PROBABILITY OF IONIZATION OF MERCURY VAPOR BY ELECTRON IMPACT

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Abstract

Electrons from a hot filament were projected into an ionization chamber A containing mercury vapor, and were prevented from scattering by a magnetic field of 400 gauss parallel to the electron beam. The positive ions produced in a definite length of A were collected on a plate electrode while the primary electrons after passing through A were collected by a special form of Faraday cylinder. The resulting curve for N, the number of positive charges produced in 1 cm path by an electron moving through the vapor at 1 mm pressure as a function of the electron energy in volts is given. This curve, in good agreement with that obtained by Compton and Van Voorhis for mercury vapor, shows a maximum value of 20.5 at 90 volts. The values of P, the average number of positive charges formed at an impact, were then calculated from N by the relation $P=N\lambda$ where λ is the electronic mean free path. Assuming the kinetic theory value for λ the curve for P shows a maximum value of 0.35 at 90 volts, agreeing well with the value 0.32 at 100 volts calculated similarly by Compton and Van Voorhis. However, when the values of λ obtained by direct experiment are employed, the curve for P shows no indication of reaching a maximum. At 400 volts, P has a value of about 1 and the curve indicates values greater than 1 at higher voltages. Since the probability of ionization at an impact cannot be greater than unity, the assumptions made in evaluating this quantity have been examined more closely.

Such consideration indicates that the assumption that only singly charged ions are produced at an impact is invalid—a view that is supported by the experiments of Smyth. If, as seems reasonable from his experiments, it is assumed that at 400 volts doubly charged and singly charged ions are produced in equal amounts; the present results show that at this voltage the probability of ionization at an impact is about 0.6 while the probabilities of formation of double ions and of single ions are both about 0.3. These results indicate that the values of the probability of ionization at an impact, obtained by former workers for other gases, may also require modification because of the possible formation of multiple ions.

THE probability of ionization in gases by electron impact, as a function of the energy of the impacting electrons, has been examined by a number of investigators[1,2,3] and it has been shown that the probability of an electron's ionizing an atom is not constant but rises from zero when the electron has less than the ionizing energy, to a maximum value when it has some energy higher than the ionizing energy. In all the gases investigated, this maximum value of the probability is less than 0.5 and occurs when the electron energy is equivalent to about 200 volts.

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[1] Hughes and Klein, Phys. Rev. **23** pp. 111, 450, (1924).

[2] W. P. Jesse, Phys. Rev. **26**, p. 208, (1925).

[3] K. T. Compton and C. C. Van Voorhis, Phys. Rev. **26**, p. 436, (1925) and **27**, p. 724 (1926).

K. T. Compton and C. C. Van Voorhis[3] included mercury vapor among the gases examined by them, and found that in this case the probability of ionization at a collision had a maximum value of 0.31 when the electron energy was 100 volts. The subject was deemed of sufficient importance to merit further study by a different experimental method. This paper contains an account of such an investigation on mercury vapor.

Experimental Arrangement and Procedure

The experimental arrangement differed considerably from that of Compton and Van Voorhis. The general method employed was to project a stream of approximately stream of electrons of approximately homogeneous velocity along the axis of a tube into a region devoid of strong electric fields and to collect the electrons and the ions produced by them on a system of electrodes. The electron stream was prevented from scattering by a magnetic field applied parallel to the axis of the tube. Compton and Van Voorhis found that when they tried to use a magnetic field in this way the ratio of the positive ion current I_+ to the electron current I_- was very irregular, being affected by small variations in the magnetic field. As they failed to eliminate or to account for these variations they abandoned the use of the magnetic field. During the course of the present work this effect of the magnetic field was experienced, but after a number of preliminary trials with different experimental arrangements the trouble was found to be due to secondary electrons and was eliminated.

