$

where x' is the distance in the dark space representing the paths through which the positive ions fall under the P.D. of V' volts before impinging on the cathode.

To determine B, take

$$K = \int_0^D xdx,$$

where K is the " normal " cathode fall of potential. From this we get

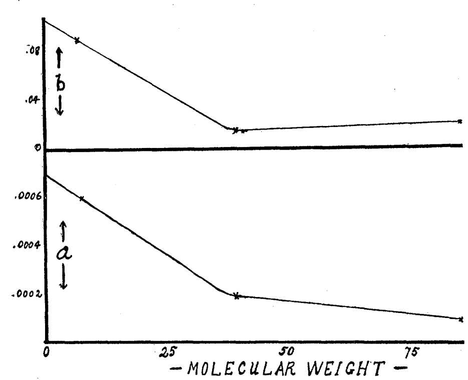

Fig. 5.

$B = 2K/D^2$ and equations (7) and (8) now become

$$V = \frac{2K}{D^2}\left(Dx - \frac{x^2}{2}\right), \tag{7'}$$

$$V' = \frac{2K}{D^2}\left(Dx' - \frac{x'^2}{2}\right). \tag{8'}$$

Equation (6) becomes

$$\gamma = a\frac{2K}{D^2}\left(Dx - \frac{x^2}{2}\right) - b. \tag{6'}$$

and finally (5) becomes

$$(5') \qquad \bar{\gamma} = \frac{1}{\lambda}\int_{x'}^{D} \epsilon^{-x/\lambda}\left[a\frac{2K}{D^2}\left(Dx - \frac{x^2}{2}\right) - b\right]dx.$$

Suppose now we consider a special case, viz., an aluminium cathode and a discharge through hydrogen with a gas pressure corresponding to one mm. of Hg. Investigators have found that under these conditions, $D = 1$ cm. approximately, $K = 200$ volts (nearly), and λ (according to Meyer) is .013 cm. for the hydrogen molecule. The values of V', a, and b, corresponding to the different kinds of positive ions, are found from Fig. 3, when aluminium was used as cathode.

Positive Ions.	Mol. Wt.	*a.*	*b.*	*V'.*
Li.	7	.0006	.09	150
K.	39	.0002	.015	75
Rb.	85	.0001	.020	200

Similar values for hydrogen are found by plotting the above values of a and b against the molecular weights (Fig. 5) and extrapolating. a is found to be .007, $b = .104$, and $V' = 150$ volts (nearly). Substituting the values of K, V', and D, in (8') and solving, $x' = .5$ cm. Substituting for the various constants their numerical values, (5') may be simplified to

$$(5'') \qquad \bar{\gamma} = \frac{1}{\lambda}\int_{.5}^{1} \epsilon^{-x/\lambda}\left[.28\left(x - \frac{x^2}{2}\right) - .104\right]dx.$$

Integrating

$$(9) \qquad \bar{\gamma} = \epsilon^{-x/\lambda}[-.28(x+\lambda) + .14\{x^2 + 2\lambda(x+\lambda)\} + .104]_{.5}^{1}.$$

Upon evaluating, $\bar{\gamma}$ is found to be of the order 10^{-17}, which, of course, is negligible.

While Aston has found no appreciable difference of potential between the cathode and the gas, others[1] have found a considerable drop in the potential right at the cathode. Under these conditions,

$$V_\lambda = \int_0^x X dx + V_0,$$

where V_0 denotes the fall of potential right at the cathode and

$$K = \int_0^D X dx + K_0,$$

where K_0 denotes the value of V_0 in the case of the "normal" cathode fall.

[1] C. A. Skinner, Phys. Rev., June and Aug., 1915, W. L. Cheney, Phys. Rev., Feb., 1916; W. E. Neuswanger, Phys. Rev., Feb., 1916.

