TOTAL IONIZATION BY SLOW ELECTRONS.

By J. B. Johnson.

1. Before the nature of cathode rays was known, Lenard discovered that these rays would pass through a thin aluminum window to the outside of the discharge tube and that they made the air through which they penetrated conductive.[1] Later experiments showed that the conductivity was due not only to the stoppage of electric charges by the air molecules, but to the production of new charges from the molecules themselves,[2] *i. e.*, to ionization of the air. The first quantitative experiments on this ionization were done by Durack,[3] who measured the number of ions produced per centimeter per electron in air at a given pressure, just after the rays had emerged through the aluminum window. His results showed that the ionization is proportional to the pressure of the air, as had been found to hold in the discharge tube itself[4]; and that at a pressure of 1 mm. of mercury an electron made on the average .43 pair of ions per cm., when the velocity of the electrons was of the order 4×10^9 cm. per sec. Using β rays from radium, whose velocity he estimated at 2.3 to 2.8×10^{10} cm. per sec., he found the specific ionization α to be much smaller, being but .17 for these faster rays.

These experiments were repeated under improved conditions by Glasson[5] and by W. Wilson,[6] the former using cathode rays and the latter the β rays from radium B and radium C. By means of magnetic deflection nearly homogeneous bundles of rays of known velocity were obtained. Glasson used a range of velocities from 4.08 to 6.12×10^9 cm. per sec., and Wilson used velocities from 1.24 to 2.90×10^{10} cm. per sec. For the value of α Glasson obtained 1.5 when the velocity of the rays was 4.8×10^9 cm. per sec. Both observers found that α is nearly proportional to the inverse square of the velocity of the electrons, or

$$\alpha = \frac{k}{v^2}$$

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[1] P. Lenard, Ann. d. Phys., 51, p. 225, 1894.

[2] P. Lenard, Ann. d. Phys., 8, p. 149, 1902; ibid., 12, p. 449, 1903.

[3] J. E. Durack, Phil. Mag., 4, p. 29, 1902; ibid., 5, p. 50, 1903.

[4] J. S. Townsend, Phil. Mag., 1, p. 198, 1901; ibid., 3, p. 557, 1902; ibid., 5, p. 389, 1903. J. S. Townsend and P. J. Kirby, Phil. Mag., 1, p. 630, 1901.

[5] J. L. Glasson, Phil. Mag., 22, p. 647, 1911.

[6] W. Wilson, Proc. Roy. Soc., 85, p. 240, 1911.

within the ranges used. From the above values of α and v the constant k is 3.45×10^{19} cm. for air at 1 mm. pressure. The loss of velocity of cathode rays in passing through a solid was measured by Whiddington.[1] Rays with velocities ranging from 5.31 to 8.58×10^9 cm. per sec. were passed through an aluminum window and the loss of velocity measured by magnetic deflection. If v_0 is the velocity of the incident rays and x the thickness of the aluminum, the velocity of the emergent beam, v, was found to be given by the expression

$$v_0^4 - v^4 = cx.$$

The value of c was 7.32×10^{42} cm^3/sec^4 for aluminum. This relation is in accord with the theory given by J. J. Thomson.[2]

That electrons lose velocity in going through matter has also been shown by W. Wilson,[3] and the amount of this loss was calculated by Seeliger[4] from measurements by Bestelmeyer.[5]

2. If we assume, in accordance with the theory of Thomson, that the constant c is proportional to the density of the absorbing substance, the results of Whiddington and of Glasson can be combined to give the total number of pairs of ions produced per electron. Substitution of the value of v from Glasson's equation in that of Whiddington gives

$$v_0^4 - \frac{k^2}{\alpha^2} = c'x$$

or

$$\alpha = \frac{k}{\sqrt{v_0^4 - c'x}}.$$

The total ionization is then

$$n = \int \alpha dx = k \int_0^{(v_0^4 - v_1^4)/c'} \frac{dx}{\sqrt{v_0^4 - c'x}}$$

$$= -\frac{2k}{c'} \Big[\sqrt{v_0^4 - c'x} \Big]_0^{(v_0^4 - v_1^4)/c'}$$

$$= \frac{2k}{c'} (v_0^2 - v_1^2).$$

The constant v_1 is the velocity at which the electron ceases to produce ions by collision. Kossel has shown that k depends only on the density

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[1] R. Whiddington, Proc. Camb. Phil. Soc., 16, p. 321, 1911.

