

Photoelectric Currents in Gases between Parallel Plates as a Function of the Potential Difference

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(Received May 3, 1932)

If one of two parallel plate electrodes in a gas emits photoelectrons, the current received at the collecting electrode is a function of the potential difference, the gas pressure, the initial velocity of the photoelectrons, and the mobility of the carrier. In the experiments reported here, a quartz mercury arc and a plane zinc electrode were used as the source of photoelectrons. Current:potential-difference curves were obtained for different gas pressures in hydrogen and nitrogen, and the ratio of the current, i , to the saturation current, I_0 , obtained in each case. A theoretical equation of J. J. Thomson gives the relation

$$i = \frac{I_0(6\pi)^{\frac{1}{2}}kX}{C + (6\pi)^{\frac{1}{2}}kX}$$

where X is the field strength; k , the mobility of the carrier; and C , its random velocity. The validity of this equation is established by the experimental data which permit the values of the electron mobility k to be determined as a function of X/p . Values so obtained agree well with those obtained by Loeb and by Townsend and Bailey. An equation recently given by Langmuir (Phys. Rev. **38**, 1656 (1931)) is shown to be applicable only at low pressures where it yields a satisfactory value of the mean free path of the electron.

INTRODUCTION

IF ONE of two parallel plate electrodes in a gas emits photoelectrons, the current which will be received at the positive collecting electrode varies with the potential across the plates and the pressure of the gas. This phenomenon has been investigated by several observers.^{1,2,3,4} It was treated theoretically by J. J. Thomson⁵ in 1906 who proposed the equation

$$i = \frac{I_0(6\pi)^{1/2}kX}{c + (6\pi)^{1/2}kX}$$

in which k is the mobility of the carrier; X the field strength at which the current i is measured; c , the random velocity of the electrons; and I_0 the saturation current. Prior to 1926, however, no satisfactory comparison between theory and experiment had been made. In 1926 in this laboratory, Woolsey, in an unpublished thesis, attempted to verify this equation taking into account the electron mobility. He measured the current which passed between

¹ Stoletow, Journal de Physique **9**, 468 (1890).

² Schweidler, Comptes Rendus **127**, 224 (1898).

³ Lenard, Ann. d. Physik **2**, 359 (1900).

⁴ Varley, Phil. Trans. **A202**, 439 (1904).

⁵ J. J. Thomson, Cond. Elec. through Gases (Cambridge University Press, Cambridge, 1928) p. 466.

two parallel plates at various potential differences and for different gas pressures, when one of the plates, of speculum metal, was illuminated with ultraviolet light. He was unable to determine accurately the saturation current; the exact interpretation to be placed upon the meaning of c was not clear; and the experiments were not conclusive.

In a recent article, Langmuir⁶ proposed an equation of the form

$$i = 4I_0\lambda\phi/3a$$

in which ϕ is a function of the potential across the plates and the initial energy with which the photoelectron is liberated; λ is the mean free path of the electron in the gas; and a is the distance between the plates. Since this equation predicted a ratio of i/I_0 of a somewhat different order than that found by Woolsey, it seemed of interest to carry out the experiments with greater accuracy to determine the applicability of the above equations. Consequent to the refocussing of attention on this problem by Langmuir the meaning to be attached to c in Thomson's equation was clarified by Professor L. B. Loeb who put the equation into a suitable form for verification. The experiments in consequence were carried out under improved conditions and have led to the results reported here.

APPARATUS AND PROCEDURE

The essential features of the apparatus are shown in Fig. 1. A quartz mercury arc was used as a source of ultraviolet radiation. The light from the arc was focused on the plate by means of quartz lenses and passed through a plane quartz window sealed to the chamber by a Pyrex-quartz graded seal. The plates and supports were entirely of zinc save for the tungsten-Pyrex leads. The upper plate was surrounded by a grounded guard ring and equipotential vanes were inserted midway between the plates to maintain a uniform field. The upper collecting plate, to which was connected the electrometer system, thus received only electrons which had traveled in a uniform field. The area of the collecting plate was 20.9 cm and the plates were 3.00 cm apart. They were kept parallel during the glass blowing by an accurate spacing block.

