THE TOTAL IONIZATION PRODUCED IN AIR BY ELECTRONS OF VARIOUS ENERGIES

By Gladys A. Anslow

Abstract

Range in air and total ionization by electrons of energy up to 2225 volts.—Electrons from a tungsten filament were accelerated to a cylindrical anode with a small axial hole through which a fraction passed into a hemispherical ionization chamber maintained at a definite pressure by means of an adjustable leak, while the filament chamber was connected to a diffusion pump. The number of electrons entering the ionization chamber and the number of positive ions formed by them was measured with an electrometer. From ionization-pressure curves the range of electrons of various energies was determined, and was found to obey the fourth-power velocity law $R \propto v^4$, or $\sqrt{R} = V/15900$, where V is the energy in equivalent volts and R is in cm at atmospheric pressure. The total ionization curve begins at 17 volts, and rises with minor peaks at 127, 250, 375 and 494 volts of 1.83, 2.70, 4.10 and 5.05 ions per electron, to 43.2 ions per electron at 1000 volts; then the increase is approximately linear to 55 ions per electron at 2225 volts, and the values of others for high speed electrons indicate that this increase continues at about the same rate. These results tend to confirm *Bohr's theory of ionization* as corrected by Fowler. The voltages at which the total ionization shows peaks are interpreted as the ionization potentials of the L-electrons of argon (250) and the K-electrons of nitrogen (375) and of oxygen (494). The ionization per cm of path at 1 mm pressure, obtained by dividing the total ionization by the range, reaches a maximum of 112 ions/cm for 40 volts and a second maximum of 13.9 ions/cm for 987 volts. The first maximum agrees with that predicted from the ionization potentials of the molecule and atom of nitrogen, and the second corresponds to twice the ionization potential for the K-electrons of oxygen and gives a value of 22.8 volts energy per ion pair produced, in agreement with theory. For electrons with 40 volts energy, Bohr's theory gives the maximum effective radius of air molecules during collision as approximately 5×10^{-8} cm. The 987 volt electrons are probably those which give the "sphere" tracks in C. T. R. Wilson's photographs. Their range is .04 mm at atmospheric pressure.

THE variation of the ionizing efficiency of electrons in air and in various gases with the speed of the ionizing particle has been determined for very low-speed electrons and for the high-speed β-particles, but no exact determinations have been made in the intervening range of velocities. In this region there should be some velocity for which the ionization per unit length of path at a given pressure is a maximum, since this quantity has been found to increase with the velocity with low-speed electrons and to decrease as the velocity of high-speed electrons increases. The experiment to be described furnishes a method of determining the total ionization produced by electrons whose velocities are in this intervening range, and affords simultaneously a measure of the range of the particles and a determination of the mean ionization produced per unit length of path at a given pressure. Some of the more important results have already been published in a preliminary note.[1]

Among the previous measurements with slow-moving electrons are those by Kossel,[2] who found in various gases that the ionization per centimeter of path at 1 mm pressure has a maximum value at less than 200 volts. This maximum was located with more precision by F. Mayer,[3] and recently by Hughes and Klein.[4] In all cases the ionization produced rises rapidly to a maximum value as the voltage increases to 100-150 volts and then decreases slowly, the magnitude and location of the maximum varying with the gases. Also, in a direct measurement of the total ionization produced in a number of gases J. B. Johnson[5] found that up to 200 volts, total ionization appeared to be a linear function of the energy of the ionizing electron.

In the region of high-speed electrons the lowest velocities were used by Durack[6] and Glasson,[7] who found, respectively, that .43 and 1.5 ions per cm of path at 1 mm pressure were produced by 4000-volt electrons, and that this number was smaller with faster-moving electrons. W. Wilson's[8] results showed that for high velocities, ionization per unit length of path is inversely proportional to the initial energy of the electrons. The total ionization produced by β-rays in air was determined by Eve[9] from the absorption coefficient; and more exact values, corrected for reflection, were obtained by Geiger and Kovarik,[10] who found that at atmospheric pressure 67 ions were formed in the first centimeter of path of a high-speed β-particle.

In connection with the present work the recent cloud experiments of C. T. R. Wilson[11] showing the tracks made by β-rays generated in a gas by x-rays, are very important. Wilson groups these tracks into classes including "spheres," "commas," "fish-tracks," and short and long-range tracks. The "sphere" tracks, of less than .1 mm length are due to β-rays

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[1] G. A. Anslow, Science, **60**, 432, (1924).

[2] W. Kossel, Ann. der Phys. **37**, 393 (1912).

[3] F. Mayer, Ann. der Phys. **45**, 1 (1914).

[4] A. Ll. Hughes and E. Klein, Phys. Rev. **23**, 111, 450 (1924).

[5] J. B. Johnson, Phys. Rev. **10**, 609 (1917).

[6] J. E. Durack, Phil. Mag. **4**, 29 (1902); **5**, 50 (1903).