[2] J. J. Thomson, Conduction of Electricity Through Gases, 2d ed., p. 378.

[3] W. Wilson, Proc. Roy. Soc., 84, p. 141, 1910.

[4] R. Seeliger, Verh. d. D. Phys. Ges., 13, p. 1094, 1911.

[5] A. Bestelmeyer, Ann. d. Phys., 35, p. 909, 1911.

of the gas.[1] The above results indicate that the total ionization is independent of the nature of the gas and proportional to the initial kinetic energy of the electrons. The equations used, though resting on theoretical considerations, were verified over only a limited range of velocities and were found to hold only approximately even over this range. The formula, therefore, cannot be expected to give more than the correct order of magnitude of the number of ions produced by electrons having velocities much outside of the range given above. Nevertheless, the following values were calculated as an example, using for c' the value 5.4×10^{36} for air at 1 mm. pressure.[2] The value of v_1 is taken as $.20 \times 10^9$ cm. per sec., corresponding to about 10 volts.

	v.	n.
β rays	2.5×10^{10}	8,000
6,500 volts	4.8×10^9	293
1,000 volts	1.88×10^9	45
100 volts	$.595 \times 10^9$	4.1

The value for β rays agrees in order of magnitude with the results of Eve and of Geiger and Kovarik, given below; while the number of ions at 100 volts is about twice as great as the result obtained in the present experiment.

3. Measurements on the total ionization of β rays have been made by Eve,[3] and by Geiger and Kovarik.[4] Eve measured the ionization at different distances from a source consisting of radium or radium B and radium C, and from the absorption coefficient found that the total ionization was 1.2×10^4 pairs of ions per electron. Geiger and Kovarik found the ionization over the first ten centimeters of path of the β rays from various radioactive sources. After correcting for reflection and determining the absorption,[5] the total number of ions produced by each β particle was calculated. The results range from 3.3×10^3 to 17.3×10^3 pairs of ions per β particle, the same order of magnitude as Eve's result. In both of these experiments the coefficient of absorption was taken to be constant for the whole path of the electrons, and refers to the loss in numbers of electrons, not to the loss of velocity.

4. In measuring the ionization per unit path of electrons, Kossel also found, indirectly, the total ionization produced by an electron in air.[6]

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[1] W. Kossel, Ann. d. Phys., 37, p. 393, 1912.

[2] Obtained from c by the density law.

[3] A. S. Eve, Phil. Mag., 22, p. 551, 1911.

[4] H. Geiger and A. F. Kovarik, Phil. Mag., 22, p. 604, 1911.

[5] A. F. Kovarik, Phil. Mag., 20, p. 849, 1910.

[6] W. Kossel, l. c.

His method is based on the following considerations. Let n_0 electrons start in a given direction in air at 1 mm. pressure, and let a_0 be the fraction of the electrons that are stopped by collisions in one centimeter of path. The number of the original electrons at any place x is then given by

$$n_1 = n_0 e^{-a_0 x}.$$

Let α be the number of collisions per centimeter which result in the production of a pair of ions, and let n_2 be the total number of pairs of ions made by the n_0 electrons.

Then

$$\begin{aligned} dn_2 &= n_1 \alpha dx \\ &= n_0 \alpha e^{-a_0 x} dx; \end{aligned}$$

and

$$\begin{aligned} n_2 &= n_0 \alpha \int_0^\infty e^{-a_0 x} dx \\ &= n_0 \frac{\alpha}{a_0}. \end{aligned}$$

The average number of pairs of ions per electron is then

$$n = \frac{n_2}{n_0} = \frac{\alpha}{a_0}.$$

From the latter of these ratios n was calculated. The assumption has been made here that the electrons lose no velocity until they are stopped, since both a_0 and α vary with the velocity.

The value of α was determined by Kossel for electrons having velocities corresponding to a range of 200 to 1,000 volts. Electrons were projected between two parallel condenser plates. A small field was applied between the plates, giving the electrons a parabolic path and causing them to be absorbed on one of the plates. The length of path was calculated from the velocity and the transverse field. One of the plates was connected to an electrometer, and on this plate could be collected either the original electrons and the negative ions produced, or the positive ions. From this data was calculated the number of pairs of ions per electron per centimeter of path. The values were reduced to the standard pressure of 1 mm. of mercury, since the ionization was found to be directly proportional to the pressure. The pressures actually used were of the order .05 mm. of mercury.[1]

The absorption coefficient a_0 which was used by Kossel was determined by Lenard over a large range of velocities.[2] He measured the decrease

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[1] For a resume of the work on specific ionization see S. Bloch, l. c., p. 580; also Frantz Mayer, l. c.

