The Diffusion of Ions Produced in Air by the Action of a Radio-Active Substance, Ultra-Violet Light and Point Discharges

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VII. *The Diffusion of Ions produced in Air by the Action of a Radio-active Substance, Ultra-violet Light and Point Discharges.*

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A GENERAL method of finding the rate of diffusion of ions into a gas has been described in a previous paper,* and an account was there given of the results obtained with ions produced by Röntgen rays. The present paper gives the results obtained with ions produced by a radio-active substance, by point discharges, and by ultra-violet light. The principle of the method consists in calculating the rate of diffusion from observations on the loss of conductivity of a gas as it passes along metal tubing.

The experiments were arranged so that the loss due to diffusion should be much greater than the loss due to other causes. In order to ensure this, there are two effects which must be considered in fixing the dimensions of the tubing: the recombination which occurs when there are both positive and negative ions present in the gas; and the effect due to the mutual repulsion of the ions which takes place when most of the ions are charged with electricity of the same sign. It is therefore necessary either to correct for these sources of error or to arrange the conditions of the experiments so that the loss of conductivity due to these causes is negligible.

The present paper is divided into five sections. The first section contains an investigation of the relative importance of the processes of diffusion, recombination, and mutual repulsion in causing loss of conductivity. The descriptions of apparatus, and the results of the experiments made on ions produced by a radio-active substance, by ultra-violet light, and by point discharges, are given in Sections II., III., and IV. respectively. The conclusions to be drawn from the experiments are discussed in Section V.

SECTION I.

In the previous paper we have shown that when a number of ions, A, are uniformly distributed throughout a gas, B, which is entering metal tubing, the ratio R, of the

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* JOHN S. TOWNSEND, 'Phil. Trans.,' A, vol. 193, 1899, p. 129.

number of ions which come through the tube without touching the sides to the number which enter is—

$$R = \cdot 193E^{\frac{-7\cdot 31KZ}{2a^2V}} + \cdot 0243E^{\frac{-44\cdot 5KZ}{2a^2V}} + \&c. \quad . \quad . \quad . \quad . \quad . \quad . \quad (1),$$

where K is the coefficient of diffusion of the ions into the gas, B, Z the length of the tube, a its radius, and V the mean velocity of the gas, B, along the tube. This value of R is obtained on the supposition that the velocity, W, of the gas, B, at a distance r from the axis of the tube is given by the formula $W = 2V(a^2 - r^2)/a^2$.

Let R_1 and R_2 be the values of R equation (1) corresponding to lengths Z_1 and Z_2, then $y = R_1/R_2$ is the ratio of the number of ions which come through tubes of lengths Z_1 and Z_2, the same uniform distribution entering each.

The ratio y can be easily determined experimentally, and the value of K can be found from the formula—

$$y = R_1/R_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2),$$

if the loss of conductivity arises principally from diffusion.

Before we proceed to estimate the loss due to recombination or mutual repulsion, we may here point out the advantages of having a small density of ionisation, and of using tubing of small bore.

The ratio y, equation (2), is independent of the number of ions used. It shows that the proportion of ions which are lost in passing through the tube is the same for large and small conductivities. When reduction in conductivity is caused by recombination or mutual repulsion, this law no longer holds. In both these cases the absolute loss is proportional to the square of the number present, so that the proportion of ions lost is proportional to the density of ionisation.

The ratio, y, is a function of $KZ_1/2a^2V$, when Z_1/Z_2 is constant. Let c be a value of $KZ_1/2a^2V$ which gives the value of y between ·3 and ·6 that can be found accurately by experiment. If the mean time, Z_1/V, during which the gas is in the longer tube be given, the radius can be selected so as to make $KZ_1/2a^2V = C$. In dealing with the corrections to be applied to y, we need only to consider the effect of recombination or mutual repulsion in the longer tube. In the apparatus which was used, $Z_1 = 4$ centims., $Z_2 = \cdot 5$ centim. The processes which give rise to errors take place during the time Z_1/V, and the rate at which they destroy the conductivity is independent of the radius of the tubing. The errors therefore arising from either of the processes which we are considering can be reduced to any desired extent by reducing the density of ionisation, or reducing the bore of the tubing.

Recombination.

Among the methods of producing conductivity with which we are dealing, it is only in the case of ionisation produced by the radio-active substance that both positive and negative ions appear simultaneously in the gas. From the results of the experiments on diffusion, we are led to conclude that the ions thus produced resemble very closely those produced by Röntgen rays, and carry the same charge. We will therefore assume that the laws governing the recombination will not be much different in the two cases. The method of finding the correction for recombination has been explained in the previous paper.* It was there shown that for small conductivities the loss due to recombination was about 4 per cent. of the loss due to diffusion to the sides.

The time, Z_1/V, in the experiments made with Röntgen rays was about $\frac{1}{10}$th of a second, the radius of the tubing being 1·5 millims. A new apparatus was made with finer tubing ($a = {\cdot}5$ millim.), so that without altering KZ_1/a^2V, the value of Z_1/V is reduced to $\frac{1}{90}$. The number, N, of ions which recombine is similarly reduced from N to N/9.

The radio-active substance was contained in a sealed glass tube, which cut down the radiation proceeding from it so as to produce densities of ionisation less than the smallest that was used in the experiments made with Röntgen rays. We may therefore assume that in the present experiments the process of recombination does not affect the value of y to the extent of ·5 per cent.

Mutual Repulsion.

When a gas contains ions of one sign (as in the case of ions produced by the action of ultra-violet light on a metal plate, or by a point discharge), the electrostatic field arising from the electric density is sometimes sufficient to exert a considerable force. It would be difficult to find the exact amount that this effect contributes to the loss of ions in a tube while diffusion is taking place, but it is easy to find an upper limit to the error it introduces.

Let us consider the case of a charged gas in a metal tube losing its electrification owing to the motion of the ions along lines of force from the axis to the surface. If we suppose that no diffusion is taking place, it is easy to show† that the density of electrification at any point is given by the formula—

$$\rho = \frac{\rho_0}{1 + 4\pi u \rho_0 t},$$

ρ_0 being the initial density, supposed uniform, u the velocity of an ion when acted on by unit electrostatic force, and t the time during which the density falls from ρ_0 to ρ.

