PROBABILITY OF IONIZATION OF GAS MOLECULES BY ELECTRON IMPACTS

By K. T. Compton and C. C. Van Voorhis

Abstract

Ionization in various gases by electrons of energy 0-325 volts.—Electrons from a hot filament were projected through an ionization chamber B containing gas at low pressure (.001 to .005 mm) and into a trap. Positive ions produced in B were collected on fine wires arranged in the form of a squirrel cage C and maintained at a potential lower than B by an amount V_r. Corrections were made for the facts (1) that the wires C lowered the potential at the center of B and hence retarded the electrons passing through B by a maximum amount of $0.4 \times V_r$, and (2) that if V_r was numerically less in value than the accelerating potential V_a, some primary electrons reached C. The pressures were measured with a McLeod gauge to 1 percent and were corrected for the heating effect of the filament, which was determined by using the apparatus as an ionization manometer to be about 26°. The resulting curves for N, the number of ions per cm path produced by an electron moving through a gas at 1 mm pressure, are believed correct within a few percent. In agreement with previous results of Hughes and Klein and others, the curves each rise to a maximum. The maximum values found and the corresponding voltages are as follows:

	H₂	He	Ne	A	N₂	Hg	HCl
N(max):	3.55	1.65	3.2	10.33	9.96	19.44	17.3
V(max):	145	210	340	140	175	135	130
P(max):	0.29	.209	.254	.466	.423	.239	.558

The values for P(max), the corresponding probability that a collision will result in ionization of the hit molecule, were computed from N(max) assuming the kinetic theory values for electronic mean free paths. These results are compared with previous experimental values. Ionization was found to begin at the ionizing potential in each case, except that with N₂ weak ionization was observed at 10 volts. This may possibly be associated with the presence of traces of active nitrogen.

TOWNSEND'S original theory of ionization by collision[1] assumed that ionization of a gas molecule occurs whenever it is struck by an electron whose speed exceeds the minimum ionizing speed, but this theory led to values of the minimum ionizing speed which were considerably in error. Bergen Davis[2] and one of the writers[3] modified Townsend's theory by assuming that the relation between the energy V of an electron at impact and the probability P that ionization of the molecule results from the impact is given by $P = (V - V_i)/V$ when $V > V_i$ and $P = 0$ when

[1] Townsend, "The Ionization of Gases by Collision."

[2] Bergen Davis, Phys. Rev. **24**, 93 (1907).

[3] K. T. Compton, Phys. Rev. **7**, pp. 489, 501, 509 (1916); Compton and Benade, ibid. **11**, 234 (1918).

$V < V_i$. This assumption led to calculated values of the minimum ionizing energy V_i which agreed better with the true values than did Townsend's original theory, but which were still incorrect. The recent advances in the study of various types of electrical discharge through gases, and especially the development of Langmuir's[4] new method for determining the distribution of velocities of the electrons in an ionized gas, have emphasized the importance of accurate knowledge of the values of the probability P of ionization by electron impacts at various speeds and in various gases.

The first experimental observations of this sort were made by Lenard[5] and were extended under his guidance by Kossel[6] and Mayer.[7] These investigators found that the probability of ionization is zero for impact energies up to the minimum ionizing potential, then increases to a maximum of less than 0.5 at impact energies of about 150 volts, followed by a decrease as the energy is further increased up to 1000 volts.

The present investigation was designed to introduce a number of refinements in technique, so as to permit the maximum possible accuracy of the observations. Shortly after we had begun, Hughes and Klein[8] published results of a research on the same problem, in which a considerable number of gases was tested over a large range of electron impact energies. In general features and in order of magnitude our present results agree with the findings of these and of the earlier investigators. We believe, however, that the present method permits greater accuracy of observation and reliability of interpretation than the methods previously used, so that we felt justified in continuing the work to its present conclusion.

The general procedure in such work is to accelerate electrons from a photo-electric or thermionic source and project them into a region in which the products of ionization are collected by a subsidiary system of electrodes. Besides obvious precautions of accuracy, calibration, gas purity, etc., there are several inherent difficulties encountered in endeavoring to measure the ionization per electron per unit path through the gas. The first of these is due to the fact that the electrode system which collects the products of ionization is subject also to charge arising from photo-electric action on the electrodes by radiation excited by electron impacts in the gas. The second difficulty is due to the necessity of apply-

[4] Langmuir, General Electric Review, **26,** 731 (1924); Langmuir and Mott-Smith ibid. **27,** pp. 444, 538 (1924).
[5] Lenard, Ann. der Phys. **12,** 474 (1903); **15,** 485 (1904).
[6] Kossel, Ann. der Phys. **37,** 393 (1912).
[7] Mayer, Ann. der Phys. **45,** 1 (1914).
[8] Hughes and Klein, Phys. Rev. **23,** pp. 111, 450 (1924).

ing a field in the region between the collecting electrodes in order to draw to them the products of ionization and to prevent any of the primary ionizing electrons from reaching these electrodes. Because of this field, the primary electrons do not pass through the gas with a constant speed, but with speeds which vary from that with which they are projected into the ionizing region down to much smaller values (down to zero in the experiments of Hughes and Klein). It is, therefore, impossible to say to just what energy of impact the observed ionization should be ascribed, and it is necessary to compute the desired result by setting up an integral equation to represent the observations and to solve it by differentiating the experimental curve. To the above difficulties might be added a third source of error which arises from any ionization of a cumulative type or from more than one impact by the same primary electron.