[7] J. L. Glasson, Phil. Mag. **22**, 647 (1911).

[8] W. Wilson, Proc. Roy. Soc. **85**, 240 (1911).

[9] A. S. Eve, Phil. Mag. **22**, 551 (1911).

[10] H. Geiger and A. F. Kovarik, Phil. Mag., **22**, 604 (1911); A. F. Kovarik, Phil. Mag., **20**, 349 (1910).

[11] C. T. R. Wilson, Proc. Roy. Soc. A **104**, 1, 192 (1923).

which produce the maximum ionization per cm and Wilson estimates that their velocity corresponds to considerably less than 2000 volts. The present experiments fix this voltage at just less than 1000 volts. The location of a maximum in this region was also indicated in the early experiments of Lenard[12] who accelerated photo-electrons to a fluorescent screen and found that the effect was a maximum near 2000 volts.

THEORIES OF IONIZATION

The effect of electronic collisions was first discussed from the standpoint of the classical theory by J. J. Thomson,[13] who assumed that the velocity of the electrons in the atom is much smaller than that of the impacting electron, and calculated the probability of ionization by an electron which passes within a minimum distance of an atom. He found that ionization should begin when the energy of the moving electron is equal to the work necessary to remove the electron from the atom, and that ionization per unit length of path should rise rapidly to a maximum value as the energy increases to twice this value and should then decrease slowly.

This theory was further developed by Bohr[14] who introduced the conception of the existence of certain natural frequencies for electrons which move in orbits around a nucleus, and the idea that the "time of collision" must be of the same order of magnitude as the period of the electron in the atom, an assumption which introduces an upper limit to the "effective radius" of the atom. This idea has also been discussed by Ramsauer.[15] Bohr also considered the emission of secondary electrons by the primary ones if the latter move away from the nucleus with sufficient energy to ionize. The work of ionization may be the same or different for the two types of ionization, and he assumes that most of the secondary electrons are emitted for the smallest energy required to ionize the gas. He found that the number of ions I formed in the distance Δx in a gas with N atoms per unit volume is given by the equation

$$I=\frac{2\pi e^4 N\Delta x}{mv^2}\sum_{W=W_1}^{W_n}\left[\left(\frac{1}{W}-\frac{1}{Q_0}\right)+\left(\frac{1}{W+W_1}-\frac{1}{Q_0}\right)+\cdot\cdot\cdot\right], \quad (1)$$

where Q_0 is the energy of the moving particle and v is its velocity, W the work of ionization for the primary electron of which there may be n types, W_1 the work of ionization for the secondary electron, and e and m

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[12] P. Lenard, Ann. der Phys. **12,** 449 (1903).

[13] J. J. Thomson, Proc. Phys. Soc. Lond. **27,** 96 (1914).

[14] N. Bohr, Phil. Mag. **25,** 101 (1913); **30,** 581 (1915).

[15] C. Ramsauer, Jahr. d. Radioact. **9,** 515 (1912); Ann. der Phys. **64,** 513 (1921); **66,** 546, (1921); **72,** 345 (1923).

are the electronic charge and mass. If Q_0 is large as compared with all the W's, Bohr obtained as an approximate expression

$$I=\frac{2\pi e^4 N\Delta x}{mv^2}\ \frac{1}{W_1}\sum_{W=W_1}^{W_n}\log\left(\frac{Q_0}{W}\right)\,. \tag{2}$$

Eq. (1) indicates that we should expect a maximum value of the mean primary ionization per cm at twice the ionization potential for a gas with only one ionizing potential, but at a higher potential for gases with several ionizing potentials; and it indicates a slow decrease in the mean ionization per cm above this potential. Eq. (2) also predicts this maximum and indicates a sudden decrease in the ionization for values of Q_0 corresponding to values of ionization potential which are large compared to the other ionization potentials.

Assuming that all the energy of the electron will be used in ionizing collisions Bohr derived an expression for its range R

$$R=\frac{m^2c^4}{2\pi e^4 N}\ \frac{\left[(1-\beta^2)^{\frac{1}{2}}+(1-\beta^2)^{-\frac{1}{2}}-2\right]}{\sum_1^n\left[\log(k^2c^2Nn\Delta x/4\pi\nu^2)-\log\left[(1-\beta^2)/\beta^2\right]-\beta^2\right]}\,, \tag{3}$$

where β is the ratio of the velocity of the electron to the velocity of light c, k is the gas constant, and ν the orbital frequency of the electron. This equation shows that for small velocities the range of an electron should be proportional to the fourth power of its velocity, a result which is confirmed by the experiments of Whiddington[16] and others.