The proportion of ions lost, $\dfrac{\rho_0 - \rho}{\rho_0}$, is practically $4\pi\rho_0 ut$ when the loss is small.

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* *Loc. cit.*, *supra*, p. 144.

† JOHN S. TOWNSEND, 'Phil. Mag.,' June, 1898.

If $t = \frac{1}{90}$, $\rho_0 = 10^{-4}$ electrostatic unit, and $u = 450$ centims. per second, then $\frac{\rho_0 - \rho}{\rho_0}$ becomes ·006. This fraction is bigger than the correction to be applied to y, as can be seen by taking a simple example. Consider a case where 50 per cent. of ions are lost in $\frac{1}{90}$th of a second when diffusion is taking place in a gas having a mean electric density 10^{-4} electrostatic unit. There are less ions per cub. centim. in the gas near the surface than in the gas near the centre, so that the effect of mutual repulsion must be much less than the above estimate, which is made on the supposition that the distribution is uniform. We may safely consider that when $\rho_0 t$ is less than 10^{-6}, the effect of the charge does not introduce an error of 1 per cent.

SECTION II.—*Ions produced by a Radio-active Substance.*

The apparatus which was used for experiments with a radio-active substance is shown in fig. 1. It consists of a large brass tube, A (60 centims. long, 3·5 centims. in diameter), and two smaller tubes, B_1 and B_2 (16 centims. long), which fitted lightly into A. The tubes B had brass electrodes, E, supported by brass rods, F, which passed through ebonite plugs, G, in the tubes B.

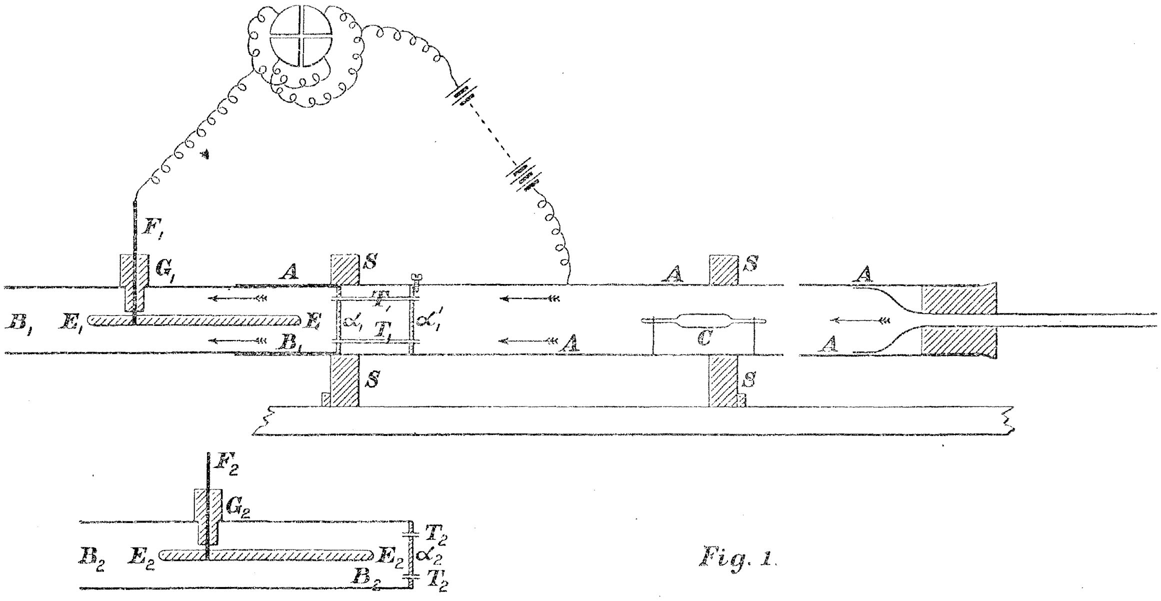


Fig. 1.

The fine tubes in which the diffusion takes place consisted of two sets of twenty-four each. The longer set T_1 (4 centims. long and 1 millim. internal diameter) passed through holes in two brass discs, α_1 and α'_1, which fitted exactly into the large tube A. The tubes T_1, two of which are represented in the figure, projected 2 millims. from the discs at either end. The set of short tubes T_2 were passed through holes in a disc α_2, and projected 2 millims. on each side of the disc, so that the conducting air should enter each set under exactly the same conditions. The holes in the discs through which the tubes T passed were arranged on a circle of 2 centims. diameter, concentric with the boundary of the disc. When either set of tubes was pushed into A, a stream of air down the large tube divides itself equally among the twenty-four channels provided by the tubes T. The disc α_1 was soldered to the front of the tube B_1, and the disc α_2 to the front of the tube B_2.

When working with air at atmospheric pressure the stream of air was obtained by putting weights on the movable cylinder of a gasometer. For experiments with dry air the delivery tube of the gasometer was connected to wide tubes of calcium chloride, and a tube tightly packed with glass-wool was put between the drying tubes and the tube leading to A, so that particles of dust should not be carried into the diffusion apparatus. When it was desired to make experiments with moist air, the calcium chloride tubes were removed, and long tubes half filled with water were substituted. The velocity of the air along the tubes T could be varied by changing the weights on the gasometer.

The radio-active substance was obtained from E. de HAËN (Chemische Fabrik, List vor Hannover), and the preparation labelled "Radio-active Substance A" was used. A tube, C, of thin glass, containing some of the radio-active substance, was held by means of wire supports inside the tube A as shown in the figure. The radiation given out by the active substance was much more intense than uranium rays, and after passing through the glass tube was strong enough to ionize the surrounding air. The tube C was sealed in order to prevent any moisture from coming into contact with the radio-active substance, which was deliquescent. The tube A was fixed rigidly by ebonite supports, S, to the top of a heavy box, so that the tube C should not get shaken when the tubes B_1 and B_2 are fixed in position.

The tube A was connected to one terminal of a battery of forty lead cells, the other terminal being to earth. The rod F was connected to one pair of quadrants of an electrometer, the other pair of quadrants and the case of the electrometer being connected to earth. The rod F and the wire connecting it to the electrometer were surrounded by metal screens, so that external electric charges should not give any deflection on the electrometer scale.