In the present work we have eliminated the first and third of these difficulties and reduced the second so that the value for the ionization per electron per centimeter path is set experimentally within rather narrow limits and may be computed within these limits with but a small probable error.

Apparatus and its Use

The apparatus employed is shown in Fig. 1. The filament F consisted of a few turns of 10 mil (.25 mm) molybdenum wire, in front of which was placed a focusing ring connected to the negative terminal. The narrow tube T through the bottom of the shielding box served to direct a narrow beam of electrons into the middle region of the chamber B. The positive ions formed in B were attracted to the collector C, which consisted of five 20 mil wires supported at each end by a ring of the same sized wire. The use of small wires for collecting the positive ions had the triple advantage of reducing to an inappreciable value the photo-electric current from this electrode, of reducing the chance that primary electrons which might be scattered in the gas would reach this electrode, and of reducing the effect on the velocity of the primary electrons due to the collecting field V_r. The ion trap S served to catch the electrons after passing through B, and also any positive ions produced after passing through the gauze at the bottom of B. The chamber B was 2.8 cm long and about 3 cm in diameter. All metal parts were made of nickel except the filament, and were freed from gas by heating in vacuo to a red heat by high frequency induction currents.

The electrical connections used in making the measurements are shown in Fig. 2. The variable accelerating voltage was measured by a voltmeter V_a, while G_- and G_+ measured, respectively, the electron

current I_- into the chamber B and the positive ion current I_+ resulting from ionization by the electrons passing through the gas in this chamber. We thought, when beginning the investigation, that a magnetic field produced by a current through a coil wound around the glass jacket and
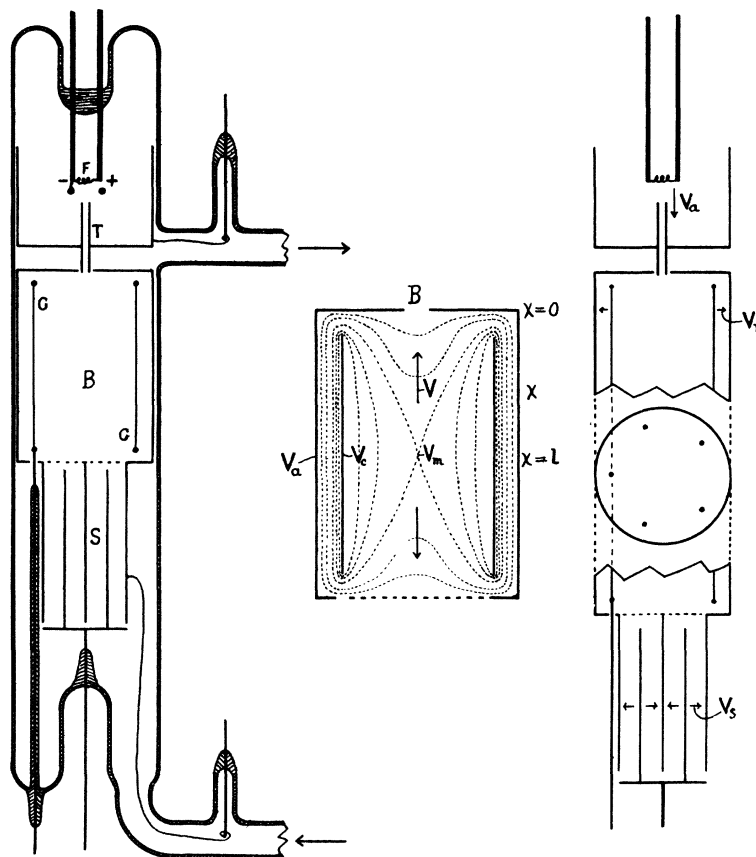

Fig. 1. Electrons from the filament F were projected through the tube T into the ionization chamber B in which the products of ionization were collected by a "squirrel cage" arrangement of wires C. The non-colliding electrons passed into the ion trap S. The dotted curves represent equipotential surfaces, with an axial point of minimum potential V_m, when the potentials of B and C are V_a and V_c, respectively, with respect to the filament.

coaxial with the chamber B would prevent electrons from reaching the collector C and thus permit us to use so small a collecting field as not appreciably to affect the speed of the primary electrons passing through the chamber. When this plan was tried, however, it was found that the ratio of I_+ to I_- for any given pressure was very irregular, being subject to small variations in the magnetic field, and that these irregularities

could be shifted from lower to higher voltages by increasing the magnetic field. Not succeeding in explaining or eliminating this effect of the magnetic field, we abandoned its use and applied a retarding voltage V_r to the collector C to prevent electrons from reaching it. A galvanometer with a sensitivity of about 300 megohms was used as G_-, while for G_+ were employed a galvanometer of about 11000 megohms sensitivity for the higher currents and a Compton electrometer with suitable India ink shunts for the lower currents.

