*Second Series* *November, 1922* *Vol. XX., No. 5*

THE

PHYSICAL REVIEW.

# THE MOBILITIES OF ELECTRONS IN HYDROGEN.

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## SYNOPSIS.

*Electron mobilities in pure hydrogen* have been measured for pressures of 73 to 635 mm., using a modified alternating field method with fields up to 70 volts/cm. Undamped oscillation of 15,000 to 200,000 cycles were obtained from a vacuum tube oscillator and were measured with a precision wave-meter. By using a constant retarding potential of 6 volts the disturbing effect of ions of impurities was eliminated and curves without the usual feet were obtained. The mobility (reduced to a pressure of 76 cm.) is found to be best represented by the equation: $k = 2.74 \times 10^6 /[399 + (Vo/d)(760/p^{3/4}]$, where $Vo/d$ is the critical field in volts per cm. and $p$ is the pressure in mm. *Comparison with kinetic theory.* This equation is practically of the same form as that found by less accurate measurements for nitrogen and since it differs from Townsend's theoretical equation: $k = a/[b + (Vo/d)(760/p)]^{1/2}$, either the mean free path of the electron or its loss of energy at impact are probably functions of the velocity of the electron. When the electrical fields are small the mobility at atmospheric pressure comes out 68.6 $m$/sec. whereas the kinetic theory gives 130.6; hence the actual *mean free path* must be only about half that assumed by the theory.

IN a recent paper[1] the writer showed that by applying the high-frequency oscillations of an audion oscillator to the Rutherford alternating current method of mobility measurement, it was possible to determine electron mobilities in pure $N_2$ whose values were much higher than any previously obtained. The investigations in $N_2$ have been extended to $H_2$ with a considerable improvement in the technique, and it is the purpose of this paper to report the progress made.

The technique of measurement was improved along the following lines:

1. By the use of a new oscillating circuit which gave undamped oscillations whose amplitude could be varied at will without changing their frequency.

2. By the elimination of the asymptotic feet of the mobility curves through the use of a small retarding field of constant value. This field acted by removing the ions formed through the attachment of electrons to molecules of impurities.

3. By the elimination of the disturbing effect due to a gradual con-

tamination of the gas by impurities. These impurities were presumably liberated from the walls of the containing vessel on standing. The effect of the impurities was avoided by introducing fresh gas into the chamber before each set of readings.

4. By the use of a precision wave meter accurately covering the whole range of frequencies worked with in place of the rough instrument first employed.

1. The new oscillating circuit employed is shown in Fig. 1. The primary oscillations were set up in the system $C_1L_1F_1G_1P_1$, where the frequency is once and for all determined by the inductance $L_1$ and the capacity $C_1$. The oscillators $F_1C_1P_1$ were two Western Electric Company "E" tubes acting in parallel. The filament current and the plate resistance were always kept constant. The secondary inductance $L_2$, closely coupled to $L_1$, took the oscillations from it and thus placed an oscillating potential difference of the frequency of that in the primary circuit between the filament $F_2$ and the grid $G_2$ of a secondary "E" tube oscillator, $F_2G_2P_2$. The steady electron current from $F_2$ to $G_2$ driven by 200 volts direct current was therefore periodically interrupted by the oscillations in the primary circuit. A series of unidirectional