Since the tube A is in metallic connection with all the parts of the diffusion apparatus except E, there is no electric force acting on a stream of gas until it comes out of the tubes T into the space between E and B. The air takes about one second to pass the electrode, and a difference of potential of a few volts between E and B would, under ordinary conditions, suffice to collect all the ions of one sign on E, but owing to the turbulent motion of the gas as it escapes from the tubes T, a much greater potential difference (80 volts) was used. The potential of the electrode during an experiment never exceeded 1 or 2 volts. It was found under similar conditions of ionisation and velocity of air that the electrometer deflection was not altered by charging A to 40 volts instead of 80. We therefore conclude that all the ions of one sign are collected on E, so that the electrometer deflection is proportional to the number of ions that come through the tubes T.

Methods of Conducting the Experiments with Air at Atmospheric Pressure.

The tube B was moved into A until the disc α_1' came up to a small screw that projected into A, and the rod F_1 was connected to the insulated quadrants of the electrometer. The tube B_2 was connected to the end of B_1 by means of a piece of tubing the same size as A. Before any observations were made the stream of air was allowed to pass for one minute through the apparatus in order to blow out the ions that accumulate in the air in A. The quadrants (connected to F_1) were then insulated, and the air, being ionised as it passes the tube C, carries some of the ions with it through the tube T_1. The electrometer deflection, n_1 divisions per minute, was then observed.

The positions of the two tubes B_1 and B_2 were then interchanged. The resistance to the passage of the air through the apparatus was unaltered, so that the stream of gas that passed through was the same as when the deflection n_1 was being observed. The rod F_2 was connected to the quadrants of the electrometer and the same observations were made, the electrometer deflections being n_2 divisions per minute. These experiments were repeated several times, and it was found that the numbers n_1 and n_2 were constant, showing that the rays emanating from the tube C did not vary with the time to any appreciable extent.

When the quadrants were insulated and the air inside A at rest, a small deflection (usually one division per minute) was obtained arising from the imperfect insulation of the plug G. This deflection has to be subtracted from the deflections obtained when the stream of air is passing along A. The leak across G gives rise to no inaccuracy, as it is perfectly constant and was easily determined. In the tables of observations the corrected values of n_1 and n_2 are given.

When the tube A is charged positively the deflections n_1 and n_2 refer to positive ions; similar numbers for negative ions were obtained by changing the sign of the potential of A.

Experiments at Lower Pressures.

In order to make experiments with air at pressures lower than the atmospheric pressure, it was found necessary to make a slight change in the diffusion apparatus. The experiments were made with the ions produced by the radio-active substance, as it is a source of very constant radiation. A flat ring was soldered to the end of the tube A, and similar rings were soldered outside the tubes B_1 and B_2. The ring on the tube B_1 was 8 centims. from the disc α_1', and the ring on the tube B_2 8 centims. from the disc α_2. The diffusion apparatus was made sufficiently air-tight by greasing the ring on A, and pressing the ring on B against it.

The arrangement of the apparatus for obtaining a stream of air at low pressure is shown in fig. 2. Rubber stoppers with glass tubes leading from them were fitted into the open ends of the tubes B_1 and B_2. A short brass tube L was soldered near the end of the tube A, and was connected to the manometer M, so that the pressure of the air in A could be found. The air from the room was admitted to the apparatus through capillary tubes K, having first passed through a tube of glass-wool G, to prevent the admission of any dust which might alter the resistance of the tubing. The capillary tubing was connected to the drying tubes, and the rest of the connections were made with wide tubing. The tube *u* leading from B was connected to two large vessels W_1 and W_2, which were exhausted by means of a water-pump.

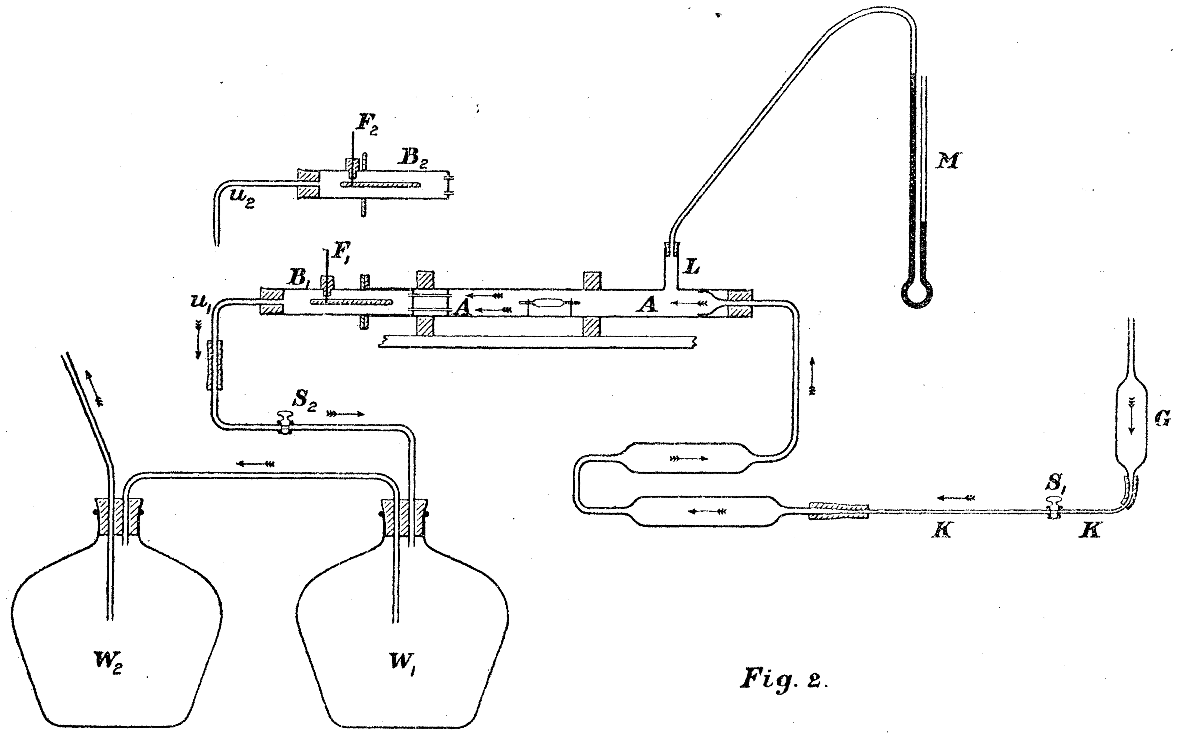


Fig. 2.

