ABSORPTION COEFFICIENT OF SLOW ELECTRONS IN MERCURY VAPOR

By T. J. Jones*

Abstract

Absorption coefficient of Hg vapor for electrons with energies from 0.5 volts to 400 volts.—An account is given of measurements by two different methods of the absorption coefficient α in mercury vapor for electrons with energies of 0.5 volts up to 400 volts. The experiments described in the first part of the paper were made by Ramsauer's method, in which a homogeneous electron beam is obtained by bending the electrons through a series of slits suitably arranged in a magnetic field. The second part of the paper deals with experiments made by an arrangement which gave a fairly homogeneous beam of electrons without the use of a magnetic field. In each method the fraction of the initial electrons which traversed a given distance through the vapor without suffering collision was measured, and this enabled α to be calculated. The results obtained by the two different methods were found to be in fair quantitative agreement. The absorption coefficient increased continually as the energy of the electrons was reduced down to 0.5 volts. No evidence was obtained of the sharp decrease in α for electrons slower than 3 volts as reported by Beuthe. The results when compared with those obtained by former workers were found to be in fairly good agreement with those of Maxwell over the whole range of electron energies and with those of Brode at the lower energies.

WHEN a beam of electrons is projected into a monatomic vapor or gas, some of the electrons are removed by the gas atoms and so disappear from the original beam. This removal is effected by the scattering of the electrons and also by the formation of negative ions.

The effective area of an atom which is instrumental in removing an approaching electron from the beam can be calculated from the kinetic theory formula

$$N = N_0 e^{-\alpha x p} \tag{1}$$

where N_0 is the number of electrons initially present in the beam, N is the number remaining after traversing a distance x in the gas, p is the pressure of the gas (in mm) and α is the effective area, or absorption coefficient, of all the atoms in 1 cc at 1 mm pressure and 0°C. On dividing α by 3.6×10^{16} the mean effective area of a single atom is obtained. The reciprocal of the absorption coefficient α is the electronic mean free path at unit pressure and 0°C.

Absorption coefficients for slow electrons in mercury vapor have been measured by R. B. Brode,[1] L. R. Maxwell[2] and H. Beuthe.[3] Brode and Maxwell found that α increased rapidly as the velocity of the electrons was

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[1] R. B. Brode, Proc. Roy. Soc. **109A**, p. 937 (1925).

[2] L. R. Maxwell, Proc. Nat. Acad. Sci. **12**, p. 509 (1926).

[3] H. Beuthe, Ann. d. Physik **84**, p. 949 (1928).

diminished, down to velocities as low as 0.5 volt. Their results agree fairly well in the low velocity regions but for the higher velocities Brode's values of α are much smaller than those of Maxwell. Beuthe studied by the Ramsauer method the behavior of the absorption for electrons with velocities less than 7 volts, and found that as the velocity decreased, α increased to a maximum at about 3 volts and then diminished rapidly until at 1 volt it was 1/6 of its maximum value. Mercury in this connection behaved like the rare gases.[4] R. Minkowski,[5] also, has obtained evidence of a maximum absorption for very slow electrons in mercury vapor.

The present investigation was made in order to obtain further information on the behavior of the absorption coefficient for the faster electrons (this being necessary because of the considerable disagreement in the values obtained by Brode and by Maxwell at the higher velocities) and also to confirm if possible Beuthe's discovery of the Ramsauer effect in mercury vapor. The general procedure in determining α was to accelerate a beam of electrons from a thermionic source into a region where they collided with atoms of mercury vapor. For each value of the accelerating voltage and for different vapor pressures, the fraction of electrons which traversed a given distance in the gas without being removed from the beam was measured. These data were sufficient to enable α to be calculated from Eq. (1). Two entirely different experimental arrangement were employed in the work and this paper is accordingly divided into two parts.

The first part describes experiments made with a method similar to that devised by Ramsauer, in which the electron stream was resolved by an arrangement of slits suitably placed in a magnetic field so that a nearly homogeneous beam passed through the vapor. The experiments described in the second part were made with a simpler apparatus in which a fairly homogeneous electron beam was obtained without the use of magnetic fields.