Potentials were applied to the lower plate by means of a bank of storage cells. The equipotential vanes were connected to the midpoint of a 100,000 ohm resistance inserted between the lower plate and ground. Field strengths as high as 300 volts/cm could be employed.

Hydrogen and nitrogen were chosen as the gases to be studied as they do not attach electrons when adequately purified. The purification was carried out in the manner previously described for the mobility experiments in pure gases. The chamber could be evacuated to better than 10^{-6} mm for determining the saturation current and before filling with purified gas.

The procedure in the experiments was carried out as follows. After the polished and cleaned zinc plates had been allowed to come into equilibrium with the gas to be studied, the chamber was pumped out and the saturation

⁶ Langmuir, Phys. Rev. **38**, 1656 (1931).

current determined. The chamber was then filled to the desired pressure with pure gas, and the current:potential-difference curve taken for the range of potentials between zero and as high as conditions permitted. The chamber was then re-evacuated and the saturation current again determined. The agreement of this value with the one taken at the beginning of the experiment was considered sufficient evidence that the photoelectric effect had not varied during the course of the measurement.

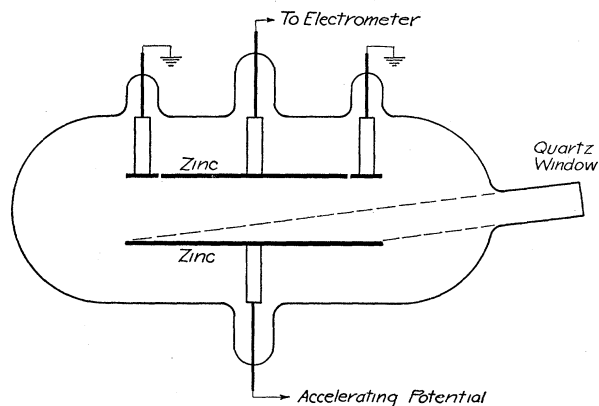


Fig. 1. Diagram of chamber showing plane parallel zinc electrodes.

EXPERIMENTAL RESULTS

A series of curves for hydrogen at different pressures is shown in Figs. 2 and 3. Curve *A* was taken with the highest attainable vacuum. The lack of saturation at the lower values of V is due to the finite size of the collecting

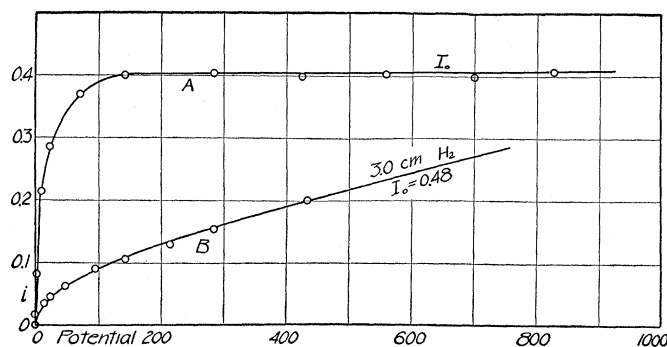


Fig. 2. Saturation current in vacuum and at 3.0 cm H₂. The current is in arbitrary units and the potentials in volts.

electrode and the random direction of emission of the photoelectrons from the cathode. Curve *B* is that obtained for hydrogen at 3 cm and *C* for hydrogen at 9.5 cm. Curves *D*, *E*, are for 33 and 67 cm hydrogen respectively. Fig. 4 shows curves for hydrogen at 1 mm pressure and at 2 mm pressure. Curves were also taken in nitrogen at 33 cm and 67 cm pressure. Their appearance is not greatly different from those reproduced here.