The apparatus employed together with the electrical connections used in making the measurements are shown in Fig. 1. The filament F, consisted of a small loop of tungsten wire just projecting through a small hole (diameter

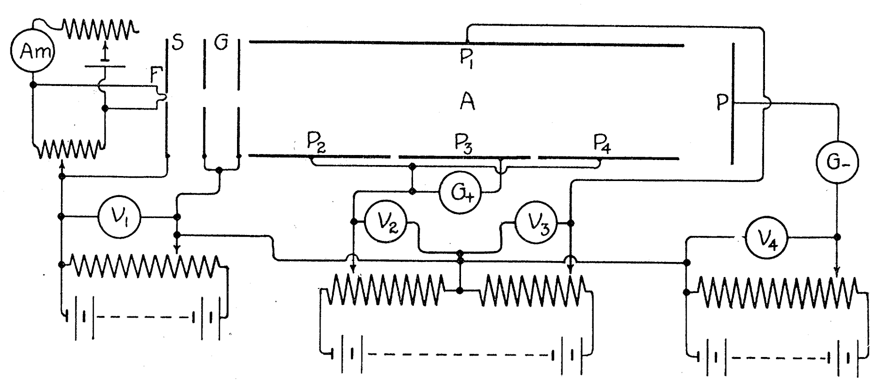

Fig. 1. Diagrammatic sketch of the tube and electrical connections.

2 mm) in the earthed plate S. The middle point of the filament was also earthed by connecting the two ends to a high resistance and earthing an intermediate point. This arrangement served to maintain an almost uniform field V_a between F and the grids G. Electrons from F were accelerated by V_1 through two holes (diameter 4 mm) in the grids into the space A. The

positive ions formed in the region were then collected on the electrodes P_2, P_3, P_4, by applying an electric field between them and P_1. P_2, P_3, and P_4 were separated by thin glass rings. Only the ions formed in the space directly above P_3 are collected on P_3 and pass through the galvanometer G_+ which was used to measure the positive ion current. One reason for adopting this "guard ring" system for the collecting plates was because the holes in the grids G, allowed the accelerating field V_1 to penetrate into the ionization chamber A so that some of the electrons that had passed through the holes would travel some distance in A before attaining their full velocity. Also with this arrangement the positive ions which are measured are produced in a distance traversed by the electrons equal to the length of P_3, i.e. in a region of definite length.

The plates P_2, P_3, P_4 were each 3 cm long and it is reasonable to assume that when the electrons were travelling in the region directly above P_3 they had their full velocity corresponding to V_1. The plate P served to catch the electrons after they had passed through the ionization chamber. Surrounding the electrode system and insulated from it was a copper sheath connected to G which served to eliminate extraneous surface potentials.

All the metal parts, with the exception of the filament, were of copper and were baked out in a small electric furnace at 450°C. At the same time, all the accessible parts were bombarded with an intense electron stream of 1000 volts velocity. The pressure of the mercury vapor was, throughout the experiment, that corresponding to the temperature of the vapor trap between the pumps and the tube. This trap was kept surrounded by melting ice so that the pressure of the vapor in the tube was 0.0002 mm.[4] At such a low pressure it was unnecessary to consider any ionization due to multiple collisions.

The temperature inside the ionization chamber was determined in some of the preliminary experiments by placing a thermometer inside the tube, and was found to be about 70°C. This was taken as the temperature in A throughout the various observations.

The experimental procedure was to measure the positive ion current I_+ and the electron current I_- (by noting G_+ and G_-) as V_1 was increased from zero to 400 volts. The electric field between the collecting plates was meanwhile adjusted so that all the ions formed in A were collected. The magnetic field was also of sufficient strength (usually about 300 gauss) to prevent electrons scattered in the gas from reaching the ion collector. The ratio I_+/I_- gives the number of positive charges produced by each electron in traversing a path 3 cm long in the vapor at a pressure of 0.0002 mm and a temperature of 70°C.

Errors. In the experiments there are several possible sources of error. The main difficulty was that experienced in collecting the electrons after they had passed through the ionization chamber. When a beam of electrons impinges on a metal surface secondary electrons are emitted from that surface. For a given metal the number of these secondary electrons is a func-

[4] A. Smith and A. W. C. Menzies, Ann. d. Physique **33**, 979 (1910).

tion of the velocity with which the primary electrons strike the surface and at the higher-voltages may exceed the number of the primaries. Farnsworth[5] has shown that for copper an appreciable fraction of the secondary electrons have velocities equal to those of the primary electrons. The type of electron collector usually employed is a Faraday cylinder of suitable dimensions. Such a collector was tried without success in the preliminary experiments. A little consideration however, shows that when a magnetic field prevents the electrons from being scattered appreciably, the Faraday cylinder is no longer a complete absorber of electrons.