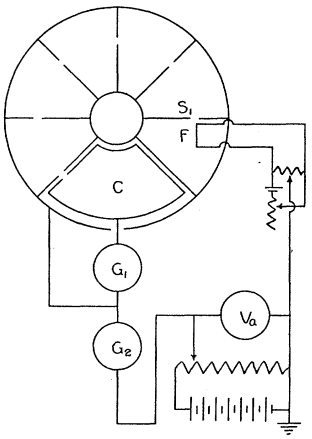

Fig. 1.

PART I

Apparatus and method. The apparatus and electrical connections are depicted in Fig. 1. The former was made of copper parts constructed so that they could be rigidly fastened together without the use of solder.

A preliminary experiment with an ionization gauge showed that, at the low pressures employed in this work, the vapor pressure of mercury was not influenced by the presence of copper. The filament F was a thin tungsten strip placed 1 cm from the slit S_1 which was crossed by several fine wires to serve as a grid. All the slits were rectangular, 1 mm wide and 1 cm

[4] C. Ramsauer, Ann. d. Physik **64,** 513 (1921).
[5] R. Minkowski, Zeits. f. Physik, **18,** 258 (1923).

long, mounted on a circle of radius 2.6 cm. A porton of the electron stream which passed through the grid was deflected through the slits by a magnetic field and finally collected in the Faraday cage C. The opening into this cage had slightly greater dimensions than those of the other slits. The slit system and the cage C were completely enclosed in a copper box so that electrons could not enter C except through the slits. The radius in a magnetic field H of an electron which has been accelerated through a potential difference of V volts is given by $r=3.37\ V^{1/2}/H$. In these experiments a solenoid 17 cm in diameter and 100 cm long was used to bend the electrons.

The total electron emission, J, from the filament was measured on a low-sensitivity galvanometer, G_2, and the initial current starting around through the slits was assumed to be proportional to this total current. (This procedure for measuring the initial current was employed by Brode[6] in measurements of the absorption coefficients of the rare, and other, gases.)

Those electrons which were not deflected from the initial beam were measured by the high sensitivity galvanometer, G_1. The length of path traversed by the beam before entering the collector C was 10.9 cm. To enable the temperature of the vapor in the space about the electron beam to be measured, a thermometer was placed in the tube with its bulb resting upon the copper box containing the slits. The pressure of the mercury vapor in the tube was varied by controlling the temperature of a mercury vapor trap, situated between the tube and the mercury diffusion pumps. This trap was always maintained at temperatures lower than the temperature of the tube, thus eliminating the possibility of condensation of mercury about the apparatus. Knudsen's[7] values of the vapor pressure of mercury at different temperatures were used in evaluating α. The procedure in making the measurements and calculating α was as follows.

The accelerating potential, V_a, was set at a given value and the magnetic field varied until the current, I, through the galvanometer, G_1, was a maximum. This value of I and the corresponding value of the total emission J were noted. A set of such corresponding values of I and J were taken for different accelerating potentials and a given vapor pressure. The pressure was then changed and for the same values of V_a as before, I and J were again noted.

At pressure p_1 and an accelerating voltage V, let I_1 be the current to the collector C and J_1 the corresponding filament emission, then

$$I_1=KJ_1e^{-\alpha xP_1+\beta}$$

Here K is the constant of proportionality between the initial current and the total emission, while β is a term to account for absorption of electrons by residual gas atoms. It is assumed that K is independent of the vapor pressure and also that β remains constant over the period in which a "run" is taken. Thus at a vapor pressure p_2

$$I_2=KJ_2e^{-\alpha xP_2+\beta}$$

[6] R. B. Brode, Phys. Rev. **25**, 636 (1925).
[7] Knudsen, Ann. d. Physik **29**, 179 (1909).

and therefore

$$\alpha=\frac{2\cdot 3026}{(p_2-p_1)}\log_{10}\left(\frac{I_1}{I_2}\cdot\frac{J_2}{J_1}\right)$$

p_1 was always the vapor pressure corresponding to 0°C (0.00017 mm) while p_2 took on different values up to about 0.0015 mm. Because of the heating due to the filament the temperature inside the apparatus was considerably higher than that of the vapor trap, and as the dimension of the tubes connecting these two regions were small compared with the molecular free paths a correction for thermal effusion was applied. This correction is a simple matter, the pressure in the apparatus being to the pressure in the trap as the square root of the ratio of the absolute temperature.