[2] P. Lenard, Ann. d. Phys., 12, p. 449, p. 714, 1905.

in the number of electrons in a beam traversing a space containing a gas at a low pressure. Careful corrections were made for secondary radiation, diffusion of ions, reflection from the walls, scattering, and other disturbing factors.

The variation of specific ionization with velocity was also measured by Mayer for velocities up to 500 volts.[1] His values are not reducible to absolute measure except by comparison with those of Kossel. Taking Mayer's value of α for air at the velocity given by 500 volts to be the same as that given by Kossel, the total ionization can be calculated. The results so obtained, together with those of Kossel, are given in Fig. 1. The two curves do not agree very well.

The value of α for 100-volt electrons in different gases at the same pressure was found by Kossel to be proportional to the density of the gas, or to its molecular weight. The only exception was hydrogen, which gave a value four times greater than the density law would indicate. Lenard found that for fast cathode rays the absorption is proportional to the density of the medium, except for hydrogen which had twice the absorption of other matter of the same density.[2] McLennan,[3] using cathode rays, and Strutt,[4] using β rays, both found that the ionization in a given distance is proportional to the density of the gas and not dependent on its chemical constitution. McLennan found hydrogen normal, but Strutt obtained values twice as great as the density law implies. Other experimenters[5] have obtained about the same values of the absorption coefficient as Lenard. The density law holds except

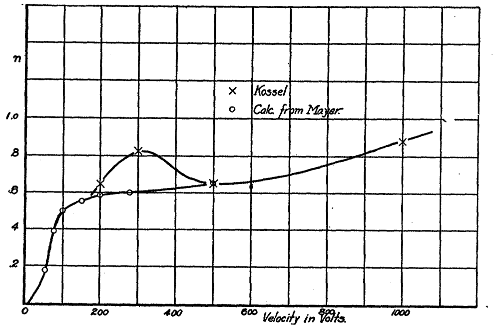

Fig. 1.

Air.

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[1] F. Mayer, l. c.

[2] P. Lenard, Ann. d. Phys., 56, p. 255, 1895.

[3] J. C. McLennan, Phil. Trans. (A), 195, p. 49, 1901.

[4] R. J. Strutt, Phil. Trans. (A), 196, p. 507, 1901; Proc. Roy. Soc., 68, p. 126, 1901.

[5] A. Becker, Ann. d. Phys., 17, p. 381, 1905. J. Robinson, Ann. d. Phys., 31, p. 769, 1910. S. Bloch, Ann. d. Phys., 38, p. 559, 1912. F. Mayer, Ann. d. Phys., 45, p. 1, 1914.

for electrons of very low speeds (below 100 volts). Hydrogen is abnormal, the more so the lower the velocity of the electrons. Since, then, in the expression α/a_0 both quantities are proportional to the density of the gas and depend on the density only, it follows that the total ionization should be independent of the nature of the gas, and depend only on the initial velocity of the electrons. Hydrogen is the only exception found and, using Kossel's value of α, should give rise to twice as many ions as are obtained in other gases.

Another experiment showing that the total ionization produced by an electron is independent of the nature of the absorbing gas was made by Kleeman.[1] Kleeman found that for the heterogeneous electrons emitted by gold when acted on by X-rays, the ratio of the total ionization produced by the electrons to that of α rays is the same for all gases. It had been found by Bragg and Kleeman,[2] and verified by Taylor,[3] that the total number of ions produced by an α particle is nearly independent of the kind of gas. This would then apply also to heterogeneous cathode rays. It was also found by Kleeman that the β rays from actinium and the β rays from uranium gave the same ratio of the ionization produced in a given distance in a gas to the ionization produced under the same conditions in air.[4] The actinium β rays differ considerably in velocity from those of uranium, and it follows that within this range the ratio of the ionization in the gas to the ionization in air is independent of the velocity. This indicates that homogeneous rays, too, make the same total number of ions in all gases. The velocities of the electrons used in these experiments differ widely and the result can not be considered as conclusive, although furnishing strong evidence that the total ionization is independent of the nature of the gas.