The subject of ionization by electrons has been discussed by R. H. Fowler,[17] who points out that Bohr's theory assumes that secondary electrons are emitted from an atom at an expenditure of only their work of ionization. He assumes that they are released with various kinetic energies and examines the distribution law for these energies. He finds that if the initial energy is at least three times the work of ionization the number of electrons set free by one electron is a function $g(z)$ of the velocity where

$$g(z)=\tfrac{3}{4}(z-\rho)/\rho\ ,\ \text{approximately}. \tag{4}$$

In this equation z represents the square of the velocity of the initial electron and ρ that required for ionization. Thus Fowler states that the expressions for the mean ionization per cm given by Bohr's theory should be multiplied by approximately 3/4, and the expression for the range by 2 or 3.

In his last paper Fowler[18] considers the effect of the reciprocal process in collisions, that is, the capture of one of two electrons which collide

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[16] R. Whiddington, Proc. Cambridge Phil. Soc. **16**, 321 (1911).

[17] R. H. Fowler, Proc. Cambridge Phil. Soc. **21**, 521, 531 (1923).

[18] R. H. Fowler, Phil. Mag. **47**, 257 (1924).

simultaneously with an ionized atom; one will be caught and the other will move on with an energy which is the sum of the initial electronic energies increased by the work of ionization. The analysis is similar to that employed by Klein and Rosseland,[19] who examined the collisions which occur when the bound electron is on an outer orbit and is caused by the collision to return to an inner stationary state. Such collisions would decrease the amount and efficiency of ionization.

Apparatus and Experimental Procedure

All previous experiments with low-speed electrons have been limited in their range due to the fact that the pressure in the chamber where the electrons are generated was the same as that in the ionization chamber. If the dimensions of the chamber are of normal size the electrons will reach the sides of the vessel before their energy has been entirely used up unless the pressure in the chamber is sufficiently high. In this case the distance between the source and the anode will not be very much less than the mean free path of the electron and a large number of ions formed in this space are uncounted. Therefore, an attempt has been made to generate electrons in a high vacuum, to accelerate them in a distance very small compared with their mean free path, and then to pass them without retardation into a chamber at a higher pressure. This pressure must be adjustable so that for all observations on total ionization the dimensions of the vessel are just greater than the range of the electrons.

Fig. 1 shows the construction of the filament tube and the ionization chamber. The tungsten filament *f* was a Coolidge tube element, furnished by the General Electric Co., to whom I wish to express my thanks at this time. The leads to the filament passed through the glass tube *t'*, which was supported by the outer tube *t* with a ground glass joint. The other end of *t* was welded to a copper tube about 5 cm in diameter, which in turn was soldered to the large cylindrical earthed container *a*, made of brass. The filament was held 2 mm from the anode *p*, which was a brass plug 1.1 cm thick and 2.5 cm in diameter with a capillary hole, .2 mm in diameter, along its axis. The plug was insulated from the ionization chamber *c* and the container *a* by a wood-fiber ring *e* which was cemented to the lid of the shield *a*. The seal, made with a venice turpentine and shellac cement and baked out at 100° C for at least two hours, withstood the great heat from the filament. The base of *a* was soldered to its sides, but the lid was held in place by Boltwax to permit frequent opening of the vessel. The ionization chamber *c* was a hemispherical

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[19] O. Klein and S. Rosseland, Zeits. f. Phys. **4**, 46 (1921).

copper bowl of radius 7.33 cm with the end of the capillary in the anode at its geometrical center. This shape was necessary because, although the beam of electrons entering the chamber was cylindrical, some of the electrons must have been scattered by collisions and this shape prevented them from hitting the sides of the vessel before the undeflected electrons had reached the end of their paths. The four rods *d* of brass, bent into arcs of circles and joined together, served as electrodes for the measurement of the ionization current. Electrical contact to these was made through the rod *m*, to the ionization chamber by the rod *n*, and to the anode by the fine wire *g*. All these leads were insulated from the chamber and shield by ebonite plugs.

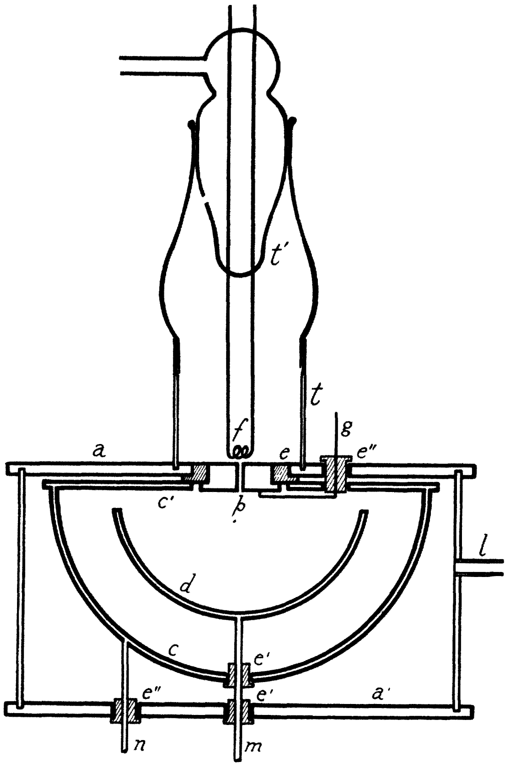

Fig. 1. Diagram of filament tube and ionization chamber.