In order to obtain a stream of air through A at a given pressure P, and with a velocity between suitable limits, the stopcock S_1 was closed and the whole apparatus was exhausted until the pressure was a few millims. below the pressure P. The tube G was connected to the delivery tube of a gasometer, the movable cylinder of which was adjusted so as to be on the point of moving downwards when the gasometer was open to the air. The vessel W_2 was then connected with the water-pump, and S_1 was turned on for a few minutes. The velocities V (through the tubing T) which were desirable necessitated a larger supply through the apparatus than could be taken out by the water-pump, so that the pressure, as shown by the manometer, gradually rose at the rate of about 3 millims. per minute. The stopcock S_1 was turned off when the pressure was as much above P as it was below P at the beginning of the experiment. The velocity V in the tubes T can be accurately found by observing the volume of air that escaped from the gasometer and the time during which the stopcock S_1 was open. If the velocity so found was too big or too small, the length of the capillary tubing was changed so as to bring the velocity V within the required limits. Any alteration in the tubing leading into the diffusion apparatus necessitates a fresh determination of V before experiments on the conductivity are made.

The tube G is connected to the gasometer only for the purpose of determining V. Since the pressure inside the gasometer is the same as the atmospheric pressure, the air from the room may be allowed to enter G directly during experiments on the conductivity.

The electrical arrangements were the same as have been already described.

Method of Conducting the Experiments with Air at Low Pressures.

The apparatus is arranged as shown in fig. 2, and the pressure is reduced until it is a little lower than the pressure P at which the experiment is to be made. The stopcock S_1 is turned on and the air is allowed to run through the apparatus for about a minute before the quadrants, to which F_1 is connected, are insulated. When the manometer shows that the pressure is about 2 millims. lower than P, the quadrants are insulated and the deflection n_1 divisions per minute on the electrometer scale is observed. The observations are continued until the pressure is about 2 millims. above P, and the mean taken. The difference between the deflections in the first and last half minute was scarcely perceptible.

Having determined n_1, the stopcock S_2 was closed, and the air is admittted into the diffusion apparatus through S_1, the tube B_1 was then removed and B_2 put in its place. Before making observations with F_2 connected to the electrometer, it is necessary to test whether the joint between the two discs is air-tight. For this purpose S_1 was closed and S_2 opened so as to let some of the air from the diffusion apparatus into W_1. The stopcock S_2 was then closed and the manometer was observed. It was found that the air did not get into the apparatus at one-thousandth the rate at which it entered when S_1 was open.

The determination of n_2 is then made in the same way as n_1. Particular care was taken in all cases to make the observations over the same part of the electrometer scale.

Generally the deflection n_2 was obtained from two half-minute observations. Since n_1 is much smaller than n_2, its value was taken as the mean of a number of observations made while the spot of light was passing the same part of the scale as was used for the determination of n_2.

The following tables give the results of experiments at different pressures. Tables I. and II. refer to positive and negative ions respectively in dry air. Tables III. and IV. are the corresponding observations for moist air. The numbers in the columns n_1 and n_2 are the deflections obtained per minute; P is the pressure of the air in A in millims. of mercury; V is the mean velocity in the tubing T_1 in centims. per second; Θ is the temperature of the air during the experiment :—

Table I.—Positive Ions in Dry Air.

n_1.	n_2.	V.	P.	Θ.
88·2	153	344	772	19
56·1	105·3	387	550	13
33·9	73·9	420	400	16
14·8	41·3	410	300	13
11·5	34·5	582	200	12

Table II.—Negative Ions in Dry Air.

n_1.	n_2.	V.	P.	Θ.
63·4	138·6	344	772	19
43·0	93·8	387	550	13
24·8	68·0	420	400	16
10·6	39·9	410	300	13
7·6	31·5	582	200	12

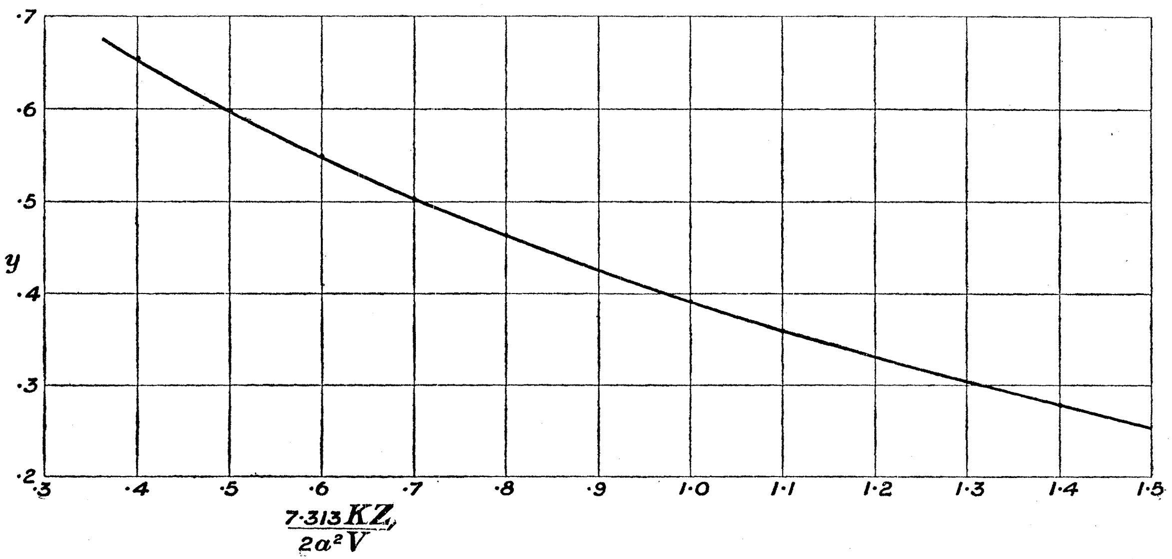
Table III.—Positive Ions in Moist Air.