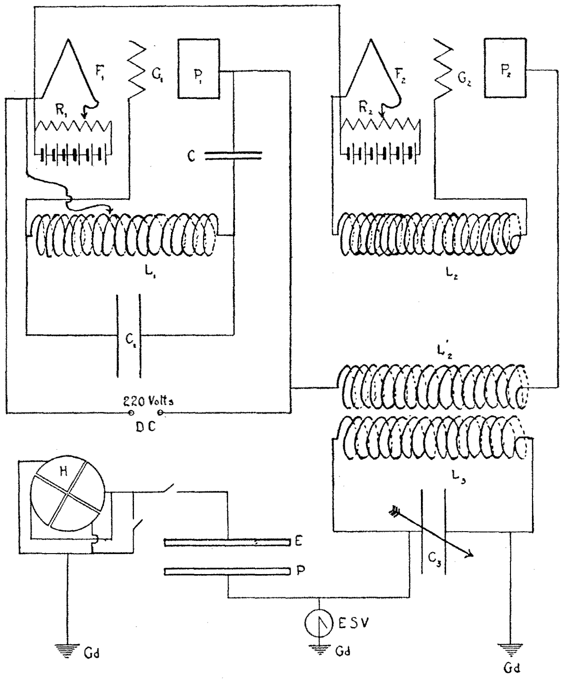

FIG. 1

current surges accordingly passed through the inductance $L_2'$. These acted on the inductance $L_3$ of the tertiary system $L_3C_3$ which was closely coupled to $L_2'$. Thus (when $L_3C_3$ was tuned to resonance with the primary system), there were set up across the condenser $C_3$ a continuous train of undamped oscillations. The inductance and capacity $L_3$ and $C_3$ were chosen to be as nearly the same as $L_1$ and $C_1$ as possible, the final sharp tuning being accomplished by a small variable air condenser in parallel with $C_3$. The amplitude of the oscillations in the system $C_3L_3$ was varied by varying the energy in the secondary circuit. This was accomplished by changing the secondary filament current through $F_2$ by varying $R_2$. One side of the condenser $C_3$ was grounded and the other side was connected to the plate source of electrons used in mobility measurement. The potential differences obtained across $C_3$ varied from 10 to 140 volts and were measured on two Kelvin electrostatic voltmeters. These were calibrated against a standard current voltmeter after each mobility determination. The frequencies used in these measurements varied from 15,000 to 200,000 cycles per second. To cover this range of frequencies and voltages it was necessary to use three sets of the inductances $L_1$, $L_2$, $L_2'$ and $L_3$, each set having values of about $4 \times 10^6$, $1 \times 10^6$, and $3 \times 10^5$ cms. The capacities $C_1$ and $C_3$ were each a battery of 20 tin plates separated by glass, the capacity of which varied by about .0012 microfarad for each pair of tin plates.

2. In the previous paper[1] it was suggested that the asymptotic feet of the current-voltage curves obtained were caused by the formation of negative ions between the plates, due to the attachment of electrons to impurities present. These ions would not be removed by the high-frequency oscillations, and thus would build up a diffusion potential which would produce just such feet. In that paper the result of an attempt made to eliminate these by means of a small field of constant value which would pull the ions back to the lower plate was reported. The attempt failed in part because the fields used were too weak, and in part because of the fact that a portion of the feet were apparently due to instrumental irregularities of small magnitude in the ion chamber. In the present case two small flash-light cells giving a total potential difference of six volts were placed between the condenser $C_3$ and the lower plate $P$, so that the plate $P$ was attached to the positive terminal of the cells. This arrangement was quite successful in eliminating the feet as may be seen in the curves of Fig. 2. In this figure the curves with crossed points represent the curves obtained without the cells, in hydrogen contaminated with about 1/3000 its volume of air. Such a contamination of the $H_2$ with air augmented the asymptotic feet very perceptibly. The curves

with the circled points are the mobility curves obtained under the same conditions with the cells inserted. It is seen that the curves obtained with the cells cut the axis sharply at a value close to six volts above the value obtained from the extrapolated portions of the crossed curves. This is just what was to be expected if the feet were due to ions, the effect of the retarding field being to remove the feet, and to increase the critical voltage by six volts.[1] Since the values of the mobilities obtained in the two cases are the same it is immaterial which method is used in measurement, both the cells and extrapolation giving correct values. The important point is that *these feet are not an essential attribute of electron mobility curves*, and are due to causes other than peculiarities of the electrons.

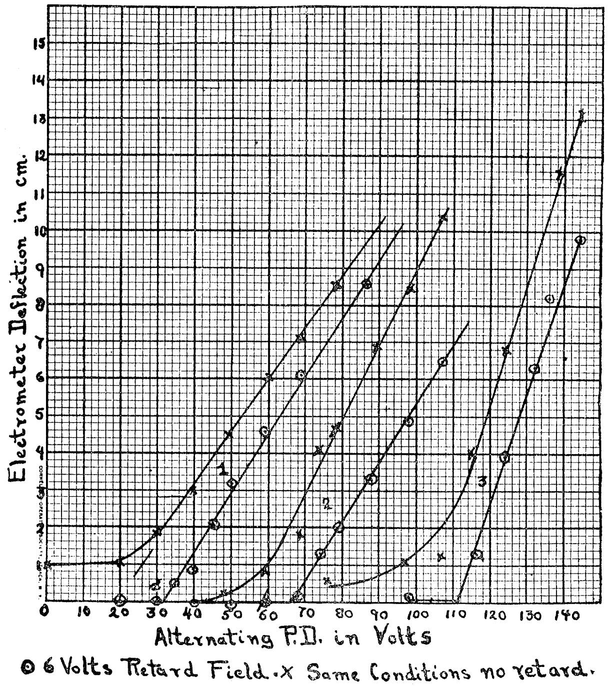

Fig. 2.