Considerable care was taken in adjusting the support for the chamber so that the axis of the chamber and of the capillary hole in the plug was parallel to the resultant earth's magnetic field at the station. This was done to avoid a magnetic deflection of the electrons as they passed from the filament to the chamber. The magnetic dip was found with a dipcircle after all the motors and other apparatus with magnetic materials had been placed in the room.

Air from a carboy at low pressure leaked through a capillary, and after having passed over a drying tube filled with phosphorous pentoxide it entered the ionization chamber at *l*. A McLeod gauge, attached close to *l* indicated the pressure in the chamber. The air leaked slowly from the ionization chamber through the plug *p* into the filament tube, where it was pumped away by a diffusion pump system. This consisted of one diffusion pump with a liquid-air trap, attached close to the filament tube, and with a large capacity oil-pump as fore-pump. The pressure in the filament tube was indicated by a second McLeod gauge, and was kept between 10^{-4} and 10^{-3} mm while the pressure in the ionization chamber was varied from 0.001 to 2.2 mm. For the readings taken at the larger pressures two diffusion pumps were used in parallel.

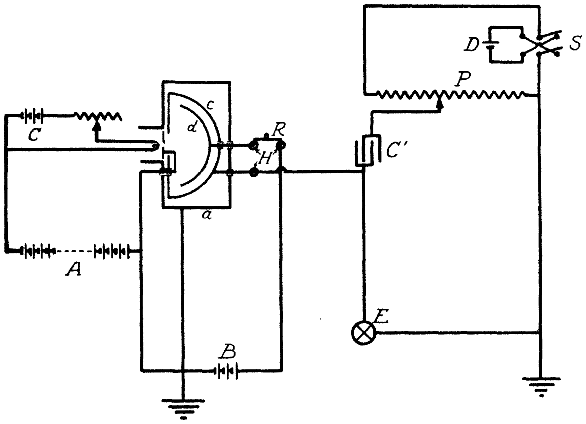

Fig. 2. Diagram of electrical circuits.

The electrical connections are shown in Fig. 2. The filament was connected to the negative terminal of a bank of storage cells for voltages up to 300 volts, and to a direct-current motor-generator for high voltages, the anode and the positive terminal being connected to earth. The voltage was measured at the leads to the filament, and half the voltage drop along the filament, 3 volts, was subtracted from the greater value to give the accelerating potential applied to the electrons. The shielding cylinder *a* and the copper tube *t* to which *a* was soldered were always connected to earth.

To measure the electrons entering the ionization chamber in a given time, the rods and the chamber were connected together and to one pair of quadrants of the electrometer, the other pair being to earth. The number of positive ions formed was taken as a measure of the ionization, and this was accomplished by connecting the rods to the positive terminal of the batteries *B*, their negative terminal being to earth. The positive ions flowed to the chamber, and charged up the quadrants of the electrometer. The reversal of the connections was made through a mercury-cup of small capacity, housed in an earthed tin box. The electrometer was used at a sensibility of about 230 divisions per volt, and 44-48 volts potential on the rods was used to obtain the saturation value of the ionization current. The Townsend null method of measurement was used; that is, the electron and positive ion currents were balanced in turn by an opposing current from a potentiometer system *P* which charged standard air condensers *C′*, shunted to the electrometer.

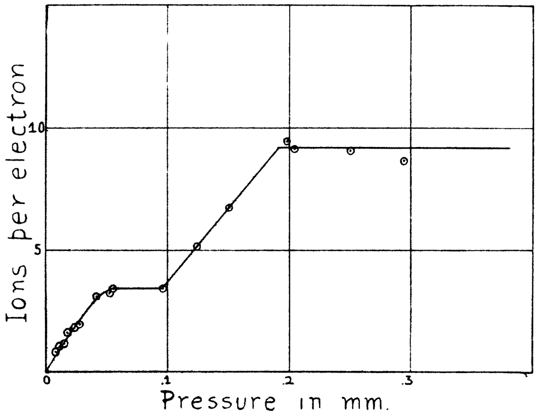

Fig. 3. Ionization-pressure curve for 700-volt electrons.

For a number of voltages readings were taken at various pressures, the pressure being read immediately after the electrometer readings. In Fig. 3 is plotted a typical ionization-pressure curve. For high pressures the ionization produced at a given voltage was practically independent of the pressure. As the pressure was decreased, however, a critical value was passed below which the ionization decreased rapidly with a decrease of pressure. This was due to the fact that at these pressures the electrons hit the sides of the vessel before they had finished ionizing, since the radius of the vessel was less than their range. Therefore the average of the values on the horizontal part of the curve just beyond the critical pressure was taken as a measure of the total ionization produced by an electron at this voltage. Too high pressures in the ionization chamber were avoided, for with these pressures the percentage of error in the results, due to the number of ions produced in the capillary and which are uncounted, is increased. If it is assumed that there is a linear drop of pressure along the capillary the percentage uncounted is measured by the ratio of the half-length of the capillary to the radius of the chamber increased by this half-length, and accordingly from the dimensions used the readings taken at the critical pressure should be increased by 7 per cent.