The gas pressures used were between 0.001 and 0.005 mm mercury in order that the chance of an electron's making more than one collision with gas molecules while passing through chamber B would be extremely small. It was, therefore, unnecessary to take account of any ionization due to multiple collisions. These pressures were measured by means of a McLeod gauge with a rather fine capillary on the gauge reservoir, and instead of using a capillary of the same size for the outside mercury level,
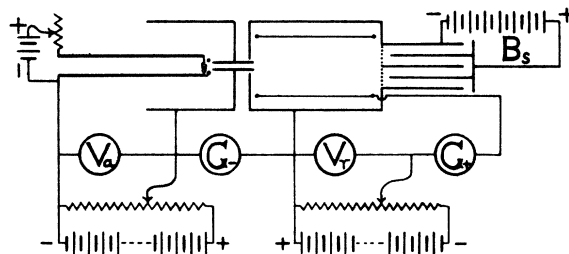

Fig. 2. Circuits. Voltmeters V_a and V_c measured the accelerating and collecting fields, and galvanometers G_- and G_+ measured the total electron current entering B and the positive ion current due to ionization, respectively.

a 1 cm tube was used. To determine the zero level of the mercury in the 1 cm tube, the capillary depression in a clicking vacuum was determined at various points along the capillary and was found to be everywhere almost exactly 12 mm. So, when a reading was taken, the outside level of the mercury was set 12 mm above the top of the capillary and the pressure read off the calibration curve as usual. The capillary tube was always tapped with a pencil while the mercury was coming to equilibrium in the tubes, to avoid any error due to the adhesion of the mercury to the walls. Also, parallax was avoided by observing the level of the mercury in the capillary through a lens mounted at the end of one edge of a small square. With these refinements the readings of the pressures varied less than 1 percent for different settings on the same pressure. A further check on the accuracy of the pressure readings was made occasionally by finding the product of the length of the gas-filled capillary times the difference in level of the mercury columns (the 12 mm capillary depression being de-

ducted of course) for different levels of the mercury in the capillary. This check was used whenever there seemed to be any pronounced sticking of the mercury in the capillary near the level used in the regular method of reading.

Determination of gas temperature. Since the chamber B became warm a short time after the filament current was turned on, it was necessary to find the actual temperature of the gas in order to know its density and to be able to reduce the results to standard conditions. Rather than reconstruct the apparatus with a thermocouple attached to B, we used the
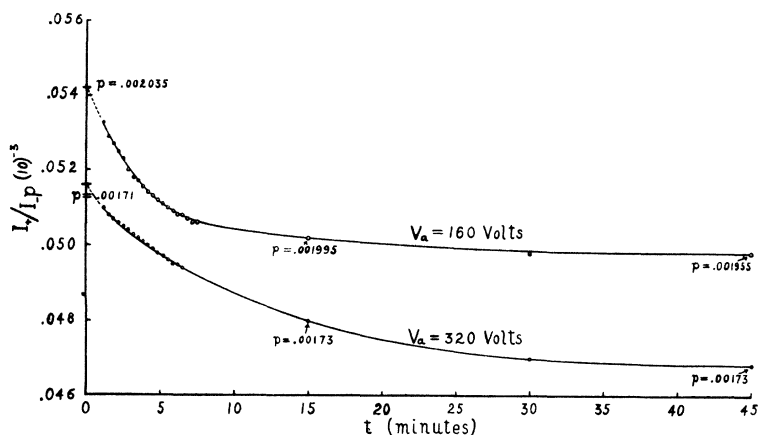

Fig. 3. Typical curves from which was found the temperature of the gas in the ionization chamber B. Time was measured from the instant of turning on the filament heating current. The decrease in ordinate (ionization per electron per 0.001 mm gas pressure) was due to the subsequent warming up of the gas. By use as an ionization gauge, the ratio of initial to final equilibrium temperature was computed.

apparatus as an ionization gauge to find the decrease in gas density due to increase in temperature just after the current through the filament was turned on. The positive ion current and electron current were measured at twenty second intervals for at least five minutes, beginning about one minute after the filament current had been turned on, and then at less frequent intervals until stable conditions were reached. Fig. 3 shows the results of two typical runs in mercury vapor, one with $V_a = 160$ volts and the other with $V_a = 320$ volts. The ordinates are numbers of positive ions produced per electron in traversing the length of B, per 0.001 mm pressure of the vapor.[9] The values of this number at time 0, i.e., at room temperature, are obtained by a short extrapolation of the curves back-

---

[9] The difference in the shape of these curves is due, for the most part, to the differences in initial pressures and in changes of pressure during the runs. That is the reason for giving the pressures in the figure.

ward. Thus with $V_a = 160$ volts the final ordinate is 91.9 percent of the initial one, and corresponds to a temperature rise of 26° above the room temperature of 25°; and with $V_a = 320$ volts the final ordinate is 90.7 percent of the initial one and corresponds to a temperature rise of 30° above the room temperature of 23°. From the consideration of nine such runs, it was decided that 51°C best represents the temperature of the gas in chamber B throughout the various observations. The possible variations from this temperature would not introduce any appreciable error.

Methods of handling the gases. The hydrogen was prepared by electrolysis of dilute sulfuric acid and was purified by passing over phosphorous pentoxide and through charcoal immersed in liquid air. It was admitted to the experimental tube through a trap immersed in liquid air, and there was also a liquid air trap between the experimental tube and the McLeod gauge and diffusion pump connections. Owing to the very rapid "clean up" of the hydrogen, a reservoir of about 5 liters capacity was attached to the tube to reduce the rate of change of pressure. The pressure was measured at about ten minute intervals during the runs, and the time of each current reading was noted, so that the proper pressure could be used for each individual calculation of the ionization per electron per unit pressure.