THEORETICAL

The theoretical equation developed by J. J. Thomson is of the utmost simplicity. As the electrons are ejected from the cathode by the incident light, they collide with the gas molecules above the plate. A certain number diffuse

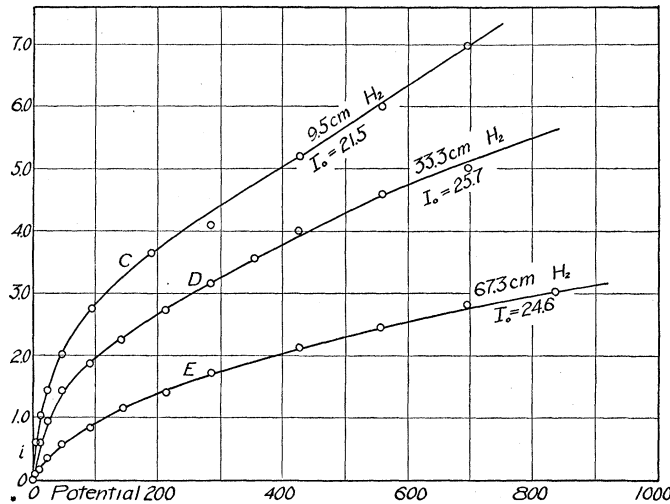


Fig. 3. Current:potential-difference curves for various pressures of hydrogen.

back to the plate in consequence and contribute nothing to the current through the gas. The resultant current is, then, that due to the total charge given off by the cathode, minus the amount returned to it by diffusion. The number of electrons which strike unit area of the plate in unit time is given by

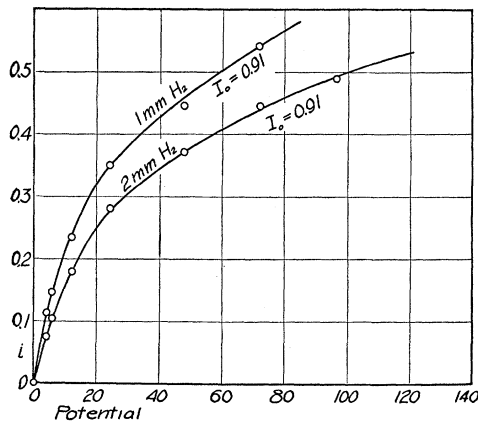


Fig. 4. Current:potential-difference curves at low pressures of hydrogen.

the expression $nc/(6\pi)^{1/2}$ where c is the root mean square velocity of translation of the electrons and n their density. Similarly the current will be given by

$$i = nekX \tag{1}$$

where k is the mobility and X the field strength. If the total number of electrons given off by the cathode be n_0 , then we can write

$$n_0 e = c n e / (6\pi)^{1/2} + n e k X = I_0 \quad (2)$$

Eliminating n from (1) and (2) we may write

$$i = \frac{I_0 (6\pi)^{1/2} k X}{c + (6\pi)^{1/2} k X}$$

where i and I_0 represent the current at a field strength X and the saturation current respectively. We are now faced with the proper evaluation of c . Heretofore this has been considered to be either the velocity of thermal agitation of electrons in equilibrium with the gas, or the energy as deduced from field strength and mobility considerations. It is obvious, however, that the greater part of the diffusion process is going to occur in the immediate vicinity of the plate *before* the electrons have reached thermal and field equilibrium. While they are then in the vicinity of the plate, they possess, owing to the small inelasticity of their impacts with gas molecules, most of the initial energy with which they were ejected. It is this energy that determines the number of collisions made and, hence, the extent of the diffusion back to the electrode. Accordingly, it seems reasonable to assign to c *the most probable velocity with which the electrons leave the plate*. This initial energy can be easily calculated from the wave-length of the incident light and the work function of the metal. The latter constant is a source of uncertainty inasmuch as it varies quite appreciably with the condition of the surface. In these experiments it was not possible to measure the work function. Accordingly the value was taken to be 3.57 volts, as given in a table by Hughes and DuBridge.⁷ The conditions of the experiments were such that the 2536A line of mercury was the only exciting radiation of importance. This, with the work function given, leads to a value of 1.29 volts for the maximum energy of emission. Since it has been shown⁸ that the *most probable velocity* is approximately 0.6 that corresponding to maximum energy, the value of c has been chosen as

$$\begin{aligned} c &= 0.6 \times 1.29 \times 5.94 \times 10^7 \text{ cm/sec.} \\ &= 4.58 \times 10^7 \text{ cm/sec.} \end{aligned}$$