The arrangement shown in Fig. 1 was tried and it was found that if a suitable electric field V_4 was applied between the ion-collectors and the plate P the number of secondary electrons from P was reduced considerably. For a certain range of values of this field the values of N were almost independent of the strength of the field and this was regarded as an indication that the secondary emission from P under these conditions was small. A further improvement in the arrangement for collecting the electrons was effected by replacing the plate P by a cylinder 14 cm long, closed at one end and having at the other end a hole just large enough to admit the electron stream. Within the cylinder the electrons passed between two copper plates maintained at a potential difference of about 1000 volts. With this arrangement the values of N were quite independent of the strength of the field between the plates when this exceeded a certain value. This could only mean that the cylinder was behaving as a complete absorber of the incoming electrons. The results given in the curves were obtained with this form of collector.

In order to ensure that all the ions formed in A were collected it was found necessary to maintain a potential difference as large as 4 volts between the collecting electrodes. This field could not appreciably affect the motion of the primary electrons as its direction was everywhere perpendicular to that motion. The potentials of the collecting electrodes were always varied in such a way that the potential along the axis of the ionization chamber was the same as that of the accelerating grids, i.e. V_1.

Charging of the collecting electrodes by photo-electric action arising from the incidence of radiation excited in the mercury vapor was prevented by the magnetic field.

The velocity distribution of the primary electrons was not determined but it is reasonable to assume that nearly all of the electrons had velocities close to the velocity corresponding to V_a.

Slow electrons in the primary beam are usually secondary electrons coming from those metal parts, such as grid-wires, which are struck by the primary electrons. The present arrangement of the accelerating grids and the use of the magnetic field enable the electrons to enter A without having struck any metal parts on their way.

[5] Farnsworth, Phys. Rev. **25**, 41 (1925).

Experimental Results and Discussion

The results of the observations are presented in the curves of Figs. 2 and 3. In order to be able to compare them directly with those of Compton and Van Voorhis the ratio I_+/I_- was divided by the pressure in mm and by the length of the electron path in cm. This gives the number of positive charges N which would be produced by each electron in traversing a path 1 cm long in mercury vapor at 1 mm pressure. If one were at liberty to assume, as

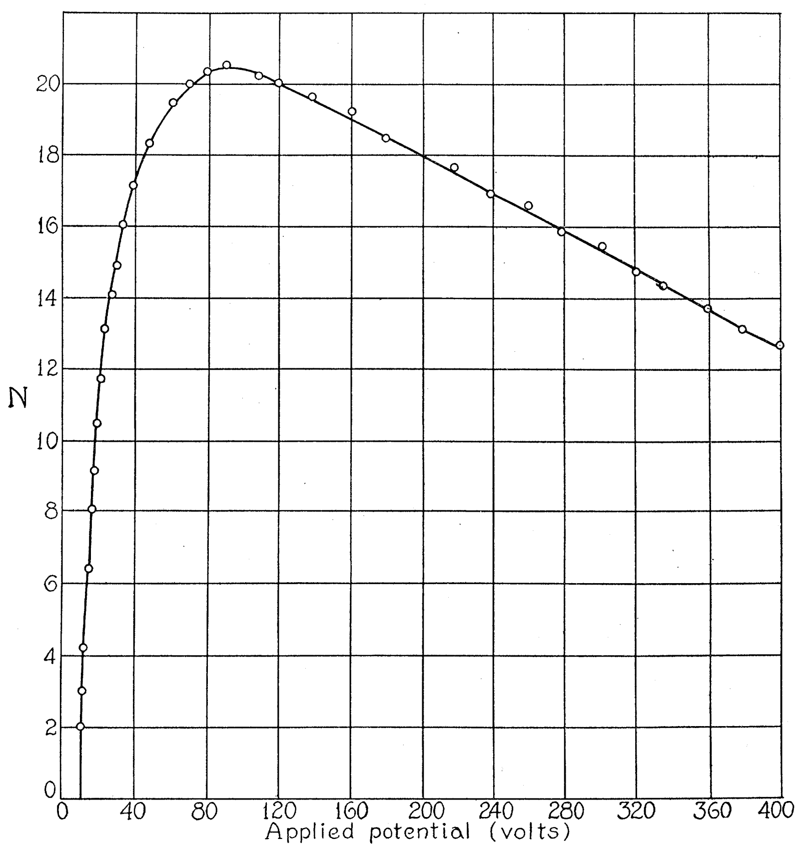

Fig. 2. Curve showing the variation with potential of the number of unit positive charges formed by each electron in traversing one centimeter path in mercury vapor at 1 mm pressure.