The argon was purified by prolonged arcing between calcium electrodes and was admitted to the experimental tube through a liquid air trap. To insure the purity of the neon and the helium in the tube, a charcoal trap, a tube containing copper and copper oxide, and a high pressure diffusion pump were added to the system in such a way that the gas could be circulated by the pump through the glowing copper and copper oxide and the charcoal, which was immersed in liquid air. This circulation was not continued while observations were being made, since the action of the circulating pump caused somewhat erratic variations in the gas pressure within the experimental tube. The helium and neon were each spectroscopically free from each other before being admitted to the system.

The nitrogen first used was generated by the reaction of sodium nitrite and ammonium chloride, stored in contact with phosphorous pentoxide and admitted through a tube immersed in liquid air. After finding that some ionization set in at about 10 volts (see Fig. 5) it was thought that possibly there might be some nitrogen oxides present, so that other runs were made using nitrogen generated by the action of bromine on ammonia and stored over phosphorous pentoxide—a method which is supposed to yield very pure nitrogen.[10] However, the experimental results with the gas prepared by the two methods were almost identical.

[10] Waran, Phil. Mag. **42,** 246 (1921).

While making the observations on mercury vapor, the liquid air was removed and the pressure varied for different runs by varying the room temperature. The slight temperature changes during a run were taken account of by noting at ten minute intervals the temperature of a thermometer placed in the vicinity of the system, and the time of each current measurement was noted, as in the case of hydrogen.

For the observations on hydrogen chloride, the gas was generated by the action of sulfuric acid on hydrochloric acid, passed through a sulfuric acid wash bottle, over phosphorous pentoxide and solidified in a tube immersed in liquid air. Then any uncondensed gas was pumped off, and the condensed material was allowed to evaporate into the 5 liter reservoir, after which it was recondensed and the residue again pumped off. This process was repeated until no uncondensable gas remained. The gas pressure in the 5 liter reservoir was then adjusted so that the rate of flow into the experimental system through a fine capillary leak would give a suitable pressure in the experimental tube when the diffusion pump was running. In this way there was no opportunity for the accumulation of products of slow reaction of the HCl vapor on the metallic electrodes. Due care was taken in the arrangement of the McLeod gauge and pump connections so that the gauge would give the true pressure in the experimental tube. Since liquid air temperature is too low to give a suitable vapor pressure of hydrogen chloride, a temperature between 10° and 25° higher than liquid air temperature was maintained in the traps for keeping out mercury vapor, by surrounding the traps with cylinders of brass closed at the bottom, these in turn being surrounded by large glass test tubes immersed in liquid air. By allowing about an inch of the brass cylinder to extend above the top of the liquid air flask, the pressure of the hydrogen chloride could be made as high as about 0.015 mm. Since there was usually a slight pressure change during a run, the same method of obtaining the correct pressure for each observation was used as in the cases of hydrogen and mercury vapor.

Potential at the center of chamber B. In order to prevent any appreciable number of electrons from striking the positive ion collector, V_r had to be made slightly larger than V_a. Thus the space through which the electrons passed within the chamber B was not field free, but had a potential distribution, probably such as shown in the central part of Fig. 1. The potential with respect to the filament would be a minimum at the center of B. Thus an electron, entering B with the speed corresponding to V_a, would be retarded until it reached the center, and then would be accelerated so that it would pass out of B with the same speed as that with which it entered, provided it suffered no inelastic collision on the way. Two

methods were used in determining the potential at the center of B. The first consisted in measuring the total electron current I_- while V_a was kept constant and V_r varied, for a series of values of V_a both in a vacuum and in hydrogen. When I_- was plotted against V_r, a marked change in slope was found in every curve at a value of V_r about 2.5 times that of V_a. This critical value of V_r was interpreted as being the one above which electrons were turned back before reaching the center of B, some striking the tube T or the under side of the shield containing it. Therefore V_m, the potential at the center of B, may be taken as $V_a - 0.4 \mid V_r \mid$, where $\mid V_r \mid$ represents the numerical value of the retarding potential applied between B and C.

The second method of determining V_m was to place a sensitive galvanometer in series with the 22.5 volt battery B (Fig. 2), connecting the two sets of vanes of the ion trap, and noting at what value of V_a, for a given V_r, electrons began getting through B into the ion trap. It was found that they began to get through when V_a was from 0.40 to 0.45 times $\mid V_r \mid$, thus confirming the conclusion that $V_m = V_a - 0.4 \mid V_r \mid$, to a close approximation.

Methods of measurement and calculation. Series of measurements were made on all the gases investigated by noting G_- and G_+ as V_a was varied from below the minimum ionizing potential to about 320 volts (410 volts in the case of neon to make sure that the voltage for maximum I_+ had been passed) with $\mid V_r \mid$ always about 1.5 volts greater than V_a. Readings were taken at intervals of one volt to above twice the ionizing potential; then of two volts to about 100 volts; of five volts to about 180, and then of ten volts over the rest of the range. Preliminary tests showed that the ratio I_+/I_- was independent of the filament temperature, i.e., of I_-, over a wide range. For convenience, about the same filament current was used all through the investigation and the galvanometers were calibrated at the beginning and end of each individual run. Several runs were made at somewhat different pressures with each gas. The only limitations in the pressures and currents which could be used were (1) that these must be large enough to give sufficient ionization for accurate measurement, and (2) that they must not be so large as to allow appreciable ionization by cumulative action or by more than one impact by an electron.