Results and discussion. The results of the measurements are given in Fig. 2 where the absorption coefficient is shown as a function of the electron energy

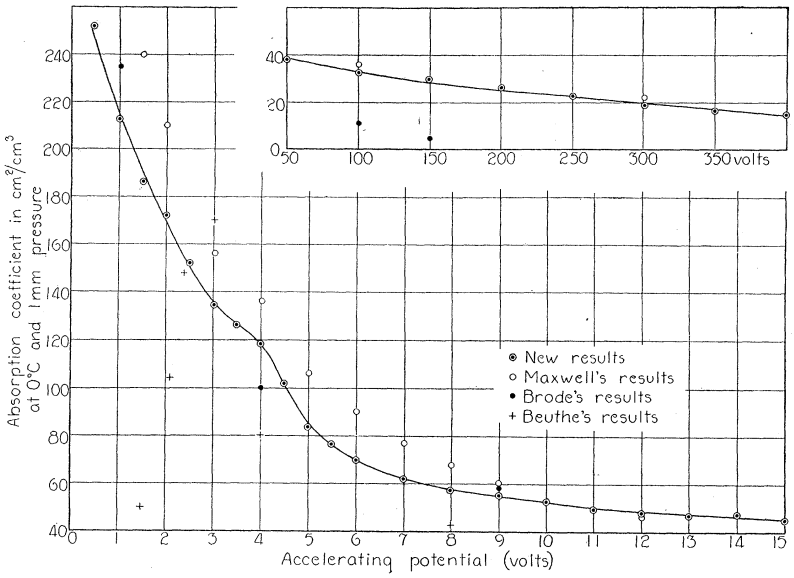

Fig. 2.

in volts. Each point on the curve is the mean of several values of α obtained at that voltage all of which differed from the mean by less than four percent. For purposes of comparison some of the values of α obtained by the other investigators are also shown.

When the accelerating voltage, V_a, was small, the determinations of α were found to be independent of the vapor pressure (over the limited range employed in this work) and also of the total filament emission if this did not exceed 10^{-4} amps. However, when V_a was greater than about 10 volts, consistent values of α could only be obtained by using the lowest possible filament emission and by keeping this emission constant, as the pressure is

varied, for each set of readings pertaining to a given value of V_a. The erratic results at higher filament emissions were probably attributable to disturbances in the space charge conditions about the filament, and consequently in the initial electron beam, by the ionization of the vapor. The effect of these disturbances would evidently be minimized and perhaps eliminated by the precautions observed in getting consistent values of α.

If this explanation is correct it is difficult to see why Brode[6] did not also experience the same difficulties in his experiments with a similar apparatus, especially when using argon for which the efficiency of ionization is almost as high as in mercury vapor. However, he used considerably higher pressures than were employed in this work, so that it was possible that the disturbing space charge effects were constant at the different pressures. Should this be the case, the computed values of α would be free from errors due to these effects.

It would seem that most of the troubles would have been avoided had the apparatus been constructed so that the initial electron current could be measured directly instead of by assuming it to be proportional to the filament emission. Beuthe's apparatus (which in other respects was similar to that used here) enabled this to be done; yet he experienced great difficulties which were only evaded by the use of low pressures.

The values of α shown in Fig. 2 are believed to be free from any appreciable errors at the lower electron energies but it is conceded that the precautions taken for obtaining *consistent* results when the electron energies were greater than 10 volts might not necessarily give *accurate* values of the absorption coefficient.

It is interesting to compare the results with those obtained by the other workers. At the lower energies there is a fairly good agreement as to general features and order of magnitude with the results of Brode and Maxwell, which were obtained by very different experimental arrangements. The significance of the small change in slope of the curve at about 4 volts is not understood. Maxwell, who also observed the same effect, attributed it to a change in the nature of the scattering, but it might equally well be due to an increase in the formation of negative ions. Beuthe's results, in spite of the essential similarity of his method with the one used in this research, show surprising differences. There is no indication of a continued decrease in the absorption coefficient below 3 volts as observed by Beuthe while above 3 volts his results agree with the present ones in order of magnitude alone. A short note added to Beuthe's paper by F. Krüger points out that the maximum in the absorption at 3 volts may not be a characteristic of the vapor, but due to some peculiarity in the electron beam itself.