6. The problem may also be looked upon from the point of view of the energy necessary to produce ions by collisions. The minimum ionization potentials have been determined for the simple gases with some accuracy.[5] This sets an upper limit to the number of ions that can be produced by an electron, if we assume that it takes the same amount of energy to produce each pair of ions, independent of the velocity of the electron. There is nothing known to justify this assumption, however; it may, indeed, be that one collision may produce several

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[1] R. D. Kleeman, Proc. Roy. Soc., 84, p. 16, 1910.

[2] W. H. Bragg and R. D. Kleeman, Phil. Mag., 10, p. 318, 1905.

[3] T. S. Taylor, Phil. Mag., 18, p. 604, 1909; Am. Jour. Sci., 28, p. 357, 1909.

[4] R. D. Kleeman, Proc. Roy. Soc., 83, p. 530, 1910.

[5] P. Lenard, Ann. d. Phys., 8, p. 149, 1902. O. v. Beyer, Verh. d. D. Phys. Ges., 10, p. 100, 1908. E. S. Bishop, PHYS. REV., 33, p. 325, 1911. J. Franck and G. Hertz, Verh. d. D. Phys. Ges., 15, p. 34, p. 939, 1913. F. Mayer, l. c. F. S. Goucher, PHYS. REV., 8, p. 561, 1916. See also R. D. Kleeman, Proc. Roy. Soc., 84, p. 16, 1910.

ions,[1] without using a corresponding multiple of the minimum ionization energy. Partzsch[2] has measured the average energy used to produce a pair of ions in a discharge tube. The values he obtained lie between 27.9 volts for nitrogen and 14.5 volts for helium, which values are considerably higher than the minimum ionization potentials (except in the case of helium). If these values also hold for the average energy lost by an electron per ionizing collision outside of a discharge tube, then the total ionization arising from electrons of a given speed in the different gases should be inversely proportional to these numbers.

7. The total ionization by electrons, then, has been measured in only two regions of the velocity range. These measurements have been made by more or less indirect means, and have given no definite relation between velocity and total ionization. A formula was found from indirect data, which gives results of the right order for the higher velocities, but which fails completely to represent Kossel's results both as to magnitude and to form of relation. On the other hand, there are several lines of evidence pointing to the conclusion that the total ionization is independent of the gas and depends only on the velocity of the electrons.

8. The object of the present investigation was to determine the total ionization by a direct method. The total ionization produced by electrons of velocities up to 200 volts has been measured in oxygen, nitrogen, hydrogen, and helium. Electrons were generated by a hot platinum wire, accelerated in a distance less than the mean free path in the gas, and were then allowed to spend themselves in the gas in a large ionization chamber. The number of positive ions produced as compared with the number of electrons entering the chamber was then measured.

9. The apparatus as finally used is shown in Fig. 2. The heavy

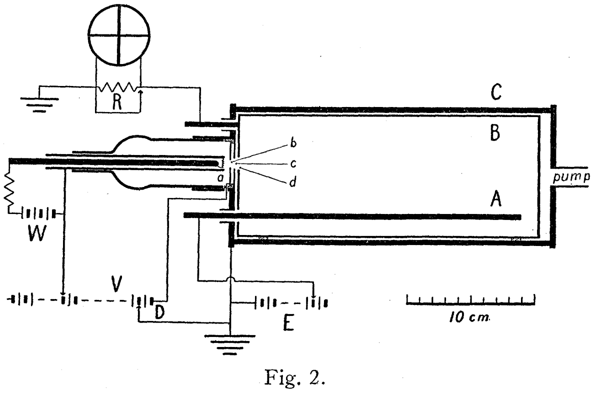

Fig. 2.

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[1] J. J. Thomson, Rays of Positive Electricity, p. 48.

[2] A. Partzsch, Ann. d. Phys., 40, p. 157, 1913. J. S. Townsend, Electricity in Gases, p. 295, 1915.

copper cylinder C contains two electrodes, A and B. B is a brass cylinder, closed at both ends except for two small openings, and insulated from C by small pieces of ebonite. A is a brass rod insulated from C by an amber plug and guard ring. Electrons from the hot platinum wire a are accelerated toward a gauze-covered opening in the diaphragm b, pass through the gauze c and opening d and are absorbed in the gas in the cylinder B, where the ionization is measured. The axis of the cylinder was placed parallel to the earth's resultant field to avoid magnetic deflection of the electrons which would otherwise be appreciable.