Thus equations (7′), (8′), (6′), and (5′) become modified to

$$V = \frac{2(K - K_0)}{D^2}\left(Dx - \frac{x^2}{2}\right) + V_0, \tag{10}$$

$$V' = \frac{2(K - K_0)}{D^2}\left(Dx' - \frac{x'^2}{2}\right) + V_0, \tag{11}$$

$$\gamma = a\left[\frac{2(K - K_0)}{D^2}\left(Dx - \frac{x^2}{2}\right) + V_0\right] - b, \tag{12}$$

$$\bar{\gamma} = \frac{1}{\lambda}\int_{x'}^{D} \epsilon^{-x/\lambda}\left\{a\left[\frac{2(K - K_0)}{D^2}\left(Dx - \frac{x^2}{2}\right) + K_0\right] - b\right\} dx. \tag{13}$$

x' is found to be .3 cm., K_0 (from the experiments of the writer) is nearly 90 volts; the values of the other constants are the same as above. $\bar{\gamma}$ is in this case of the order 10^{-10}.

Thus, it appears from calculations based on either Aston's or Skinner's experiments, that in the case of the "normal" cathode fall of potential in a discharge of electricity through hydrogen at low pressure extremely few electrons are set free from the cathode. The above calculation, however, is subject to error since one is not quite sure of the value V'. As already stated above, it was difficult to obtain any accurate observations of γ for low values of V and one is not certain that the curves in Fig. 3, which we have assumed to be nearly straight lines, do not become asymptotic to the V-axis. At any rate, the calculation shows that $\bar{\gamma}$ is very small.

Skinner,[1] working with the "normal" cathode fall in hydrogen at low pressures, calculated $\bar{\gamma}$ to be of the order 10^{-4}, for an aluminium cathode. The writer,[2] making use of Skinner's theory, found under similar conditions the same order of magnitude for $\bar{\gamma}$.

Skinner's theory, however, does not take into account the collisions of positive ions with the molecules of the gas. H. A. Wilson,[3] taking into the account the ionization by collision of the positive ions has shown that $\bar{\gamma}$ is probably small.

Townsend consider $\bar{\gamma} = 0$ except at very low pressures when high potentials are necessary. Aston[4] has made some investigations under these conditions. Here is one set of values which he obtained when using aluminium cathode in hydrogen: $V = 700$ volts, $D = 2.09$ cm., $p = .157$ mm. of Hg. From these values x' works out to be .25 cm. and $\lambda = .083$ cm. Applying these to equation (5′) $\bar{\gamma}$ is found to be of the order 10^{-2}.

[1] C. A. Skinner, loc. cit.

[2] W. L. Cheney, loc. cit.

[3] H. A. Wilson, PHYS. REV., Sept., 1916.

[4] F. W. Aston, Proc. Roy. Soc., *A*, Vol. 87, p. 437.

It appears, therefore, that $\bar{\gamma}$ increases very rapidly as the pressure is diminished. The experiments described in this paper show that in the case of a thermionic current in a vacuum γ is appreciable for lower values of the P.D. corresponding to the "normal" cathode fall in hydrogen.

Summary.

1. The magnitude of the thermionic current in a vacuum corresponding to various P.D.s has been compared with the thermionic current corresponding to a P.D. of 15 volts.

2. The ratio of the number of electrons leaving the cathode to the number of positive ions striking it has been found with positive ions of different velocities and for two different metals, viz., aluminium and platinum. It has been found that this ratio depends on the velocity of the positive ions.

3. It has been found that the effect is diminished somewhat after the metal has stood in a vacuum for some time and increased slightly after it had stood in hydrogen. It appears, then, that the effect is at least partially due to gas in the metal.

4. The ratio of the number of electrons emitted from the cathode to the number of positive ions bombarding it has been calculated for the case of a discharge in hydrogen.

The writer wishes to express his indebtedness to Professor H. A. Wilson, at whose suggestion this investigation has been undertaken, and whose interest and kindly counsel have been very valuable in surmounting many difficulties.

The Rice Institute,
Houston, Texas,
March, 1917.