It is difficult to understand why such a profound change in the absorption for slow electrons, if it really exists, had not been noticed previously in some of the many experiments dealing with electronic collisions in mercury vapor. Minkowski,[5] it is true, observed a small decrease in α for electrons slower than 1 volt but his experiments were indirect and capable of other interpretations.

At the higher velocities the values of α shown in Fig. 2 are in fair agreement with Maxwell's and differ considerably from those of Brode. As Maxwell has pointed out, there is probably a considerable source of error in Brode's measurements because of the emission of secondary electrons from the collectors in his apparatus.

Summing up, the results obtained in this work confirm reasonably well those obtained by Maxwell, and do not show the Ramsauer effect for mercury as reported by Beuthe.

PART II

Measurement of the absorption coefficient by another method. The apparatus and electrical circuits used in this determination of the absorption coefficient are shown diagrammatically in Fig. 3. Electrons from the electron "gun" A were accelerated into the chamber B where some of them after colliding with mercury atoms were deflected from the initial beam. The remainder passed on into the Faraday cylinder C and were measured by galvanometer G_2. The total initial current entering B was measured by G_1. Both G_1 and G_2 were high-sensitivity galvanometers.

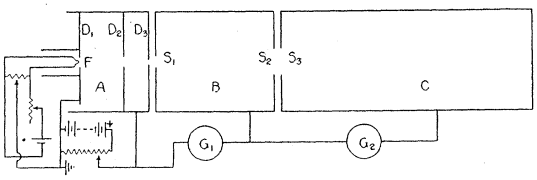

Fig. 3.

The chamber B was 5.2 cm long, 5 cm in diameter, and was lined on the inside with nickel gauze so as to make it a more efficient collector of the scattered electrons. The openings S_1 and S_2 were 4 mm and 1 cm in diameter respectively.

It was important that the Faraday cylinder C completely absorbed all the incoming electrons. To insure this, C was made 12 cm long and 5 cm wide while the aperture S_3 was 1.1 cm in diameter. Experiment showed that the cylinder acted as a perfect absorber of electrons.

The initial electron beam going through chamber B had to be fairly narrow, homogeneous, and of sufficient intensity to allow the currents in G_1 and G_2, at the lower accelerating potentials, to be measured accurately.

For producing such a beam, the electron "gun" A was designed. The filament F, consisting of a small loop of tungsten wire, just projected through a hole of 2 mm diameter in the earthed plate D_1. The middle of the filament was also earthed by the usual procedure of connecting the two ends to a high resistance and earthing an intermediate point.

The accelerating grids D_2 and D_3 were circular plates connected together, each 5 cm in diameter with circular openings 2 mm in diameter at their centers. D_1 and D_2 were 2 cm apart while D_3 was 1 cm from D_2. The edges

and sides of the holes in the grids were coated with lamp black to diminish secondary electron emission.

All the metal parts of the apparatus were of nickel, and were thoroughly outgassed both before assembling and after mounting in the Pyrex tube in which the measurements were made. This tube was placed with its axis parallel to the earth's magnetic field.

With liquid air surrounding the mercury vapor trap, measurements of the velocity distribution of the electron beam were made and the results for accelerating potentials of 5, 15, and 30 volts are shown in Fig. 4. It is seen