One of the leads of the hot-wire cathode was a brass tube, which also served as a focusing ring; the other was a brass rod inside the tube, and the whole was mounted in a glass holder cemented to the outer cylinder. A 6-volt storage battery furnished the heating current. A small electron current had to be used and this was found to be steadier without an oxide coating on the filament. A set of storage cells V connected between a and b gave the electrons the desired velocity, and by the same cells the electrons could be retarded by any potential D in steps of 2 volts, in the space bc. The distance ab was about 4 mm., bc and cd each about 2 mm. The holes a, b, and c were about 5, 8, and 10 mm. in diameter, respectively. The electrometer, used at a sensitiveness of about 150 mm. per volt, measured the drop of potential over a high resistance R due to the ionization current (steady deflection method). By this means any erratic behavior of the cathode could at once be seen. An adjustable xylol and alcohol resistance was at first used for R, but this was found to polarize slightly. An India-ink line on paper gave perfect satisfaction.

10. Three different measurements could be made by changing the electrometer connections: the original electron current, the positive ions produced, or the sum of the original electrons and the negative ions. The diagram shows the connections for measuring the sum of the electrons and the negative ions. C is to earth, B to earth through the shunted electrometer, and A is connected to the negative side of the battery E, the other side of which is earthed. To measure the positive ions, A was connected to the electrometer, B and C connected to the positive side of E, the negative side being earthed. To measure the original electron current, C was earthed and A and B both connected to the electrometer and used as a Faraday chamber. The connections were made through a commutator, not shown in the diagram, so that the change from one arrangement to another could be made in one operation and readings taken in rapid succession. For low pressures the reading for the sum of the electrons and the negative ions was

quite accurately the same as the sum of the other two readings. For higher pressures, however, the first named quantity was usually a few per cent. lower, probably because at the higher pressures a larger proportion of the ions were formed near the hole and were driven out through it by the field. For this reason, only the readings for the original electrons and for the positive ions were used in the final experiments, the other reading serving merely as a check.

In this way the ionization was measured at different velocities and with different pressures. The results thus obtained for the four gases are illustrated by the values for nitrogen, Fig. 3, which gives the number of ions per electron, *m* at different pressures and different velocities. For the lowest velocities used the ionization soon reaches a maximum as the pressure increases, and then falls off slightly, while for the higher velocities the maximum value comes at much higher pressures; for the highest velocities the maximum is not reached with the greatest pressures used. This is caused by the greater penetration of the fast rays. Unless the pressure is high enough they strike the sides of the cylinder before their energy is spent and do not produce as many ions as at higher pressures. The slower electrons are comparatively easily absorbed as the curves show. In taking these curves the potential *E* used to drive the ions to the electrodes was 20 volts except for the lowest pressures, where 10 or 12 volts were sufficient to insure saturation. There was no appreciable additional ionization if the potential greatly exceeded these values.

Since the space *ab*, where the electrons are accelerated, can not be a vacuum but must contain gas at the same pressure as the ionization chamber, it is to be expected that many electrons collide within this distance and produce new electrons that enter the ionization chamber with low velocities. This then necessitates a correction to the values

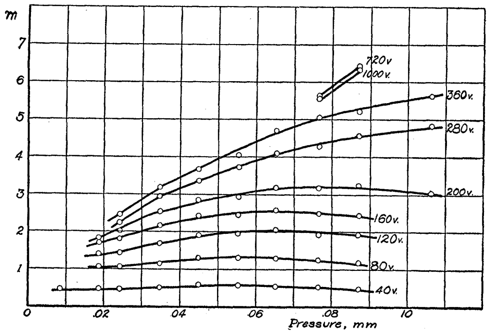

Fig. 3.

Nitrogen.

given in Fig. 3. The velocity distribution of the electrons was determined by applying an opposing potential D in the space bc and measuring the number which got through. The gauzes at b and c were smoked in order to avoid δ-rays. Some curves obtained in this way are reproduced in Fig. 4, where each ordinate represents the number of electrons with velocities greater than the corresponding abscissa. At the lowest pressure the number of electrons does not fall off much until D approaches V, when the number falls off quite abruptly and is zero at $D \geqq V$. For higher pressures, as D increases, there is at first a sharp decrease in the deflection, then a more gradual slope, and finally a fairly sharp drop to a positive value at $D = V$ which remains constant as D is further increased. The positive deflection can be ascribed to positive ions made by the electrons in the space bc. These are swept into the cylinder with the first 10 volts of the retarding field where there is the sharpest drop in the curve. Ordinates should then be measured from the lowest part of the curve, where $D = V$, except for values of D between 0 and 10 volts. The gradual slope of the central portion of the curve is due to slow electrons, either new electrons produced near the gauze b or original electrons that have lost part of their energy in collisions.