From the readings of G_- and G_+, the galvanometer and electrometer calibrations and the gas pressures, the ratio $I_+/(I_- p)$, where p is the pressure of the gas in mm of mercury, was calculated. Then from the results of three or more such runs which agreed within 2 percent with one another over most of the range for each gas, the mean values of this ratio were found for each voltage V_a. When these mean values were plotted

against the values of V_a they gave such curves as curve a in Figs. 4 and 5. The ordinates of this curve should give the average number of ionizing collisions made per electron while moving a distance equal to the length of B (2.8 cm) through the gas at 1 mm pressure with velocity corresponding to V_a, if it were not for the fact that the space within B is not field free and consequently the electrons do not all have the velocity V_a when they strike the gas molecules. Two methods were used to take into account this uncertainty, (1) by calculation based on the distribution of potential within B, and (2) a direct method whereby the desired quantity can be set by experiment between narrow limits.

First method. Of several assumptions made regarding the variation of potential along the path of the electrons in B, the one which gave the most reasonable results was the assumption that the potential varies at a uniform rate from the end to the center. Then the value of the potential V (with respect to the filament) at any point x in B is given by

$$V = V_a - \int_x^l E\,dx = V_a - E(l-x) \ ,$$

where l is the distance from the center to the end of B, x is the distance of the point x from the center of B and E is the electric intensity (supposed constant). At the center, $x = 0$, hence

$$V_m = V_a - El = V_a - 0.4(V_a - V_c)$$

where $V_c = V_a - |V_r|$ is the potential of the collecting electrode. Thus $E = 0.4\ (V_a - V_c)/l$. Substituting this above, and remembering that V_c in our experiments was only 1.5 volts, we have approximately

$$V = V_a(0.6 + 0.4x/l) \ . \tag{1}$$

Let $M = I_+/(I_-p)$ stand for the observed ionization per electron per unit pressure in the chamber B. Let $f(V)$ be the average number of ionizing collisions made by an electron if it passed through B with uniform velocity of V volts, at unit pressure. Then we should have

$$M = \int_{V_m}^{V_a} f(V)d(x/l) \ .$$

Since $V_m = 0.6 V_a$, and differentiation of Eq. (1) gives $d(x/l) = (2.5/V_a)dV$, we have

$$M = (2.5/V_a)\int_{0.6V_a}^{V_a} f(V)dV \ .$$

By differentiation,

$$0.4\ d(MV_a)/dV_a = f(V_a) - f(0.6\ V_a) \ . \tag{2}$$

In applying this equation to determine $f(V_a)$ from the experimental values of V_a and M, we have two cases to consider:

If $V_a < 1.67$ times the minimum ionizing potential V_i, then $f(0.6\ V_a) = 0$, and we have

$$f(V_a) = 0.4\ d(MV_a)/dV_a\ . \tag{3}$$

If $V_a > 1.67\ V_i$, then

$$f(V_a) = 0.4\ d(MV_a)/dV_a + f(0.6\ V_a)\ . \tag{4}$$
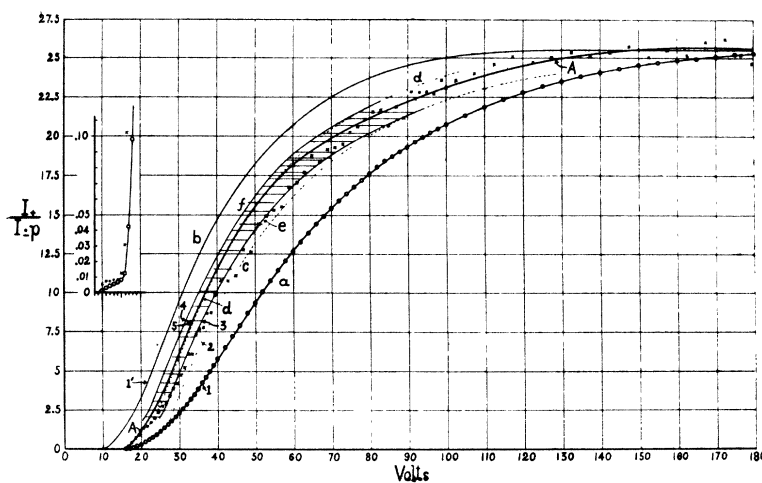

Fig. 4.   Curves for nitrogen; positive ions formed per electron per mm pressure per 2.8 cm path as a function of energy of electrons, in volts. Curve a gives experimental results when $V_r = V_a + 1.5$ volts, thus with primary electrons prevented from reaching C. Curve b gives the same values plotted against the minimum energy V_m instead of the maximum energy V_a. The true curve lies between these. Curve c gives experimental values when V_r was adjusted for maximum ionization, and curve d gives the same for minimum voltage V_m. Curves e and f were obtained by correcting c and d for stray electron current. The true curve lies between e and f and is taken as curve A. Crosses are points which were computed from curve a by method (1).