n_1.	n_2.	V.	P.	Θ.
81·3	145·8	368	772	18
24·7	58·5	430	400	11
9·5	31·2	609	200	9·5

Table IV.—Negative Ions in Moist Air.

n_1.	n_2.	V.	P.	Θ.
71·1	135	368	772	18
21·0	56·3	430	440	11
7·6	27·1	609	200	9·5

The connection between the ratio y (= n_1/n_2) and the coefficient of diffusion can be shown graphically by means of a curve representing equation 2, Section I. The



accompanying curve has for co-ordinates y and $\frac{7\cdot31\,\mathrm{KZ}_1}{2a^2\mathrm{V}}$, and from it we can deduce the values of K corresponding to the different pressures. These values are given in the following tables :—

TABLE V.—Positive Ions, Dry Air.

P.	K.	P × K.	θ.
772	·0317	24·5	19
550	·0420	23·1	13
400	·0578	23·1	16
300	·078	23·4	13
200	·118	23·6	12

TABLE VI.—Negative Ions, Dry Air.

P.	K.	P × K.	θ.
772	·0429	33	19
550	·0542	29·8	13
400	·078	31·2	16
300	·103	30·9	13
200	·155	31·0	12

TABLE VII.—Positive Ions, Moist Air.

P.	K.	P × K.	θ.
772	·0364	28·0	18
400	·0668	26·7	11
200	·134	26·8	9·5

TABLE VIII.—Negative Ions, Moist Air.

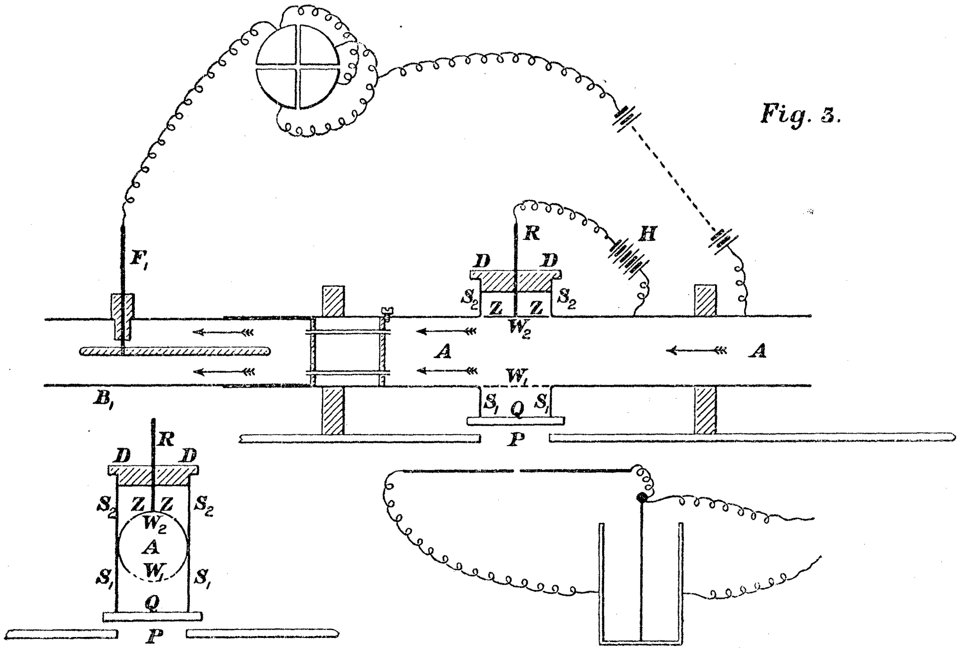
P.	K.	P × K.	θ.
772	·0409	31·5	18
400	·0771	30·8	11
200	·147	29·4	9·5

These tables show that in each case the rate of diffusion of ions into a gas is inversely proportional to the pressure of the gas.

The coefficients of diffusion at 772 millims. show a discrepancy from this law which is somewhat greater than the probable error of the experiments, but we should not expect closer agreement between the products P × K unless the temperature of the air was the same in each case. It will be noticed that the experiments at 772 millims. pressure were made when the temperature of the air was higher than the temperature during the other experiments.

SECTION III.—*Ions produced by the Action of Ultra-violet Light on a Metal Surface.*

The apparatus which is described in Section II. can, with slight alterations, be used for ions produced by various methods. In order to distribute ions produced by ultra-violet light in the stream of air passing along the tube A, the changes shown in fig. 3 were made. The windows W_1 and W_2 were cut in the long tube, and two short pieces, S_1 and S_2 were saddled on to it, each of them surrounding one of the windows. A quartz-plate, Q, was fixed to the end of S_1 by means of sealing wax, which made the joint air-tight, and a piece of wire gauze, having the same curvature as A, was placed in the window W_1, completely filling it. A piece of zinc, Z, of the same shape and size as the piece of brass which was cut out of the window W_2, was fixed to a brass rod, R, which passed through the ebonite disc D. The disc fitted tightly into the end of S_2, and the joint was made air-tight. The zinc did not touch the tube A, so that its potential relative to A could be varied as desired. When ultra-violet light passes through the quartz and the gauze, it falls on the zinc, and negative ions are produced at the surface of the metal. Some of these ions can be sent into a stream of air passing along A by lowering the potential of the zinc relative to A. For this purpose a small battery, H, was insulated and its positive terminal was connected to A and its negative terminal to R.



A spark between two aluminium wires was used as the source of ultra-violet light. The apparatus for producing the spark was contained inside a box covered with lead, with a small opening at P_1 through which the light from the spark fell on the quartz-plate Q. One of the terminals of the secondary of a Ruhmkorff coil was connected to the outer coating of a Leyden jar, and the other terminal to the inner coating. The jar was charged by the coil, and the discharge took place across the spark-gap formed by the two aluminium wires. The air in the neighbourhood of the spark becomes positively electrified, so that it was found necessary to pack wool round the tube S_1 to prevent the electrified air from coming into the neighbourhood of the rod F and the wire connecting it to the electrometer. When this precaution was taken it was found that the electrometer gave no deflection when the coil was turned on for several minutes.