After a number of ionization-pressure curves had been plotted, the square roots of the critical pressures were plotted against the corresponding voltages, as in Fig. 4, and a linear relation was found to exist between these quantities. The equation of this line, which passes through the origin, is

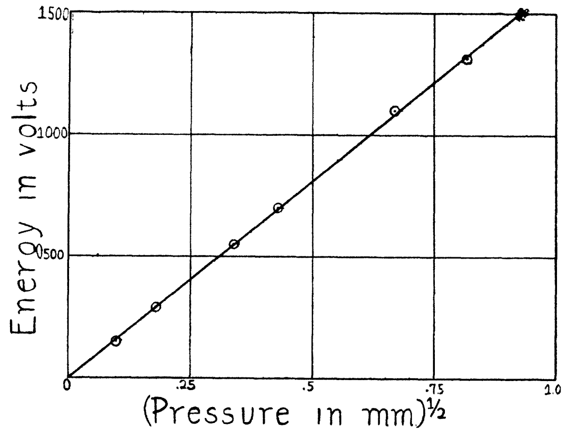

Fig. 4. Energy of the electrons expressed in volts plotted against the square-root of the critical pressures.

$$V = 1620\sqrt{p}\ ; \tag{4}$$

where V is measured in volts, and p in mm. From this equation the critical pressures could be calculated for different voltages and these were used in taking the observations for total ionization.

Finally, the total ionization produced per electron was plotted against the energy of the electron in volts, readings being taken at frequent voltage intervals throughout a range of 2225 volts. The graph of the results is given in Fig. 5, where each point on the curve is the average of from two to five separate observations. For convenience in plotting, the scale for the ordinates at high voltages is one-fifth of that at low voltages. Readings at higher voltages were not taken because the diffusion pumps used were unable to maintain the pressure in the filament tube sufficiently low when the pressure in the ionization chamber was much above 2 mm. The critical pressure is proportional to the square of the voltage used and would have to be over 6 mm for 4000-volt readings.

DISCUSSION OF RESULTS

The graph in Fig. 5 shows that ionization of air by slow electrons starts at about 17 volts, which is in agreement with the result obtained by Smyth[20] for the ionization potential for the L-electrons of the nitrogen molecule, the ionization potential for the atom being found by him at 24.1 volts. The curve rises steadily with the increasing energy of the electrons until it reaches 125 volts, after which ionization increases slowly, the character of the curve up to this voltage being similar to that found by Mayer[3] who, however, found the curve to fall very slowly after 130 volts. This is probably due to the fact that at the pressure he used, .0035 mm, the range of electrons of energies corresponding to more than about 100 volts is greater than the length of the path they travel as estimated from the diagram in his paper, so that beyond this voltage he measured only the ions which were formed in the part of their range included in this path. At approximately 170 volts, secondary ionization causes the curve to rise until the first ionization potential for an electron on the second ring of one of the atomic constituents of air is passed, at which voltage there should be a sudden decrease in total ionization according to Bohr's theory. This occurs at 250 volts and may be due to argon. Fowler[17] quotes 250 volts as an ionization potential for argon and

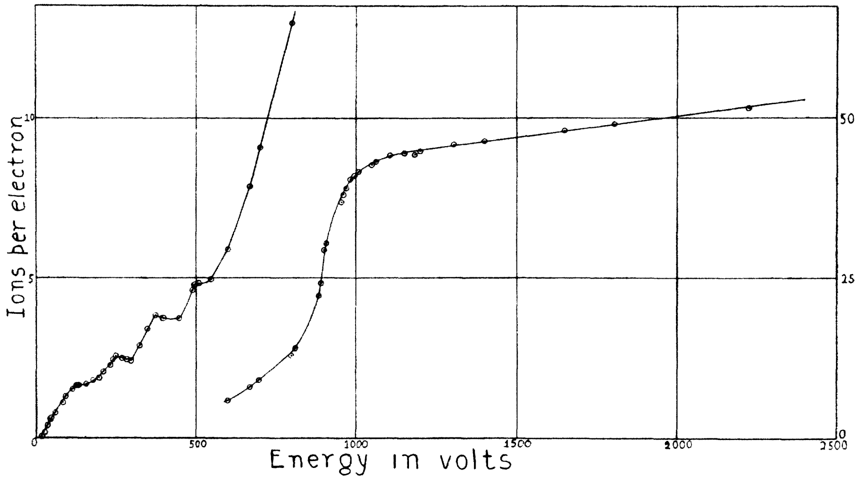

Fig. 5. Total number of ions produced per electron at the various voltages used.