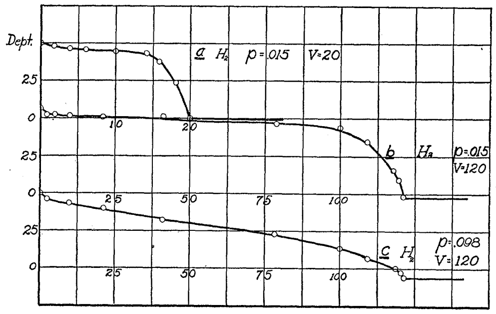

Fig. 4.

Velocity distribution curves.

11. The method of procedure was then as follows: At the lowest pressure to be used, the ratio m between the number of positive ions and the number of electrons producing them was determined for a series of different velocities, beginning with the lowest velocity at which any appreciable number of ions was produced. At least four determinations of m were made at each velocity, using the same or different electron currents. Then distribution curves were obtained with the same velocities before the pressure was changed. This was repeated at a series of increasing pressures, the lower velocities being gradually dropped and

higher ones used. In this way were obtained curves similar to those in Fig. 3, and velocity distribution curves for corrections to be applied at each point.

The distribution curves show the presence of velocities ranging from that given to the electrons down to zero, the slope depending on the pressure. The slow electrons produce ions as well as the faster ones, and the ratio *m* does not give the ionization due to any one velocity. To get the number *n* of the ions produced per electron at a given velocity, successive corrections were applied to *m* from the distribution curves. At a certain velocity, 10 volts for oxygen, no ionization could be detected. At the next velocity used, 14 volts, the ionization was produced only by the electrons having a velocity over 10 volts, the number of which was found from the distribution curve at that pressure. The number of ions *n* produced by an electron having a velocity in the range 10 to 14 volts could then be found by dividing *m* by the fraction of all the electrons which have a velocity in this range. The number *n* was used in correcting the value for the next interval, 14 to 20 volts, and so on. The correction formula takes the form

$$N_{10}n_{10} + N_{14}n_{14} + N_{20} + n_{20} + \cdots + N_v n_v = m_v,$$

where the *N*'s denote the fraction of the electrons havng speeds in a given range, as found from the distribution curve, and the *n*'s are the number of ions per electron at that range as previously determined. The sum of these products is the ratio m_v of the ions to the electrons as observed, and from this n_v was determined. This process was repeated for the next higher pressure and so on until all the curves were corrected as far as was thought consistent with accuracy. It is to be noted that the first few terms in the correction formula are almost negligible, but as the electron velocities increase in value the total correction becomes considerable. The reason for this is that although there are many slow electrons, their ionizing power is small. There is an upper limit beyond which the corrections could not be carried because for fast rays such high pressures must be employed that the distribution curves became very unfavorable for an accurate determination of the exact number of the high-speed electrons. With the present apparatus this limit was reached at velocities corresponding to about 200 volts. At this velocity the probable error is quite high, of the order of 25 per cent.

12. The results for the various velocities were plotted against pressures, as shown in Figs. 5 and 6 for nitrogen and helium. From these curves the values of *n* were taken in the region where they are independent of the pressure and in Figs. 7 and 8 the number of pairs of ions per electron

is plotted against the energy in volts. The curves are practically straight lines, represented by the equations

$$n = .0276(V - 12) \text{ for nitrogen,}$$
$$n = .0275(V - 11) \text{ for oxygen,}$$
$$n = .0258(V - 11) \text{ for hydrogen,}$$
and
$$n = .0244(V - 20) \text{ for helium,}$$

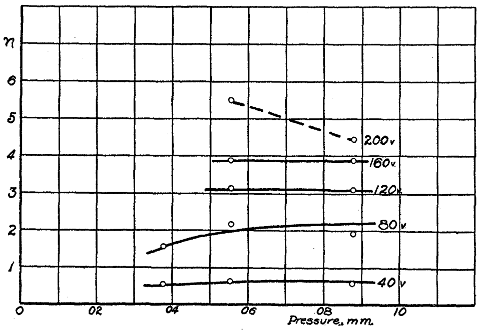

Fig. 5.
Nitrogen, corrected.