Method of Conducting Experiments with Ultra-Violet Light.

The small battery of Clark cells (H, fig. 3) was insulated, and its terminals were connected to R and A so as to make the potential of R about 6 volts less than A. The tube A was connected to the negative terminal of a battery of 40 lead cells, the other terminal being to earth. The tubes B and the electrometer connections were arranged in the same way as when experimenting with the radio-active substance. The observations were made in a slightly different manner.

The quadrants connected to F were insulated and the stream of air allowed to run through the apparatus. About fifteen seconds were allowed for the stream of air to become constant; the coil working the spark gap was then turned on for a fixed time (twenty seconds generally). The electrometer deflection can be read when the spot of light becomes steady, which is an advantage of this method. When the coil was not working the electrometer reading did not vary more than ·5 division per minute, and was not affected by letting the stream of air pass through the apparatus.

The deflections n_2 (obtained in a similar manner when the ionized air passes through the short tubes T_2) were about twice as big as the deflections n_1, so that the latter observations were made twice in order to cover the same part of the scale.

The deflections obtained when the rod R was connected directly to A were about $\frac{1}{10}$th of the deflection obtained when the zinc plate was 6 volts negative compared with A.

The potential of A was changed to 80 volts positive, and the zinc plate made positive with respect to A, and no deflection was obtained on allowing the coil to run for two minutes.

The following tables give the deflections obtained with different velocities V through the tubes T. The numbers n_1 and n_2 are deflections per minute, and the coefficients of diffusion K were deduced from the curve, Section II. The air in these experiments was at atmospheric pressure H. The temperature only varied from 16° to 18° during the experiments, so that the rates of diffusion may be taken as corresponding to a temperature of 17° centigrade :—

TABLE IX.—Dry Air.

H.	n_1.	n_2.	V.	K.
761	32·8	65·1	356	·0427
748	44·0	76·2	475	·0438
761	55·7	109·3	377	·0440

TABLE X.—Moist Air.

H.	n_1.	n_2.	V.	K.
762	45·0	81·1	368	·0368
772	47·0	90·0	337	·0380

The density of ionization depends greatly on the state of the zinc surface, which has to be polished from time to time in order that the ionization should not be too small. In the above experiments the greatest density of electrification occurs in the third experiment with dry gas. The mean time, t, spent by any portion of the gas in the tubes T_1 is $\frac{4}{377}$ second. The total volume of gas that passed through the apparatus per minute was 4260 c.c.

On standardising the electrometer, it was found that each scale division corresponded to a charge of ·0044 electrostatic unit. The mean density of the electrification ρ was therefore $8{\cdot}5 \times 10^{-5}$ electrostatic unit per c.c. We have shown in Section I. that the product $\rho \times t$ must be less than 10^{-6} in order that the loss of ions due to self-repulsion should be less than 1 per cent. of the loss due to diffusion to the sides. In the present case the product $\rho \times t$ is $\cdot 9 \times 10^{-6}$, so that no correction need be made for the loss due to self-repulsion.

SECTION IV.—*Ions produced by the Point Discharge.*

In order to make the apparatus suitable for experimenting with the point discharge, the changes shown in fig. 4 were made. Two circular holes (1·6 centims. in diameter) were made in the tube A, and two tubes, Q and R, of the same diameter as

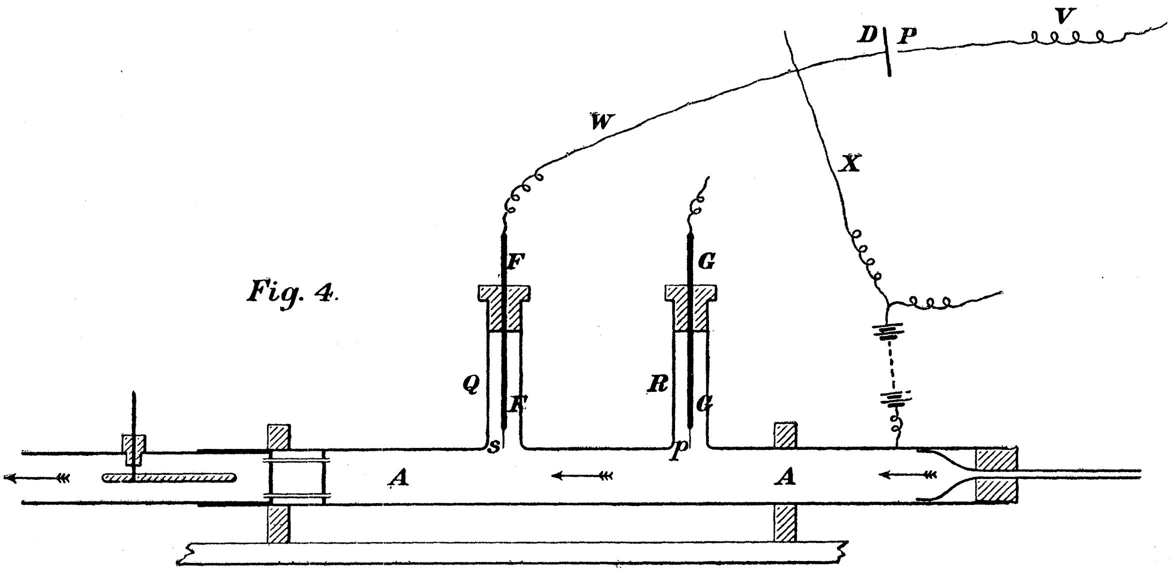


Fig. 4.

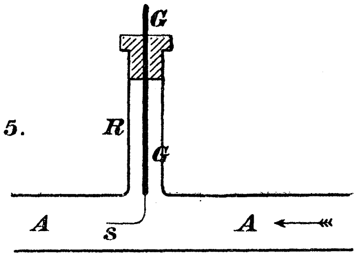


Fig. 5.

the holes were soldered to A in the positions shown in the figure. Ebonite plugs were fitted tightly into Q and R so that no air should escape by the side tubes. The brass rods F and G passed through holes in the plugs, and could be moved up and down so as to bring the metal points which were soldered to their ends to any desired position in the tubes. The point S at the end of F was a steel needle, and the point p was a short platinum wire.