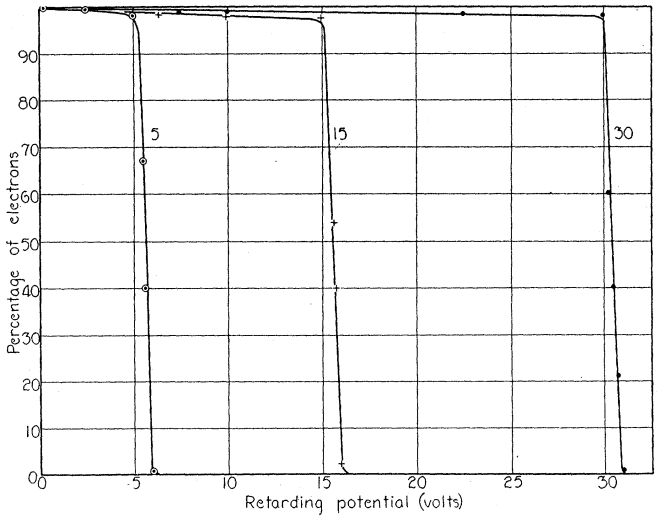

Fig. 4.

that at each voltage about 97 percent of the electrons are transmitted with the full velocity. Because of the initial thermal velocity of the electrons when they leave the filament and also the voltage drop along the filament a sharp upper limit to the velocity in the beam cannot be attained, unless the beam is magnetically analyzed as in the previous experiment. Measurements were also made of the current reaching the walls of the cylinder B when there was no vapor in the tube and it was found that the current was always less than 1 percent of the current collected by C. This indicated that the electron beam was narrow and also that the Faraday cylinder C was an efficient collector of electrons. Currents of the order 10^{-7} amps were obtainable from the gun even at potentials as low as a volt.

The procedure in determining α was the same as that described in Part I. Thus if J_1 and J_2 were the initial currents (indicated by G_1) at pressures p_1 and p_2 while the corresponding currents measured by G_2 were I_1 and I_2, then

$$\alpha=\frac{2\cdot 3026}{x(p_2-p_1)}\log_{10}\left(\frac{I_1}{I_2}\cdot\frac{J_2}{J_1}\right)$$

A possible source of error lay in the fact that electrons scattered through small angles would be able to pass through S_2 and be collected among the unscattered electrons in C. The magnitude of this error depended upon the solid angle subtended by S_2 at the place of collision and also upon the angular distribution of the scattered electrons. Assuming a uniform distribution of scattering the error in α due to this cause was negligible.

In Fig. 5, the absorption coefficient is shown as a function of the accelerating potential in volts. Some of the values obtained in the previous work are also include for purposes of comparison. The present results are consistently higher than those obtained in Part I, but exhibit the same general features. Thus the values of α continue to increase for values of the accelerating potential down to 0.5 volt.

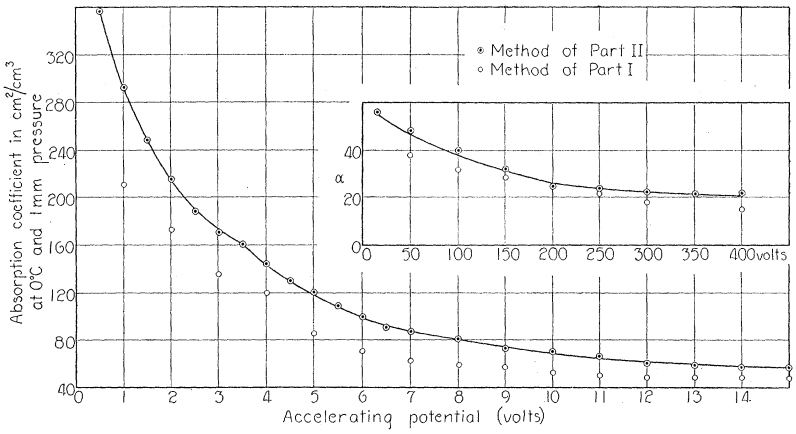

Fig. 5.

In the Ramsauer method a collision is defined more completely than by the method described in this part, as the latter does not measure collisions in which the electrons lose energy without having their direction appreciably changed. The values of α obtained by the Ramsauer arrangement should accordingly be somewhat larger than the others. The present experiments however indicate the reverse of this. A comparison of the results obtained in other gases by the Ramsauer method and by methods similar to the one here described shows that there is no appceciable difference between them.

In conclusion, the writer wishes to thank Professor H. A. Erikson for extending the facilities of the Laboratory at Minnesota, and also Professor J. T. Tate for his interest and helpful suggestions during the investigations. The work was done while the author was a Commonwealth Fellow.

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