3 and 4. The improvements numbered 3 and 4 are self evident. As regards 3 it might be pointed out in passing that the inaccuracies present in the measurements of mobilities in $N_2$ made it impossible to detect the gradual contamination of the gas which remained in the metal chamber

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[1] The latter will obviously cease to be true when the fixed potential becomes an appreciable fraction of the critical voltage. However at the critical voltages below 20 volts the asymptotic feet are generally negligible, in pure $H_2$, and retarding fields may be dispensed with.

more than three or four days. This contamination caused changes in the mobility of less than ten per cent., and these occurred chiefly in the case of mobilities taken with low fields where the impurities were most active. Thus the mobilities at a given pressure in $N_2$ seemed to be quite reproducible over several days when high fields were used, while those at low fields showed a change. With the inaccuracies due to other causes of the same magnitude superimposed on this effect it became impossible to correlate it with the ageing of the gas. In $H_2$ where the precision was far higher, such a change at once became evident.

The hydrogen used came from a commercial tank and was carefully purified by passing over hot copper, NaOH, $CaCl_2$, through two tubes of $P_2O_{50}$, and through two traps cooled with liquid air. Spectroscopic examination showed only $H_2$ and Hg present, though it is doubtful how delicate this test was. The procedure of measurement was precisely that followed in the case of $N_2$. The mobility constant $K$, as computed from $K = (2.2nd^2/760 V_0)p$, was plotted as ordinate against the value of $V_0$ as abscissa as before. The points thus obtained under the best conditions are shown in Fig. 3. It is seen that in $H_2$ the mobility varies in much the same manner as it did in $N_2$. The full lines represent an attempt to fit an equation of the form $K = a/(b + V_0)$ to the points obtained for the pressures 635, 303, 151, and 73 mm. respectively. The dotted lines represent an equation of the form

$$K = \left(\frac{a}{b + V_0}\right)^{3/4}$$

applied to the same points. The equations fit the points nearly equally well, the dotted curve showing perhaps a slightly better fit. In the case of the full line curves, the curves for different pressures fall quite closely into a family of curves whose equation is

$$K = \frac{2.74 \times 10^6}{399 + \frac{V_0}{d}\left(\frac{760}{p}\right)^{3/4}}.$$

The attempt to incorporate the dotted curves for different pressures into a family of curves of the form

$$K = \left(\frac{1.09 \times 10^7}{81.3 + \frac{V_0}{d}\left(\frac{760}{p}\right)^{5/8}}\right)^{3/4}$$

was nearly as successful. Thus we must conclude that the equation

$$K = \frac{2.74 \times 10^6}{399 + \frac{V_0}{d}\left(\frac{760}{p}\right)^{3/4}}$$

seems to represent the observed results with the greatest accuracy. Here $K$ is the mobility, $p$ the pressure in mm., $V_0$ the critical voltage in volts, and $d$ the plate distance in cm.

This equation for $H_2$ differs from that for $N_2$,

$$\left(K = \frac{5.71 \times 10^5}{21 + \frac{V_0}{d}\left(\frac{760}{p}\right)}\right),$$

in form only in that the pressure ratio $(760/p)$ in the case of $H_2$ is raised to the 3/4 power, while the power of $760/p$ in $N_2$ is 1. It seems likely that this difference is due to the uncertainty of the earlier measurements in $N_2$. For by applying the correction to the results in $N_2$ indicated by the conditions of the improved technique the curves obtained show changes which would make the factor $(760/p)$ in the present equation become $(760/p)^{3/4}$.

The theoretical equation for the mobility of electrons in a gas where they make partially elastic impacts with gas molecules as suggested by Townsend[1] is of the form

$$K = \frac{.815eL}{mc\sqrt{1 + \frac{.575V_0eL}{me^2d\sqrt{f}}}},$$

where $L$ is the electron mean free path, $e$ its charge, $m$ its mass, $c$ its velocity of thermal agitation, and $f$ the fraction of its energy lost at each impact. This equation demands that the mobility $K$ should vary as

$$K = \left(\frac{a}{b + \frac{V_0}{d}\left(\frac{760}{p}\right)}\right)^{1/2},$$

where $a$ and $b$ are functions of $L$ and $f$. As the experimental equation has the form above one may then conclude that in $H_2$ as in $N_2$ either the mean free path ($L$) of the electron, its loss of energy on impact $f$, or perhaps both of these quantities, vary as a function of the energy of the electron, *i.e.*, depend on $V_0/d$ and $760/p$. No conclusion can at present be drawn as to which one of these factors is the more important variable,

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[1] L. B. Loeb, PHYS. REV. (N. S.), 19, 1922 (24).