The potential of the point was raised by means of a Wimshurst machine driven at a constant speed by an electric motor. One of the conductors of the machine was connected to earth and the other to the wire V, which terminated in a point P at a distance of about 5 millims. from the metal disc D. The disc was connected to one of the rods F or G by the insulated wire W. When the Wimshurst machine was working no discharge took place from the point inside the diffusion apparatus while the earth-connected wire X rested on W. When the earth-connected wire was raised off W, a discharge immediately took place from the point at the end of the rod F. A constant discharge could therefore be obtained inside the tube for any desired time, independent of the initial and final variations of the machine.

Most of the electricity discharged from the point inside A goes to earth through the battery, and only a small fraction is carried by the stream of air along the tube A.

Owing to the charges carried about in the air of the room (emanating partly from P and partly from points of the machine), it was found that gauze screens were not sufficient protection for the wire leading from F to the insulated quadrants; it was found necessary to cover the screens with tinfoil. When this precaution was taken the electrometer showed no deflection when the Wimshurst had been working for several minutes.

The experiments were conducted practically in the same manner as the experiments on ultra-violet light. The following tables give the results of the experiments, the numbers in the columns n_1, n_2, V and K having the same signification as in the previous tables :—

TABLE XI.—Positive Ions in Dry Air.

Expt.	H.	n_1.	n_2.	V.	K.
1	766	162	262	324	·0263
2	760	81	129	334	·0251
3	761	101	150	378	·0245
4	754	89·4	142	329	·0247
5	753	180·6	299	324	·0257
6	767	52·4	77·4	342	·0216

Experiment 1.—Made with steel point in the tube Q, the point being at the aperture in the tube A.

Experiments 2 and 3.—Made under same conditions as experiment 1, except that the tube R was used in order that the gas should have a smaller electrification when it reaches the tube T.

Experiment 4.—Same as experiments 2 and 3, with a platinum point substituted for the steel point.

Experiment 5.—The point was held in the tube A in the position shown in fig. 5.

Experiment 6.—Same as experiment 1, except that the point was drawn up the side tube Q 5 centims. from the aperture in A.

Experiments 1 and 5 are the only ones in which the effect of self-repulsion may contribute appreciably to the loss of ions in the tube T_1, so that the values of K deduced from these experiments may be a little too big.

The difference of about 5 per cent. which occurs between the values obtained in experiments 1 and 5 and the values obtained in experiments 2, 3, and 4, is probably due to this effect and not to any difference in the ions.

The ions which get into the stream of air in A from a point some distance up the side tube are larger than the others, as Experiment 6 shows that they diffuse more slowly.

TABLE XII.—Negative Ions in Dry Air.

Expt.	H.	n_1.	n_2.	V.	K.
1	768	72	138	337	·0382
2	766	86·2	165	326	·0367
3	758	78·5	150	323	·0368
4	767	91·2	160	342	·0324

Experiment 1.—Made with a steel point in the tube Q, the point being at the aperture in the tube A.

Experiment 2.—Same as Experiment 1, with a platinum point substituted for the steel needle.

Experiment 3.—The point was held in the tube A, as shown in fig. 5.

Experiment 4.—Same as Experiment 1, except that the point was drawn up the tube Q 2 centims. from the aperture in A.

The first three experiments give practically the same values for the coefficient of diffusion, but the fourth experiment shows that larger ions are produced when the point discharge takes place in the narrow tube Q.

Table XIII.—Positive Ions in Moist Air.

Expt.	H.	n_1.	n_2.	V.	K.
1	765	44·1	74·7	318	·0277
2	750	71·0	112	396	·0291
3	750	60	100	323	·0271

Experiment 1.—Made with a steel point in the tube R, the point being at the aperture in A.

Experiment 2.—Made with a platinum point in the tube Q (in order to get larger deflections).

Experiment 3.—Steel point in tube Q 3 centims. from the aperture in A.

The effect of drawing the point up the tube has not so much effect in this case as when the air is dry.

Table XIV.—Negative Ions in Moist Air.

Expt.	H.	n_1.	n_2.	V.	K.
1	774	56·4	113·6	321	·0395
2	750	66·7	121·5	396	·0399
3	774	45·8	97·4	321	·0376

These three experiments were made with the discharge from the wire in the side tube Q. In Experiments 1 and 2 the point was at the centre of the aperture in A, steel and platinum points being used in the two cases respectively. The third experiment was made with a steel point drawn up the tube Q 2 centims. from the aperture in the tube A.

Considering the experiments made with the point at the junction of Q and A, it will be seen that the electrification (n_2/V in arbitrary units) is greatest for those ions which move the slowest. This arises partly on account of the loss of charge in the tube A before the gas reaches the tubes T. If equal electrifications were produced at the source, we would expect less of the small ions than of the large ions to reach the tubes T with the gas.

SECTION V.—*Effect of Pressure.*

The theory of the interdiffusion of gases shows that the coefficient of diffusion is inversely proportional to the total pressure of the two diffusing gases. This law has been confirmed by the experiments of LOSCHMIDT and others.* The results given in Section II. show that the law can be extended to the case where one of the gases consists of ions. The pressure that the ions exert is so small that it does not contribute to the total pressure by an amount which could be measured. The total pressure in this case is the pressure of the gas into which the ions are diffusing, and we see that between the pressures 772 and 200 (millims. of mercury) the rate of diffusion is inversely proportional to the pressure.

We conclude from this that the size of an ion does not change when the pressure varies between these limits.

Ions produced by Various Methods.

The experiments on diffusion show that the ions produced by Röntgen rays, radio-active substances, and ultra-violet light are nearly of the same size, and subject to the same changes arising from the presence of moisture. The following table of coefficients of diffusion of ions into air shows that there are differences in the various cases which are greater than what might arise from experimental errors.

The ions produced by the point discharge are larger than those produced by the other methods, since their rate of diffusion is much slower, except in the case of negative ions in moist air.