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[20] H. D. Smyth, Proc. Roy. Soc. A **104**, 121 (1923).

it is indicated in the graph of the voltages which excite L-radiations as given by McLennan and Clark.[21] Hughes and Klein[4] have also found an indication of a break in the ionization curve for argon at this voltage. As soon as the increase in secondary ionization balances this decrease the curve begins to rise again near 300 volts, until the K-limit for nitrogen is reached by 375 volts. This value agrees with the one found by Mohler and Foote[22] at 374 volts by a photo-electric method. Here ionization decreases until the curve reaches 450 volts, and then rises to 494 volts, the ionizing potential of the K-level electrons of oxygen, which was found by Kurth[23] to be at 518 volts and by Mohler and Foote at 478 volts. The rapid rise in the ionization from the K-ring electrons of nitrogen partially offsets the decrease in ionization due to the ionizing of oxygen at this voltage, so that there is a slow decrease in ionization up to about 550 volts where the amount of ionization starts to increase rapidly.

In the region just covered the ionizing efficiency of the electron is seldom much more than 20 per cent. Hughes and Klein[4] found that even at their maximum value for primary ionization only 20-30 per cent of the collisions are ionizing. This is probably due to the fact that many collisions result in the transference of an electron from an inner level to a level of higher quantum number, with a resulting emission of radiation when the electron returns to its former orbit.

When the energy of the ionizing electrons is greater than that corresponding to 550 volts the total ionization produced increases again, and the ionization curve rises rapidly between 800 and 900 volts; after 1100 volts it rises steadily but slowly as the accelerating voltage is increased.

From Eq. (4), assuming that the pressure in a vessel and the range of an ionizing particle are inversely proportional at a given temperature, the equation between the voltage and the range in cm at atmospheric pressure was found to be

$$V=15900\sqrt{R}\,; \tag{5}$$

or at 1 mm pressure

$$R=3.00\times10^{-6}V^{2}\,. \tag{6}$$

From this formula the range of the electrons at the observed voltages was calculated and the average ionization per unit length of path at the corresponding voltage found by dividing the experimentally determined value of the total ionization by the range. The numerical values for some

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[21] J. C. McLennan and M. L. Clark, Proc. Roy. Soc. A **102,** 389 (1922).

[22] F. L. Mohler and P. D. Foote, Sci. Papers Bur. Standards. No. 425 (1922).

[23] E. H. Kurth, Phys. Rev. **18,** 461 (1921).

of the more critical voltages are tabulated in Table I and all the results are shown in Fig. 6, where the average ionization per cm is plotted against the voltage. In Fig. 7 the average ionization per cm produced by electrons of at least 600-volt energies is plotted against the range of the ionizing electron. The corresponding curve for lower voltages is similar but should be plotted on a different scale since the range of electrons of less than 577-volt energy is less than 1 cm at 1 mm pressure.

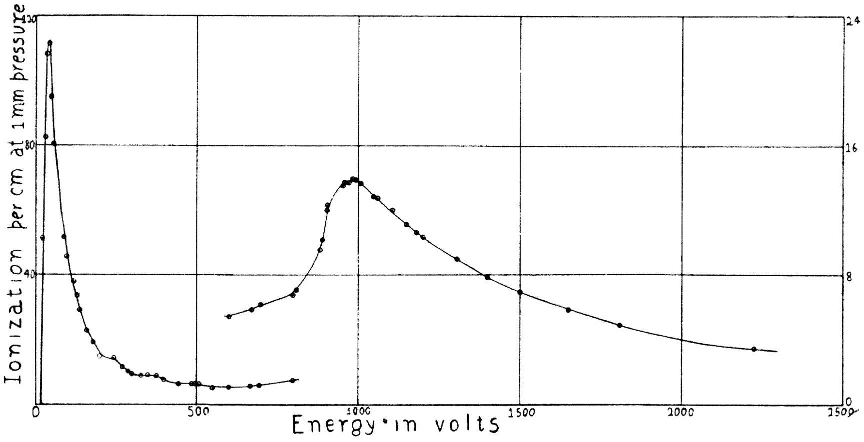

Fig. 6. Ionization per cm of path at 1 mm pressure plotted against the energy of the electrons expressed in volts.

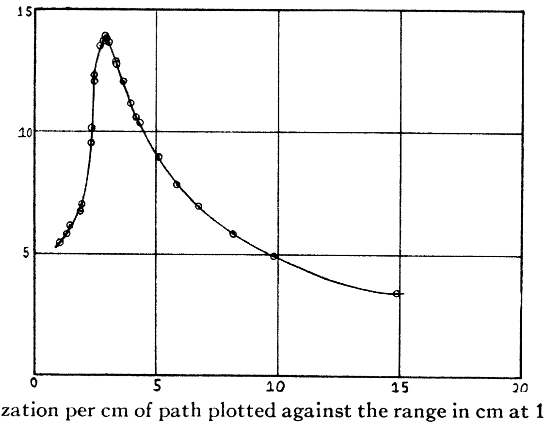

Fig. 7. Ionization per cm of path plotted against the range in cm at 1 mm pressure.