has tacitly been done by all other investigators in this field, that the positive ions are all singly charged, N would be equal to the number of positive ions formed by each electron under the above conditions. That the assumption is not justified, particularly at the higher electron velocities, is shown by the observations of Smyth[6] on the formation of multiple ions in mercury vapor and is made further apparent by an analysis of the results of the present experiment. Fig. 2 gives the values obtained for N as a function of the

[6] Smyth, Roy. Soc. Proc. **A102**, 283 (1922).

electron energy in volts. It is seen that N has a maximum value of 20.5 at 90 volts. This value for which N is a maximum together with the voltage at which it occurs agree very well with the values obtained by Compton and Van Voorhis, viz. 21.3 at 100 volts. The temperature of the chamber A was, in their case, 51°C and the difference between that temperature and the temperature in the present experiment is sufficient to account for almost all the difference in the value of the maximum N. After passing its maximum value the curve in Fig. 2 drops almost linearly and more rapidly than in the curve obtained by Compton and Van Voorhis.

If the values of N are divided by the numer of collisions n, made in 1 cm. path by an electron moving through the vapor at 1 mm pressure, the average number P, of positive charges formed per electron impact, is obtained. If the ions were all singly charged P would be the probability of ionization at an impact. The number of collisions, n, is evidently the reciprocal of the electronic mean free path λ, so that $P=N\lambda$. The precise significance of P depends upon the choice of values for λ. If the kinetic theory value of λ is taken, P represents the average number of positive charges formed by each electron when the apsidal distance of its path from the center of an atom is less than the kinetic theory value of the radius of the atom. Compton and Van Voorhis assumed the kinetic theory value of λ in calculating P. The kinetic theory value of λ is $4\sqrt{2}$ times that of the mean free path of the gas molecules and for mercury vapor at a pressure of 1 mm, and at 70°C is 0.0174 cm. The values of P shown in curve 1, Fig. 3, were obtained by multiplying the values of N in Fig. 2 by this kinetic theory values of λ. P is seen to have a maximum value of 0.35 at 90 volts which compares well with the maximum value of 0.32 at 100 volts obtained by Compton and Van Voorhis.

If one takes for λ the values obtained experimentally by Brode[7] and Maxwell,[8] P would represent the average number of positive charges formed by each electron which is deflected appreciably from its rectilinear path. Curve 2, Fig. 3, gives the values of P obtained when Maxwell's values of λ are used. P continues to increase up to the highest voltages and shows no sign of approaching a maximum. At 400 volts P has the value 1 and the curve indicates that at still higher voltages P would have values greater than 1. Brode's values of λ are much greater than those of Maxwell; at 100 volts his value of λ is more than three times as great as the value obtained by Maxwell at that voltage. This would make P greater than 1 even at 100 volts. Maxwell, however, has shown that Brode's values are certainly too large.

Under the assumption that the ions are all singly charged, values of P greater than unity would be meaningless and would throw suspicion on the values of λ used in the calculations. In their determinations of the electronic mean free paths in mercury vapor, Maxwell and Brode consider a collision as a deflection of the electron through an angle greater than

[7] Brode, Roy. Soc. Proc. **A109,** 397 (1925).

[8] Maxwell, Proc. Nat. Ac. Sci. **12,** 509 (1926).

some arbitrary critical angle, whereas in experiments on ionization a collision would be more completely defined as a process in which the colliding electron is deflected from its path or loses energy (possibly without appreciable deflection). Thus the values of λ obtained by these workers may not be appropriate for the evaluation of P. More appropriate values would