With this value of c , the equation of Thomson may be put into the form

$$\frac{I_0}{i} - 1 = \frac{c}{(6\pi)^{1/2} k_0 X p / 760} = \frac{4.58 \times 10^7}{(6\pi)^{1/2} k_0 X p / 760}$$

from which it is possible to calculate the values of k_0 from the data given in Fig. 2 and 3. The values of k_0 so obtained are plotted against X/p and the results shown in Fig. 5. Similar calculations carried out for nitrogen are shown in Fig. 6. The trend of the curves is exactly that obtained by Loeb⁹ and the

⁷ Hughes and DuBridge, Photoelectricity (McGraw Hill, N. Y., 1932) p. 76.

⁸ Lukirsky and Prilezaev, Zeits. f. Physik 49, 236 (1928).

⁹ L. B. Loeb, Kinetic Theory of Gases (McGraw-Hill, N. Y., 1927). p. 504.

absolute values differ less than might be expected from the uncertain value employed for the work function of the zinc electrode. An increase of 0.3 volt in the work function would bring them into almost exact agreement. In the case of hydrogen the measurements at low pressures enabled k_0 to be found for values of X/p as great as 20. At this point the value of k_0 was found to be 845 cm/sec per volt/cm. Townsend and Bailey¹⁰ have studied k_0 for values of X/p as high as 0.85 where they found a value of k_0 of approximately 1600.

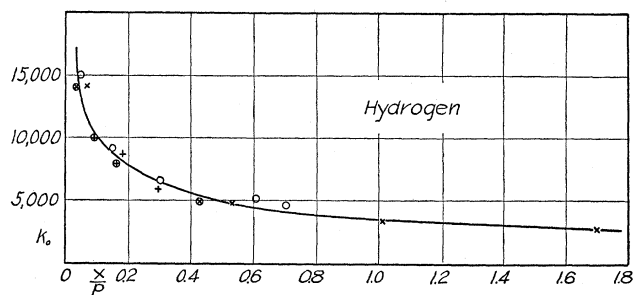


Fig. 5. Electron mobility in hydrogen as a function of X/p . The circles are values computed from data taken in hydrogen at 33.3 cm pressure; the crosses at 9.5 cm pressure; and the remaining points at 67.3 cm pressure.

As far as is known, the present measurements are the only ones that have been attempted at such high values of X/p . While, owing to the approximate nature of the calculations involving an average energy of emission and a doubtful value of the work function, too much confidence cannot be placed

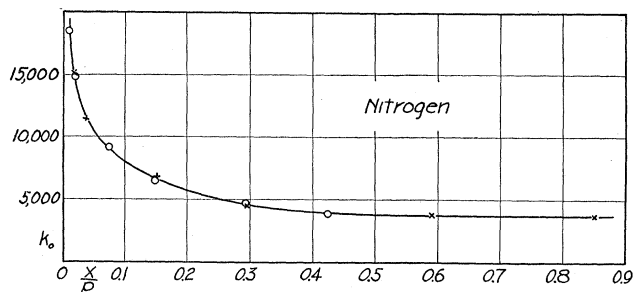


Fig. 6. Electron mobility in nitrogen as a function of X/p . The circles are values computed from data taken at 68 cm, and the crosses data taken at 33 cm.

on this procedure as a method of accurately determining electron mobilities, the method is useful in giving orientating data in this field. In any case, it is clear that the Thomson equation adequately accounts for the facts within the limitations of the calculations.

One may now turn to a test of the equation recently proposed by Langmuir. The derivation of this relation is based on a well-known diffusion equation of electrons in an electric field proposed by G. Hertz.¹¹ Substantially the

¹⁰ Townsend and Bailey, Proc. Roy. Soc. **A87**, 357 (1912).

¹¹ G. Hertz, Zeits. f. Physik **32**, 298 (1925).

derivation is carried out on the same principles as the Thomson equation, i.e., to consider the number of electrons lost from the initial saturation current by diffusion back to the emitting electrode. The form of the equation which applies to parallel plate electrodes is given by

$$i = \frac{4}{3} \frac{I_0 \lambda}{a} \frac{V}{V_0} \frac{1}{\log [(V + V_0)/V_0]}$$

where V is the potential across the plates and V_0 the energy with which the electron is ejected from the cathode, and the other symbols have been defined above. The function ϕ has been replaced by its definition in terms of V and V_0 in this equation.