The values of $f(V_a)$ were calculated for the different voltages used, by means of Eq. (3) and (4) and plotted at the mid-points $V_a - \frac{1}{2}\ dV_a$, giving results such as are shown by the crosses in Figs. 4 and 5. A rather marked change in slope was noted in all of the M curves at a value of V_a approximately twice the ionizing potential, and this break was still more pronounced in the $f(V_a)$ curves.   It was at first suspected that these breaks might be due to ionization of highly excited molecules, or by the double ionization which might occur if a molecule, excited by an energy at least twice the minimum ionizing energy, should make a collision of the second kind with a neutral molecule. Such effects should, however, tend

to disappear at very low gas pressures, whereas we found that the curves, including this break, were identical down to extremely low pressures. In the second method, described below, it was found that this break shifted according to the value of V_r, so that we are inclined to attribute it to a peculiarity of the field within B, due to lack of radial symmetry of the collecting electrode system. It probably indicates a second order error in the values of M and $f(V_a)$ in the lower voltage ranges.

The second method for finding the number of ionizing collisions which would be made by an electron moving with a uniform speed V_a through B in gas at unit pressure, can be best explained by referring to Fig. 4. Consider, for instance, the experimental reading marked 1. Here the electrons entered the chamber B with velocity of 36 volts and reached the center of B with velocity of 0.6 of 36, or 24 volts. The ordinate at 1 must therefore be the value of $f(V_a)$ corresponding to some value of V_a between 36 and 24 volts. In other words, the corresponding point on the $f(V_a)$ curve must be somewhere between 1 and 1'. Similarly for every point on curve a there is a corresponding point on curve b which is shifted to the left by an amount 0.4 of V_a. The true curve for $f(V_a)$ must lie between the curves a and b.

Now, by decreasing the field V_r to a value considerably less than V_a, keeping V_a constant at 36 volts, it was found that the current I_+ increased to a maximum value when V_r was 11 volts, and then decreased with further decrease in V_r. The reason for this is that decrease in V_r produced two opposing effects: (1) It diminished the retardation of the electrons, thus causing them to traverse B with speeds more nearly equal to V_a, and thus increased the ionization produced by them; (2) it permitted some electrons to reach the collecting electrode, and thus diminished the apparent amount of ionization. The observed value of I_+ corresponds to point 2 in Fig. 4. Owing to the electrons which reached the collecting electrode, the true ionization must have been somewhat greater than this. The amount by which it was greater was determined by making a similar measurement with the gas removed from the tube, so that the stray electron current only was measured, and this was checked by similar measurements in the gas at values of V_a less than V_i. Adding this to the current corresponding to point 2 gives the current which would have been observed with V_r equal to 11 volts, had there been no reverse current due to electrons. This ordinate at point 3 corresponds to electrons which entered B with velocity 36 volts, and whose velocity fell by 0.4 of 11 volts, or by 4.4 volts within B. Thus the ordinate is the value of $f(V_a)$ for some value of V_a between 36 and 31.6 volts. Thus the limits within which the value of $f(V_a)$ must lie have been much narrowed down; it must lie be-

tween points 3 and 4. A consideration of all the factors involved led to the choice of point 5 as the most probable point, and it is certain that this value of V_a and $f(V_a)$ cannot be in error by more than a few percent. In this way, the values of $f(V_a)$ were found and plotted as curve A, which lies between the experimentally fixed limits shown by curves e and f.

Of the two methods, the second is the more reliable in that it does not depend on any assumption regarding the distribution of potential within B. The agreement between the two methods is indicated by the way in which the crosses are distributed with respect to the experimental limits
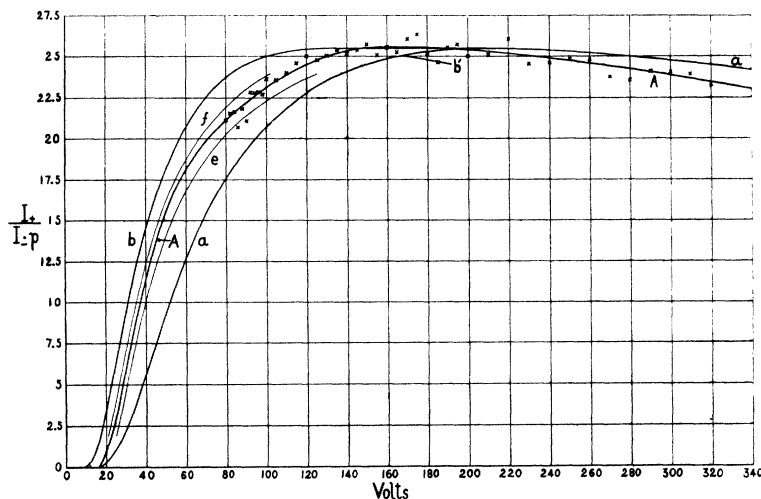

Fig. 5. Extension of Fig 4 to 340 volts.

shown by the shaded region between curves e and f. The agreement is best at the higher voltages, where the variation of $f(V_a)$ with V_a is less rapid. Curve A has been drawn with reference to the second method at the lower voltages, and with reference to the first method at the higher voltages, where the two methods converge to give the same results. Curve A gives, for nitrogen, the average number of ionizing collisions which would be made by an electron moving with constant speed V_a through chamber B containing the gas at 1 mm pressure. Fig. 5 shows the same results, continued to the higher voltage ranges.