COEFFICIENTS of Diffusion of Ions produced in Air by different Methods.

Method.	Dry air.		Moist Air.	
	Positive ions.	Negative ions.	Positive ions.	Negative ions.
Röntgen rays	·028	·043	·032	·035
Radio-active substance	·032	·043	·036	·041
Ultra-violet light	—	·043	—	·037
Point discharge	{ ·0247 { ·0216	·037 ·032	·028 ·027	·039 ·037

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* MEYER, 'The Kinetic Theory of Gases,' Chap. VIII.

We shall first examine the relative values of the charges on the ions in the different cases. For this purpose a knowledge of the velocities of the ions through air, when acted on by a known electric force, is required.

If N is the number of molecules per c.c. of a gas at atmospheric pressure (10^6 dynes per square centim.), e the charge on the ion of the gas in electrostatic units, u the velocity of the ion in a field of 1 volt. per centim., and K the coefficient of diffusion of ions into the gas; then—

$$\mathrm{N} \times e = \frac{3 \times 10^8 u}{\mathrm{K}}.$$

If E is the charge on a hydrogen ion in a liquid electrolyte, then $\mathrm{N} \times \mathrm{E} = 1{\cdot}22 \times 10^{10}$, E being expressed in electrostatic units.

From these formulæ we see that when u and K are known, we can find e in terms of E.

It has already been shown in this manner, in the case of Röntgen rays, that the charge carried by the positive and negative ions is in all cases very nearly the same as the charge E, the differences not being greater than possible experimental errors. In order to make a similar investigation for ions produced by other methods, a complete knowledge of the velocities u would be necessary, but it is only in a few cases that these velocities have been found.

The value of u for ions produced by ultra-violet light given by Professor RUTHERFORD is 1·5 centims. per second in air at atmospheric pressure.* If we take the mean of the two values of K which we have found for dry and moist air, we find that in this case $\mathrm{N}e = 1{\cdot}12 \times 10^{10}$. The effect of moisture on the velocity under an electric force has not been examined, so that we cannot expect to obtain a nearer agreement with the electrolytic value of NE.

The velocities of the ions produced by point discharges have been investigated by Professor CHATTOCK.† The values given for the positive and negative ions are 1·37 and 1·80 (centims. per second in a field of 1 volt per centim.) respectively. Other values were also obtained smaller than these, which would agree better with the observed coefficients of diffusion, but Professor CHATTOCK is of opinion that the low values he obtained for the velocities are less reliable, owing to experimental errors.

The arrangement of the apparatus for the determination of the velocities was such that the point was not surrounded by a narrow tube, so that the larger values obtained for the coefficient of diffusion may be taken in conjunction with the above values of the velocities. The numbers so obtained for $\mathrm{N}e$ are $1{\cdot}66 \times 10^{10}$ and $1{\cdot}46 \times 10^{10}$ for the positive and negative ions respectively.

These results would seem to show that some of the ions carried a double charge, but we cannot attach much importance to the above numbers, since the coefficients of

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* E. RUTHERFORD, 'Cambridge Philosophical Society Proc.,' vol. 9, Part VIII., 1898.

† A. P. CHATTOCK, 'Phil. Mag.,' Nov., 1899.

diffusion show plainly that the sizes of the ions produced by point discharges vary with the arrangement of the apparatus in the neighbourhood of the point. What is necessary in order to come to a definite conclusion with regard to the charges is to examine the coefficients of diffusion and the velocities of ions produced under similar circumstances. This would be possible with the apparatus I have used for the determination of the coefficients of diffusion, and I hope to be able to make observations on the velocities which will lead to an accurate determination of Ne.

This method of obtaining the charge on an ion in a gas in terms of the charge on an ion in a liquid electrolyte is of some importance, as it enables us to obtain evidence of the atomic nature of electricity.

The results show that there is a similarity between the minimum subdivisions of electric charge in liquids and in gases.

The methods hitherto used for the determination of the charge in absolute units apply to ions produced in moist gases, and since all the determinations depend upon the rate at which a cloud falls, great accuracy cannot be expected. The results show that the charge on the carrier is of the same order for ions obtained by various methods. The charges have been obtained by Professor J. J. THOMSON for ions produced by Röntgen rays,* and by ultra-violet light;† the values are nearly the same, being between 6×10^{-10} and 7×10^{-10} electrostatic unit. These values do not differ very much from the value 5×10^{-10} which I obtained for the charge on the carrier in the charged gases given off by electrolysis.‡

If we consider that the charge is the same in all cases, we must assume that the mass surrounding the ion varies in order to account for the differences observed in the coefficients of diffusion. MCCLELLAND,§ by examining the velocities of the ions produced by an arc and by glowing wires, found that the mass attached to the ion depends to a great measure on circumstances connected with the ionization. The velocities undergo large changes for small differences of temperature of the wire, showing that the mass which collects round an ion is very variable. We would not expect that Röntgen rays or radio-active substances would have an effect upon the air, which would alter its tendency to collect round a charged ion, but it is possible that ionization is produced in different ways by different kinds of rays, so that the masses are not identical. With point discharges in air there are actions taking place which would tend to make the carrier increase in size. Thus the oxides of nitrogen which are formed might condense round the charge and lower the rate of diffusion by increasing the mass of the ion.

It is uncertain whether ultra-violet light has any effect on dry air, but WILSON‖

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* J. J. THOMSON, 'Phil. Mag.,' Dec., 1898.

† J. J. THOMSON, 'Phil. Mag.,' Dec., 1899.

‡ J. S. TOWNSEND, 'Phil. Mag.,' Feb., 1898.

§ J. A. MCCLELLAND, 'Camb. Phil. Soc. Proc.,' vol. 10, Part VI.

‖ C. T. R. WILSON, 'Phil. Trans.,' A, vol. 192, 1899.

has shown that if the light acts on moist air for some minutes, a cloud begins to appear. This effect must be very small in the present experiments, but it may account for the difference between the rates of diffusion of ions produced by Röntgen rays and ultra-violet light.

In conclusion, I must express my thanks to Professor THOMSON for many valuable suggestions in connection with this research.