L. B. Loeb, Proc. Nat. Acad. Sciences, 7, 1921 (307).

though it is hoped that results obtained in He may shed light on this question. The results of Ramsauer,[1] Mayer,[2] and Townsend[3] on the variation of the electronic mean free path in argon with the electron velocity, and the results obtained by Townsend[3] on the variation of the mean free paths with the electron velocity in other gases, indicate that a variation of the mean free path may possibly be the cause of the deviation of the observed mobilities from those demanded by the theory.

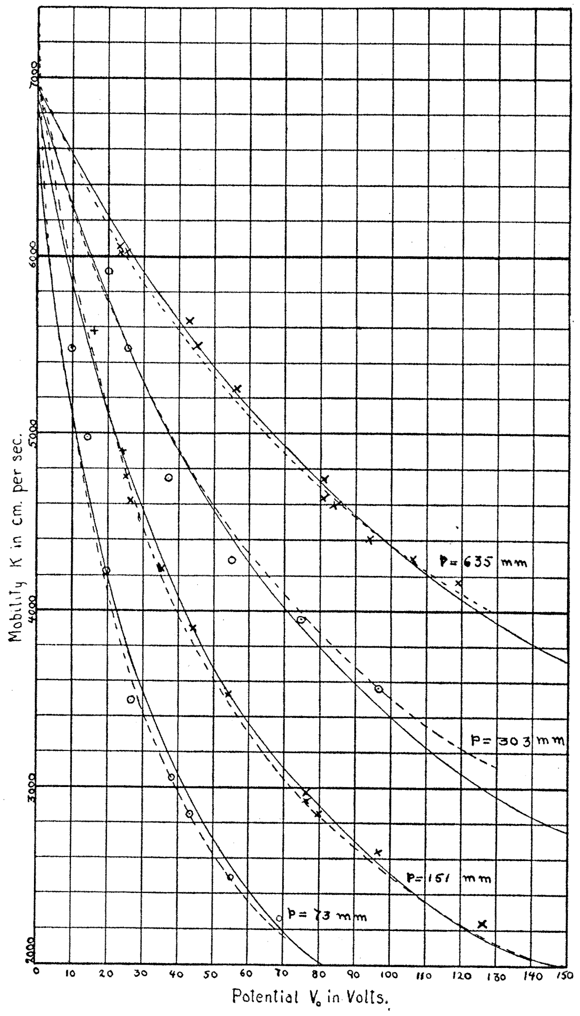

Fig. 3.

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[1] C. Ramsauer, Ann. d. Phys., 64, 1921 (513).

[2] H. F. Mayer, Ann. d. Phys., 64, 1921 (451).

[3] J. S. Townsend and V. A. Bailey, Phil. Mag., 43, 1922 (593).

In the case where the field becomes very small (*i.e.*, for $V/d$ approaching 0), the observed equation for the variation of $K$ with $V_0$ approaches a constant value $K_0 = a/b$ which may be compared with the value of $K_0$ predicted by the kinetic theory. For in this case the electron absorbs no appreciable energy from the field, and its energy is that of the agitation of the molecules. The kinetic theory gives $K_0$ for electrons as

$$K_0 = \frac{.815e}{m}\frac{L}{c}.$$

Computing $K_0$ for $N_2$ it was found that the observed value was about 3.9 times as great as the computed value. In the case of $H_2$, $K_0$ computed is 13,060, while $K_0$ observed turns out to be but 6860. The observed mobility is then .53 the computed one. This difference of observed and computed values must be interpreted as meaning that the mean free paths assumed by the kinetic theory differ from those actually existing. For the mean free paths are the only factors of the equation which could vary in this case.

Thus the mean free path of electrons in $N_2$ is about four times that assumed by kinetic theory, a result similar to that found by Townsend, Mayer, and Ramsauer, for argon at much higher electron velocities; while the mean free path of electrons in $H_2$ is .53 that assumed by kinetic theory. An explanation for the low value of the mean free path found in hydrogen may be sought in the explanation given to the low values of the mobilities found for *gas ions* on the "small ion" theory. On this theory the reduction of the mobility is explained by assuming that the field of the electron acts on the surrounding gas molecules, and so by either losing momentum it has gained in the field, or by making its collisions with molecules more frequent, it effectively seems to shorten its mean free path. Why $H_2$ should show this latter effect while in nitrogen this effect seems to be absent furnishes a problem for the future.

NATIONAL RESEARCH FELLOWSHIP,
RYERSON PHYSICAL LABORATORY,
June 12, 1922.