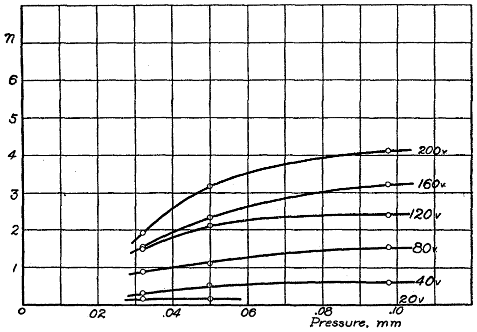

Fig. 6.
Helium, corrected.

where the electrons have a velocity corresponding to V in volts. For oxygen and hydrogen the curves point to about 11 volts as the energy necessary to produce positive ions, in good agreement with the generally accepted values.[1] The nitrogen curve cuts the axis at 12 volts whereas ionization has been found to begin in nitrogen at 7.5 volts[2] or 11.5 volts.[3] The helium curve points to 20 volts as the minimum ionization potential, while ionization was observed at 14 volts. The helium prob-

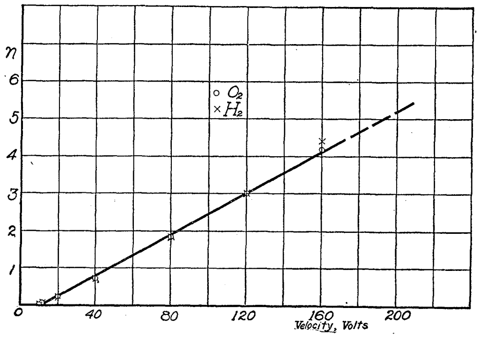

Fig. 7.
Oxygen and hydrogen.

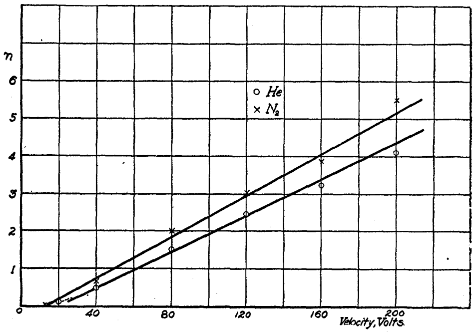

Fig. 8.
Helium and nitrogen.

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[1] J. Franck and G. Hertz, l. c.

[2] Ibid. F. S. Goucher, l. c.

[3] F. Mayer, l. c.

ably contained hydrogen as an impurity. No attempt was made to determine the minimum ionization potentials closely because this has already been done by more sensitive methods.

The three most prominent facts shown by these curves are, that the total ionization is proportional to the excess of the initial energy of the electrons above the minimum ionization energy, at least for the lower and more accurate parts of the curves; that the results for the four gases are practically the same; and that the values are much higher than those obtained by Kossel's method.

As to the first of these observations, it is seen that the electrons with velocities just above the ionization limit are very inefficient ionizers. Only a small fraction of them produce ions, the rest losing their energy in inelastic collisions.[1] Though the electrons *can* produce ions, for example in hydrogen at about 11 volts, they do not average one ion per electron until a velocity due to about 50 volts is attained. The average energy used per ion, as found from the curves, is 36 volts for nitrogen and oxygen, and 41 volts for hydrogen and helium, above the minimum ionization energy. The average energies in volts given by Partzsch for the discharge tube are 27.9 for nitrogen, 23.9 for oxygen, 27.8 for hydrogen, and 14.5 for helium. The values are probably too low, however, as they are calculated on Townsend's assumption of perfectly inelastic collisions. Mayer calculates the ratio of the ionizing collisions per centimeter to the number of "kinetic theory" collisions for electrons of about 130 volts velocity. With the aid of this ratio the energy loss per non-ionizing collision could be calculated by assuming that not much more than the minimum ionization energy is used in producing ions. Mayer's values, however, depend on the results of Kossel's experiments, and reasons will be given presently for believing that Kossel's values of α are not correct.

That the total ionization should be nearly the same for the four gases is in accord with the results for electrons of higher velocities. The interpretation of this must be that the less energy a gas absorbs in ionization, the more it absorbs in non-ionizing collisions; or, the more inelastic a molecule is to electrons, the more easily it is ionized. That this is so in a general way is seen from the available data on minimum ionization potentials and elasticity of collisions. The monatomic gases are elastic, but require in general a higher velocity for ionization than the other gases. Exceptions to this are mercury vapor on the one hand, and hydrogen on the other. The differences are not so marked in the gases used in this investigation. The curves do differ in slope by

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[1] J. Franck and G. Hertz, Verh. d. D. Phys. Ges., 15, p. 373, 1913. K. T. Kompton and J. M. Benade, Phys. Rev., 8, p. 449, 1916.

a slight amount, and it may be that a gas like argon would show a higher total ionization than the gases employed here.