DISCUSSION OF RESULTS

If the values of the ordinates of curve A are divided by the length of the chamber B, they give the average number N of ionizing collisions per electron per cm path per mm gas pressure as a function of the velocity. The assembled results of our experiments are shown in Fig. 6, where N

stands for the quantity defined just above. It is of interest to note that the value of N continues to decrease with still greater electron speeds. For air, according to Kossel[6] N decreases from about 10 at 200 volts to 3.3 at 1000 volts, 0.4 at 30,000 volts and 0.18 for β-rays.

The probability P of ionization at an impact may be found by dividing these values of N by the number of collisions per cm path made by an
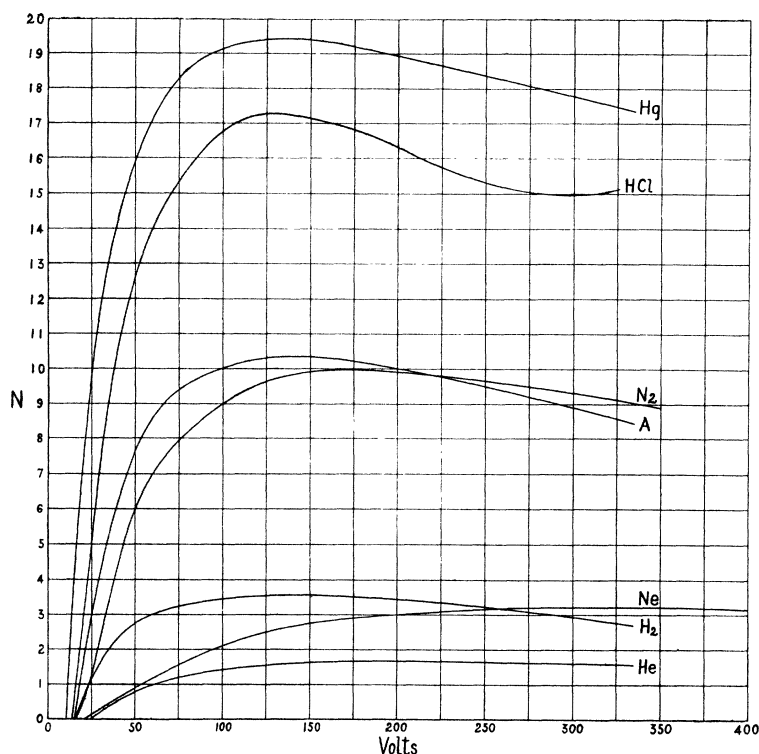

Fig. 6. Number of positive ions formed per electron per cm path through gas at 1 mm pressure, as a function of the electron energy in volts.

electron moving through the gas at 1 mm pressure. Although there is some uncertainty regarding the true values of this number, the experiments of Ramsauer[11] and Mayer[12] indicate that the ordinary kinetic theory value of electronic mean free path is at least approximately correct at speeds as large as those in which we are interested, except for argon at the lower speeds. We shall, therefore, assume that the electronic mean free path equals $4\sqrt{2}$ times that of the gas molecules. The values are given

[11] Ramsauer, Ann. der Phys. 64, 513 (1921); 66, 546 (1921).

[12] Mayer, Ann. der Phys. 64, 451 (1921).

in Table I. They are calculated from values given in "High Vacua," by Dushman, except in two cases for which the data were not available there and were obtained from Kaye and Laby's Tables. All are calculated for a temperature of 25°C. The values of the probability P are shown in Fig. 7.

TABLE I

Gas:	He	Ne	A	H_2	N_2	Hg	HCl
l :	0.1259	0.0787	0.0451	0.0817	0.0425	0.0149	0.0322
$1/l$:	7.95	12.80	22.18	12.24	23.52	66.70	31.05

A comparison of our results with those of Hughes and Klein, while showing agreement as to general features and orders of magnitude, brings out discrepancies which are difficult to explain. The fact that
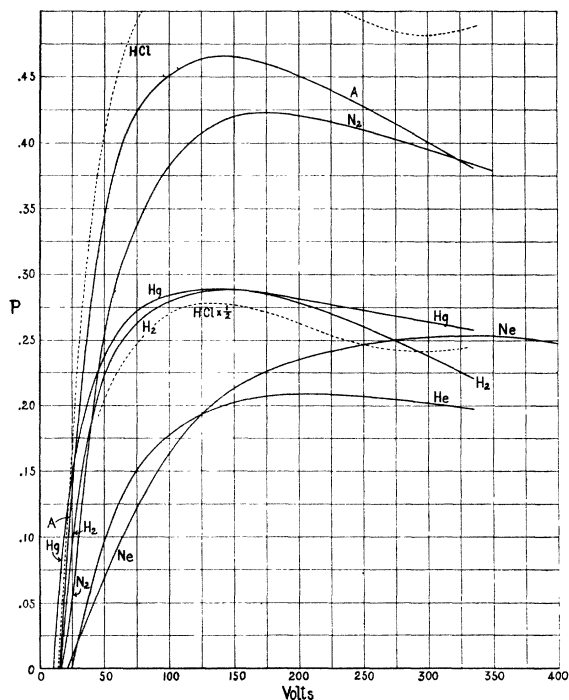

Fig. 7. Probability of ionization at an impact as a function of the electron energy in volts, assuming kinetic theory values of electronic mean free paths.

their values are consistently smaller than ours may be due to the fact that they appear not to have taken account of the heating of the gas in the apparatus by the filament. We feel that their results are definitely too low, since they fall below the lower limit set by curves, such as curve e of Figs. 4 and 5, which are the direct result of measurement and depend on no calculations or assumptions, but only on the calibration of the gal-

vanometers and the McLeod gauge. Some aspects of this comparison are shown in Table II. This table also contains values from a recent paper by Jesse.[13] Although he does not claim much accuracy for his absolute values of N, his results agree more closely with ours than do those of Hughes and Klein.