In deducing this relation, however, a natural assumption is made which is barely applicable at a pressure of 1 mm in hydrogen and certainly not applicable at greater pressures. It is assumed that an electron starting out with an energy V_0 and going through a potential field to a point of potential V will have its kinetic energy expressible by

$$\frac{1}{2}mv^2 = (V_0 + V)e.$$

This is correct provided the electron does not lose energy in its impact with gas molecules. Compton and Benade¹² have shown that even in He, an electron loses a fraction f of its energy in collision with a gas molecule where f is approximately equal to $2m/M$; and more recently Harries¹³ has shown that even greater losses can occur in CO and N₂. Therefore, if the Compton¹⁴ theory of electron behavior in gases is correct, the electron continually loses energy to the gas molecules as it gains it from the field between mean free paths, and eventually reaches a steady state where it possesses its terminal energy. To gain an idea of the error introduced by neglecting this loss of energy in the case of hydrogen, it is easy to calculate the energy of an electron after it has gone a distance of 1 cm in H₂ gas in a field of unit gradient. The results are shown in Table I. The assumption that the electron gains the

TABLE I.

ϕ (mm)	X	Distance	Energy (volts)
1	1	1	0.94
2	1	1	0.804
30	1	1	0.075

entire energy of the field through which it has passed would lead to a value of the energy of one volt in each case. It is thus seen that such an assumption is barely sufficient at pressures of 1 mm and fails very badly at higher pressures. Accordingly we would not expect the Langmuir theory to be applicable in the region to which we have successfully applied the Thomson equation.

¹² Compton and Benade, Phys. Rev. **9**, 187 (1918).

¹³ Harries, Zeits. f. Physik **42**, 26 (1927).

¹⁴ Compton, Phys. Rev. **22**, 333 (1923).

We should, however, expect it to apply with fair accuracy to the data taken at 1 and 2 mm pressure. Computation of the experimental results given above in Figs. 2, 3, and 4 on this basis lead to the results given in Table II. The

TABLE II. *Computed values of mean free path.*

Pressure	I_0	i	V	Mean free path
1	0.91	0.145	6	1.76×10^{-5}
1	0.91	0.23	12	1.80
1	0.91	0.50	60	1.17
2	0.91	0.10	6	2.44
2	0.91	0.16	12	2.50
2	0.91	0.39	60	1.77
30	0.96	0.14	60	9.4
95	2.15	0.22	60	20.8
330	7.15	0.42	60	41.0

kinetic theory mean free path for H_2 to which the values given above should correspond (the value of λ determined from Langmuir's equation having been reduced to 760 mm and multiplied by $4(2)^{1/2}$), is variously given, but 1.8×10^{-5} cm is an average value. It is seen that at low pressures and voltages, the Langmuir equation gives excellent agreement—probably better than the data warrant. At higher pressures, where the assumptions of his derivation do not apply, we find the expected deviation. It might be noted that in Langmuir's equation there is a fortuitous escape from the dangers of the assumption that $\frac{1}{2}mv^2 = (V + V_0)e$. This happens because of the fact that in the final equation, V appears in the equation independently of this assumption, V_0 is a true representation of the electron energy where most of the diffusion to the electrode is taking place; and as a result, only the function $\log [(V_0 + V)/V_0]$ neglects the loss of energy to gas molecules. In consequence, the deviation in λ above computed at higher pressures is much less than might be expected from Table I. An attempt was made to carry through an analogous derivation employing the Compton equations for the rate of energy gain as the electron moves through the gas. The resulting equation, however, was a complicated function of X/p and λ and was totally unsuited to experimental comparison. It is not reproduced here in view of the fact that the Thomson equation satisfactorily accounts for the observed phenomena.

In conclusion, it is desired to extend sincere thanks to Professor L. B. Loeb for his continual interest and inspiring suggestions during the course of these and previous experiments.