13. The values of the total ionization as obtained by the direct method differ from the results due to Kossel's method by a factor varying from 3 to 7. The discrepancy exists not only at 200 volts but continues up to the higher velocities. The uncorrected curves for nitrogen in Fig. 3 show velocities up to 1,000 volts, and these point to values as high as the straight line relation in Fig. 8 indicates. This is larger than any ordinary experimental error and must be due to a fault in one method or the other. There are two causes that might make Kossel's values too low. The first of these is the presence of slow electrons in the electron stream. Correction was made for electrons stopped between the condenser plates but not for the slow electrons entering with the stream. That these may have been present in appreciable quantities at the pressures used is shown by the distribution curves obtained in the present investigation. The effect of this would be to make the values for α too low. The second objection to the method is that Lenard's absorption coefficient which Kossel used is not applicable here. There are two absorption coefficients that can be considered in connection with an electron stream. One is that defined, and measured, by Lenard, which is the loss of *numbers* of electrons from the beam. It is not concerned with what happens to an electron after its course is changed. The other absorption coefficient is that deduced theoretically by J. J. Thomson (l. c.). This refers to the *loss of kinetic energy* of the average individual electron. C. T. R. Wilson[1] has shown for fast electrons that the direction of the path is often changed while the electron continues to make ions. The same undoubtedly takes place at lower velocities, and, though the electron is lost from the beam, it is not lost for the purpose of ionization. The absorption coefficient deduced from this point of view may be considerably smaller than Lenard's absorption coefficient. A striking illustration of the difference is given by hydrogen. The absorption of slow rays in hydrogen is twelve times that predicted from the density law,[2] and still hydrogen has been found to reflect these electrons with little loss of energy. It seems probable, then, that if the correct absorption coefficient were used Kossel's method would give considerably larger values for the total ionization. There are no data available on this coefficient, however. The discrepancy between the two methods may be largely explained by these considerations.

14. There remains to be discussed the preparation of the gases and the effects of impurities in them. The nitrogen was prepared by heating

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[1] C. T. R. Wilson, Proc. Roy. Soc. A., 87, p. 277, 1912.

[2] F. Mayer, l. c.

a solution of $NaNO_2$ and NH_4Cl. After the flask and connecting tubes had been well washed out, the gas was collected over water, which it displaced in a large bottle. Before being used it was passed over P_2O_5 to remove the water vapor, and over hot copper and copper oxide to remove oxygen and hydrogen. The hydrogen was obtained by diffusion through a hot palladium tube. The gas was collected directly in a reservoir connected with the apparatus. Oxygen was prepared by heating potassium permanganate and was collected over a KOH solution free from other gases. The helium was purified by passing it over hot copper oxide to remove hydrogen which was known to be present, and by passing it through charcoal in liquid air to remove all other impurities. The hydrogen was probably not entirely removed since ionization began at 14 volts instead of the accepted value of about 20 volts.

To see whether vapors from the sealing-wax joints and the stop-cock grease, and also mercury vapor, had any disturbing effect on the results, a trap was introduced near the ionization tube. After immersing the trap in liquid air for a number of days no difference was observed in the ionization or in the distribution curves. The liquid air was therefore not used in the final observations. It is not to be expected that impurities should have so disturbing an influence as, for instance, in minimum ionization experiments, where the limit of an effect is measured, or in experiments where surface films on the electrodes might collect disturbing charges.

Summary.

1. The total ionization produced by electrons of velocities up to 200 volts has been determined for nitrogen, hydrogen, oxygen, and helium by a direct method.

2. The total ionization in these gases is proportional to the energy the electrons possess above the minimum ionization energy, at least up to 150 volts.

3. The results are practically the same in the four gases, in accord with results at higher velocities.

4. Reasons have been pointed out showing why the values for total ionization obtained by Kossel are too low.

In conclusion, the writer wishes to express his thanks to Professor H. A. Bumstead, who suggested the problem and whose advice cleared away many of the difficulties; he is also indebted to Dr. H. M. Dadourian for many valuable suggestions during the course of the work.

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Yale University,
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