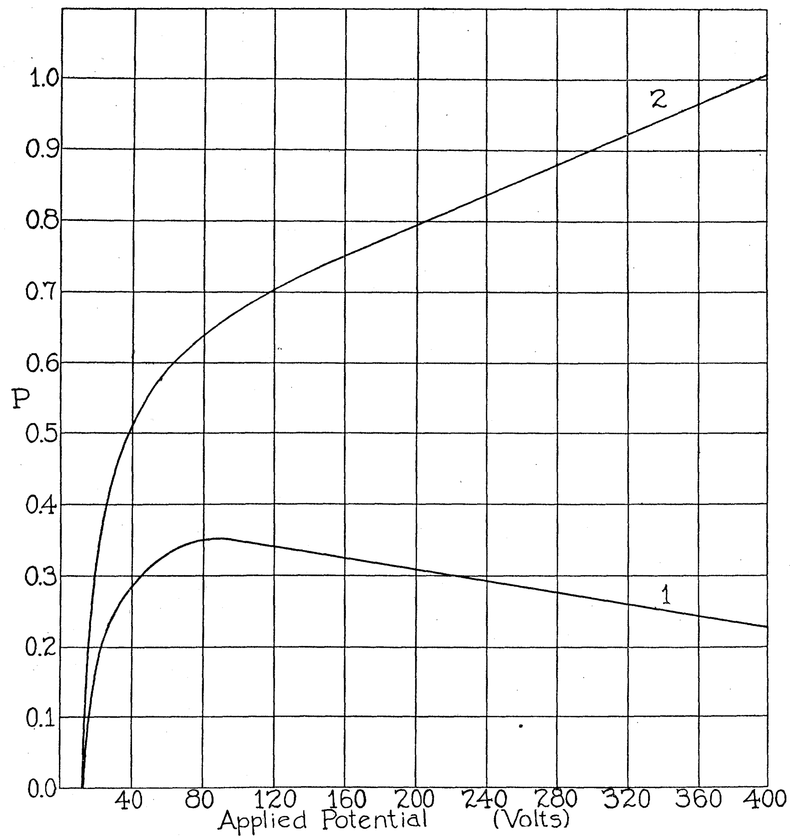

Fig. 3. Curve 1 shows the average number of unit positive charges formed by each electron in traversing a distance equal to the kinetic theory value of its mean free path. Curve 2, shows the average number of unit positive charges formed by each electron in traversing a distance equal to the mean free path as determined by Maxwell.

be those obtained by the method of Ramsauer[9] in which either a deflection or a loss in energy or both is counted as an impact. Unfortunately no measurements by this method have been made for mercury vapor. However, mean free paths which have been obtained by both methods on the same gas indicate that, in the range of velocities used in the present experiment, there is no appreciable difference between them. In other words the chance that an electron loses energy without appreciable deflection is small.

[9] Ramsauer, Jahrb. Rad. u. Elek. **19**, 345 (1923).

It may also be pointed out that if the values of λ in nitrogen and in argon obtained by Brode,[10] using the Ramsauer method, are used to calculate P from the values of N obtained for these gases by Compton and Van Voorhis, P at 325 volts for both argon and nitrogen is about 1.8.

It is therefore probable that the abnormal values of P cannot be accounted for on mean free paths considerations alone. It remains to consider N, the factor other than λ used in calculating P. In regarding P as the probability of ionization at an impact we have assumed that all the ions are singly charged. This assumption, as we have seen, leads to meaningless values of P and consequently we are forced to give up the assumption that all the ions are singly charged.

H. D. Smyth[6] has investigated the formation of multiple ions in mercury vapor. His results show that double ions begin to be formed when the impacting electrons have energies corresponding to 20 volts. At the higher voltages (up to 300 volts) the curves show as many double ions as single and it is believed that the majority of these double ions were produced by single impact. Evidence was also obtained of the formation of triple ions.

If, in the present experiment, it be assumed that only single and double ions are produced and that at the higher voltages these are produced in equal amounts, it is readily seen that the number of positive ions formed by an electron at these voltages would be two-thirds of the corresponding values of N shown in Fig. 2., and the values of the probabilities of ionization in 2, Fig. 3, would be correspondingly decreased. These reduced values of the probability would then be regarded as giving the sum of the probabilities of the formation of single and of double ions, so that at 400 volts the probability of formation of single ions would be about 0.3. It is also probable that the values of P obtained by previous workers for gases other then mercury vapor may also require modification in view of the possible formation of multiple ions. It seems best to postpone any further discussion or speculation suggested by these results until further data are available both on the nature of the collision between electron and atom and also on the formation of multiple ions.

It is a pleasure to acknowledge my indebtedness to Professor John T. Tate who suggested the problem together with the general method of attacking it, and also rendered valuable assistance in overcoming some of the difficulties encountered. The work has been done while the author was a Commonwealth Fellow.

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[10] Brode, Phys. Rev. **25**, 5 (1925).