TABLE II

Gas	N(max) (authors)	(H. & K.)	(Jesse)	V_a(max) (authors)	(H. & K.)	(Jesse)
He	1.65	0.881	1.61	210	150	140
Ne	3.22	1.828	3.16	340	160	220
A	10.33	7.65	14.5	140	80	100
H_2	3.55	2.518	.....	145	73.5	...
N_2	9.96	7.640	10.3	175	100	100
Hg	19.44	.....	.....	135	.....	...
HCl	17.30	.....	.....	130	.....	...
CO	.....	.....	12.8	...	.....	120
CH_4	.....	8.06	.....	...	80	...

Mention should also be made of a recent paper by Gladys A. Anslow[14] on "Total Ionization Produced in Air by Electrons of Various Energies," in which conclusions are reached with regard to the ionization per electron per cm path at 1 mm pressure which differ very markedly from the conclusions of the present paper, both in magnitude and in the nature of the dependence upon electron speed. In considering Miss Anslow's work, it should be noted that the gas pressures at which her observations were taken were determined by extrapolation of a certain curve which was interpreted as giving the "critical pressure" at which the electrons just failed to reach the walls of the ionization chamber before having completed their total ionization, so that it was assumed that all electrons lost their ionizing energy by collisions with gas molecules before escaping from the chamber. This cannot have been true, however, as a simple calculation based on electron mean free paths shows. For all of her voltages below 1000 volts, an appreciable number of electrons would have traversed the ionization chamber without having collided at all; below 300 volts the majority would have thus escaped collision, while at the maximum of her curve, Fig. 6, not more than one percent of the electrons would have collided. Thus the interpretation of the results at the lower voltages is incorrect and these results cannot be taken as inconsistent with the results of the present paper. Incidentally, we believe that the maximum in Miss Anslow's Fig. 6 is due to the combination of the variation in the number of electrons which collide and the variation of the probabilities of ionization at the different pressures and voltages used.

[13] W. P. Jesse, Phys. Rev. 26, 208 (August, 1925).
[14] Gladys A. Anslow, Phys. Rev. 25, 484 (1925).

On the basis of measurements with the ionization gauge, Dushman[15] suggested that the ionization in different gases is proportional to the total number of electrons in the molecules of the gases. The present results do not support this suggestion as a quantitative relation. It may be, however, that the proposed relation is more accurate at higher voltages than those at which we worked—as might be expected on theoretical grounds and as is indicated by the early work of Kossel,[16] who made the same suggestion on the basis of measurements at 1000 volts.

Finally, the apparent ionization of nitrogen at about 10 volts (see Fig. 4) raises an interesting question of interpretation. As shown in the insert, this is extremely weak as compared with the ionization setting in at the ordinary ionizing potential. Three possibilities present themselves: (1) It may represent a weak and hitherto undiscovered type of ionization of nitrogen; (2) it may be due to photo-electric effect on the collecting electrode C by radiation excited in the gas; (3) it may be due to electron emission from the collecting electrode C produced by contact with "excited" or "active" molecules of nitrogen. In opposition to the second suggestion is the fact that in no other gas was there any detectable current which could be ascribed to photo-electric effect; the scheme for eliminating complications from this cause seemed to be quite successful. In favor of the third suggestion is the fact that this observed critical potential agrees well with the internal energy of at least one type of active nitrogen, which has been placed at 9.52 volts by Saha and Sur,[16] as revised by Foote, Ruark, and Chenault.[17] If this is the correct interpretation, the detection of the active nitrogen by an apparatus relatively insensitive to the photo-electric effects would be due to the greater probability of electron emission at a collision of the second kind between an excited molecule and the metal than by photo-electric action of radiation. If this be true, it must still be remarked that the efficiency of these low voltage impacts in producing active nitrogen must be quite small, else Duffendack would have detected it in his low-voltage arcs.[18] We hope later to be able to give a definite answer to this question.

Note added with proof. Further consideration of the work by Hughes and Klein[8] and by Jesse[13] indicates that in both cases the assumed values of primary electron current must be in error. The former are too large, owing to an incorrectly assumed linear relation between current and field on one side of the grid. The latter are too small on account of neglect of

[15] Dushman, "High Vacua"; Dushman and Found, Phys. Rev. **23,** 734 (1924).
[16] Saha and Sur, Phil. Mag. **48,** 421 (1924).
[17] Foote, Ruark, and Chenault, Phys. Rev. **25,** 241 (1925).
[18] Duffendack, Phys. Rev. **20,** 665 (1922).

secondary electrons which subtract from the primary electron current. Experiments are being undertaken to see whether these corrections are adequate to account for the discrepancies in the three experiments on this subject. It may be noted that in the present work both the ionization and the primary electron currents were measured directly, and that secondary electrons were avoided by use of the electron trap.

PALMER PHYSICAL LABORATORY,
   PRINCETON, NEW JERSEY,
    July 16, 1925