The curve in Fig. 6 shows two maxima at about 40 volts and 987 volts. The first maximum is probably due to the simultaneous ionization of nitrogen molecules and atoms, whose ionization potentials are 17 and 24.1 volts as already stated, since according to Bohr's theory a gas with these two ionization potentials should show maximum primary ionization per cm at 39.8 volts. Similarly, the second maximum occurs at twice the ionization potential for the K-electrons of oxygen; the maximum ionization per cm due to the ionization of nitrogen which should appear at about 750 volts is probably masked in air by the ionization of oxygen. For voltages beyond these which give the maxima the average ionization per cm decreases suddenly at the ionization potentials 250, 375, and 494 volts, precisely as in the case of total ionization.

TABLE I

Accelerating voltage	Range at 1 mm pressure	Ions per electron	Ions per electron per cm at 1 mm pressure
18	.00098 cm	.05	51.2
28	.00236	.19	82.7
35	.00368	.40	108.2
41	.00505	.56	111.2
47	.00663	.63	95.0
84	.0212	1.09	51.4
122	.0447	1.69	37.8
156	.0730	1.72	23.6
198	.128	1.87	14.6
247	.183	2.52	13.8
295	.262	2.39	9.12
347	.363	3.40	9.36
372	.415	3.82	9.18
397	.473	3.71	7.84
494	.733	4.72	6.43
600	1.080	5.87	5.43
700	1.470	9.08	6.19
800	1.920	12.9	6.72
890	2.37	24.1	10.14
905	2.46	30.4	12.36
952	2.72	36.7	13.50
972	2.83	38.8	13.69
985	2.90	40.4	13.91
992	2.95	40.8	13.82
1050	3.31	42.5	12.85
1105	3.66	44.1	12.04
1200	4.32	44.6	10.32
1400	5.88	46.2	7.85
1500	6.75	47.0	6.96
1808	9.80	48.8	4.98
2225	14.85	51.4	3.46

The total number of ions produced at the 987-volt maximum, corrected for the 7 per cent loss of ions in the capillary tube, was found to be 43.2, which means that 22.8 volts of energy were expended in producing each ion pair. As Fowler has pointed out, ionization by collision should require approximately four-thirds of the lowest ionization potential of a gas per ion pair. Air consists mainly of nitrogen with an ionization potential of 17 volts, and, therefore, about 22.7 volts of energy should be used in this way. C. T. R. Wilson[11] found by counting the number of primary and secondary ions along his β-ray tracks a value of 26 volts per ion pair.

The ionization produced by 987-volt electrons is shown by the sphere tracks in his photographs where ionization is at its maximum efficiency. Equation (5) gives the range of these electrons as 0.04 mm at atmospheric pressure.

Wilson also obtained a value of 21,000 for the coefficient in the voltage-range equation from the measurement of ionization tracks which are probably due to electrons of 7700 and 8600-volt energies. For such voltages the variation of the mass of the electron with its velocity is not negligible and becomes large in the range of velocities used in the absorption experiments of Schonland[24] with cathode rays, and of Varder[25] with β-rays, whose determinations yield a coefficient which varies from 22000 to 7000 as the velocity of the particle increases. The value predicted by the Bohr theory is about 7000, and as Fowler has pointed out, this value should be multiplied by a numerical factor of 2 or 3. These experiments indicate that for slow-moving electrons the multiplying factor is approximately 2.

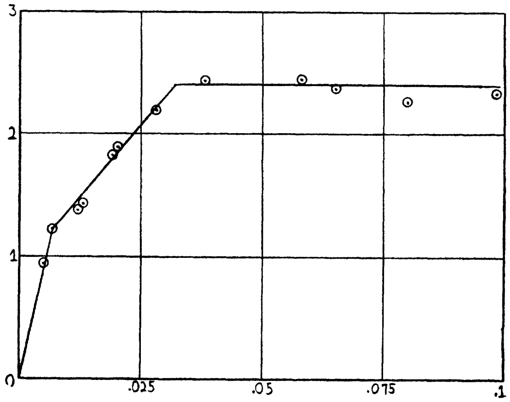

Fig. 8. Ions per electron as a function of the pressure in mm for 295-volt electrons.

The experimental curve showing the relation between the total ionization produced and the pressure is also of interest. The curve obtained for an electron of energy corresponding to 700 volts was given in Fig. 3. The curve obtained at 295 volts is given in Fig. 8. Although the emission of secondary electrons from the bowl may be the cause of some of the irregularities in the curves at low pressure, it is believed that the sharp breaks correspond to changes in the type of ionization produced at different points in the range of the particle. At the beginning of its range the electron will ionize by the removal of electrons whose natural period

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[24] B. F. J. Schonland, Proc. Roy. Soc. A **104**, 235 (1923).

[25] R. W. Varder, Phil. Mag. **29**, 725 (1915).

is of the same order of magnitude as the "time of collision." Part of its energy will be absorbed in these collisions and after this has decreased below the amount required to ionize these electrons there will be a change in slope of the curve. The values of the pressure at which these breaks occur indicate that the unutilized parts of the ranges correspond to 250-volt energies in the 295-volt curve, and to 495-volt energies in the 700-volt curve. These are critical voltages in the curve for total ionization. The change in slope in the first part of the 700-volt pressure curve is probably gradual.

The voltage-pressure readings seem to substantiate the evidence given by the total ionization-voltage readings that a colliding electron ionizes an atom by removing one of the electrons whose period is approximately the same as the "time of collision." If the colliding electron is moving too rapidly this time is not sufficient for the transfer of enough energy to completely remove an electron from its atom, and if the "time of collision" is greater than the natural period, its energy, even though entirely transferred, is too small to produce ionization.

An estimate of the upper limit for the effective radius of the atom during primary ionization can be obtained from the maximum values of the ionization per unit length of path, for Bohr[14] has given an approximate expression from which this radius p may be calculated

$$Q = 2e^4/mv^2p^2$$

where Q is the energy exchanged in the collision, and v the velocity of the colliding electron. Hence, if on the average 20 volts of energy are lost during the primary collisions of 40-volt electrons, p should be 5.12×10^{-8} cm, approximately. The results of this experiment show that about .56 of the collisions of these electrons in the range .005 cm are ionizing, which indicates that the mean collision frequency for these electrons is nearly 200, or 10.3 times the value predicted by the kinetic theory for the frequency of collision between electrons and air particles, and that the effective radius of the latter during such collisions is approximately 5.03×10^{-8} cm. At higher voltages the mean frequency of ionizing collisions decreases rapidly, approaching the kinetic theory value at 150 volts, and becoming about 1/4 of this near 600 volts, for in this region the number of secondary collisions is very large and the value of the effective radius derived from ionization data is a mean value due to primary collisions with electrons on inner atomic orbits, and secondary collisions with those on outer orbits. Near the second maximum, at 987 volts, the experiment shows that each electron produces 40.5 ions at the rate of 13.9 ions per cm, which indicates that the mean frequency of primary collisions is .343 per electron, and that the effective radius of the particle during collisions is approximately $.208 \times 10^{-8}$ cm. Assuming as before that when the efficiency of ionization is a maximum, half the energy of the electron is transferred in a collision, the Bohr formula gives $.207 \times 10^{-8}$ cm as the upper limit for this radius when 987-volt electrons collide with electrons on inner atomic orbits.

Finally, it is possible to extrapolate along the experimental curve of total ionization plotted against the corresponding energy, for there is a steady rise in the curve beyond the voltage which gives the maximum ionization per cm of path to the last experimental reading at 2225 volts, and since the K-rings of both nitrogen and oxygen have undergone ionization at lower voltages there is no reason to expect that there will be any large change in the rate of increase of ionization in the next 2000-volt interval. Deriving a value, corrected for the 7 per cent capillary tube error, of 68.2 ions at 4000 volts, and calculating the range by Eq. (6) to be 48.0 cm, it is found that 1.42 ions per cm should be produced at 1 mm pressure by electrons with 4000-volt energies. Glasson's[7] experimental value at this voltage was 1.5. Also, assuming the same rate of increase of ionization to continue indefinitely, it is found after calculating the energy of β-rays whose velocities are 0.8 and 0.985 times that of light using the relativistic formula for energy, that 2.4 and 17.9×10^3 ions should be formed by β-rays with these velocities. The number of ions counted by Geiger and Kovarik[10] in their experiment dealing with β-rays of these velocities ranged from 3.3 to 17.3×10^3. The agreement is at least of the same order of magnitude. Therefore, it seems probable that electrons whose energy is more than that which produces the maximum ionization generate ions at the rate of approximately .72 of an ion per 100 volts of energy.

CONCLUSION

The importance of the results of the experiment lies in their confirmation of the Bohr theory of ionization as corrected by Fowler, (1) by the determination of the voltages at which the maxima for the mean ionization per unit length of path occur in air and of the number of ions then produced; (2) by the location of ionization potentials corresponding to electrons on inner atomic rings shown by a decrease in the total ionization produced at these voltages; and (3) by a verification of the fourth-power velocity-range law. In the near future the author expects to extend these experiments to a number of pure gases.

In conclusion the author wishes to express her deep appreciation of the interest taken in the experiment by Professor A. F. Kovarik, who proposed the problem and gave many helpful suggestions, to Professor John Zeleny for his valuable advice, and to the other members of the Physics Department of Yale University for their interest and encouragement.

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