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XXXIII. On the charge of electricity carried by a gaseous ion

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present as well as short ones; but supposing that a violent disturbance, lasting an indefinitely short time, leaves the inner side of a Röntgen tube, where it is generated, it will quickly become modified. Before it has traversed the glass walls, the impulse has already spread out owing to the absorption of some of the periods in the glass, and if this modified impulse is further sent through a screen like a thin sheet of aluminium or black paper, all the visible rays are cut off, and the invisible ones down to at any rate very short lengths. The Röntgen radiation that affects a fluorescent screen or a photographic plate therefore can only contain waves which are either exceedingly short or very long, provided it consists of transverse waves at all.

That an impulsive motion of æther cannot possibly remain an impulsive motion, after traversing media with selective absorption, or media in which dispersion takes place, should be clearly understood. I may, perhaps, in connexion with this, quote a sentence from a letter I wrote to 'Nature' a few weeks after Röntgen's discovery was first announced. At that time there was no theory put forward, except the original one of Röntgen, that the rays were due to longitudinal vibrations. The absence of interference was considered to be an objection to any undulatory theory.

"The absence of interference would not, however, be sufficient to show that the radiation is not of the nature of ordinary light, but only that it does not possess sufficient regularity, or, in other words, that the disturbance is not sufficiently homogeneous. That this is the case is not at all impossible, for the radiation is produced by an impact which, in the first instance, may be an impulsive motion propagated outwards, and, after passing through the screen, would only possess such regularity as is impressed upon it by the absorption of the longer waves"*.

I think that the theory of impulses, as well as its limitations, is clearly expressed in this passage.

XXXIII. *On the Charge of Electricity carried by a Gaseous Ion.* By J. J. THOMSON, *Cavendish Professor of Experimental Physics, Cambridge*†.

IN the Philosophical Magazine for December 1898, I gave a determination of the electric charge carried by an ion in a conducting gas. The method employed in this investigation was as follows:—If n is the number of charged positive and negative ions per unit volume of the

* 'Nature,' vol. liii. p. 268.

† Communicated by the Author.

gas, e the charge carried by an ion, u the mean velocity of the positive and negative ion in a given electric field, the current through unit area of the ionized gas in this field will be neu ; hence if we measure this current we can determine the value of ne , as u the velocity of the ions in a field of known strength has been determined by Zeleny and Rutherford. The number of ions n was measured by depositing by C. T. R. Wilson's method a cloud on the ions and determining the number of particles of water vapour in unit volume of the cloud.

Since these experiments were made, the progress of our knowledge of the electrical properties of gases has made several improvements in the method possible. The discovery of radium has furnished us with a constant source of radiation very much easier to work with than the variable Röntgen rays, which were the source of ionization in the earlier experiments. The introduction of the Dolezalek electrometer, which can be made to give a deflexion of 20,000 or more scale-divisions for the potential-difference of one volt, makes the determination of the exceedingly small currents passing through the ionized gas much more accurate than was possible with an electrometer of the type used in the earlier experiments, which only gave a deflexion of 50 divisions for a volt; and although the Dolezalek electrometer has a much greater capacity than the older form, the difference is not sufficient to neutralize the advantage gained by the increased sensitiveness.

The consideration which influenced me most in repeating the experiments was the increase in our knowledge of the laws governing the deposition of the cloud round the charged ions. The cloud is made by cooling the air by a sudden expansion. I had noticed in the earlier experiments that when this expansion was increased so that the ratio of the volume of the air after expansion to that before exceeded the value 1.3, there was a noticeable increase in the number of particles in the cloud. Mr. C. T. R. Wilson, who has made (Phil. Trans. cxci. p. 289) a systematic study of the relative efficiency of negative and positive ions as nuclei for condensation, found that while a cloud begins to be deposited round negative ions when the expansion is 1.25, it is not until the expansion is equal to 1.31 that the positive ions are caught by the cloud; thus if all the particles are caught by the cloud, the number of water particles in the cloud formed with the larger expansion when both positive and negative ions are caught ought to be twice that with the smaller when only the negative ions are caught. In my earlier experiments the increase in the number of particles with the larger expansions,

though marked, was not so great as this, pointing to the conclusion that all the positive ions had not been caught by the larger expansion.

It is obvious that since the moisture begins to deposit first on the negative ions, unless the rate of expansion is very rapid, the drops formed in the earlier stages of the expansion round the negative ions will have time to grow and form convenient nuclei for further condensation, so that as the expansion increases, the tendency will be for the moisture to deposit on the drops already formed rather than to form new drops round the positive ions. Thus with slow expansions we should expect the number of drops formed to be more nearly equal to the number of negative ions than to the sum of the positive and negative ions.

The results of the present experiments show that this was the case in the expansions used in the earlier experiments. The value of n determined in those experiments was but little greater than the number of negative ions; as ne is the quantity determined by the electrical experiments this caused the value of e to be nearly twice its real value.

The results of Mr. C. T. R. Wilson's experiments give us the means of testing whether the expansion is rapid enough to catch the positive as well as the negative ions, for if we determine the number of drops in the cloud when the expansion is less than 1.31, and again for expansions considerably greater than this value, and find that the latter number is twice the former, we may feel sure that the large expansion has been rapid enough to catch the positive ions. This test has been applied throughout the experiments described in this paper.

The apparatus for producing the cloud was of the kind used by Mr. Wilson. The expansion is produced by the motion of a light glass piston P which slides freely up and down the larger tube C, the lower end of the piston is always below the surface of a layer of water at the bottom of the tube. The inside of the piston is put in connexion with a vessel E by means of tube F, which passes up through the layer of water. H is a large vessel exhausted to as low a pressure as possible; H and E are connected by the tube G, the end of this tube in E is closed by an indiarubber pad which can be quickly removed by means of the rod R; when this is done (the piston being at the top of its range) the pressure of the air drives the piston down, and the air in C and the vessels connected with it expand. The amount of this expansion can be adjusted by altering the height to which the piston is raised before the expansion begins.

In order to make the expansion take place with sufficient rapidity the piston was made of very light glass. The vessel H was exhausted until the pressure in it was but little greater than that due to the water vapour, and especial care was taken that all the tubes, through which air had to rush during

the expansion, were of as wide a bore as possible and without any constrictions; when these precautions were taken, it was found that the expansion was rapid enough to catch all the positive ions. This is shown by the following results, which are a sample of those obtained in a large number of experiments.

Ionization produced by a sample of radium A placed at a height 10 cms. above the top of the vessel in which the cloud is formed.

Pressure of atmosphere 768 mm. Temperature 19.5.

Expansion.	Time taken by drops in cloud to fall 1 centim.	Number of drops in cloud reckoned per c.c. of the volume of the gas before expansion.
1.346	9.7 sec.	6.6×10^4
1.333	9.8 "	6.7 "
1.32	9.1 "	5.7 "
1.31	8.25 "	4.8 "
1.29	7.1 "	3.6 "
1.28	7.12 "	3.6 "
1.27	7 "	3.55 "
1.257	6.5 "	2.9 "

Thus we see that when the expansion is greater than 1·33, the number of nuclei caught by the cloud does not depend upon the amount of the expansion. When this is between 1·33 and 1·29 this number diminishes, until when the expansion is 1·29 the number caught is only half that at the higher expansions. The number now remains independent of the expansion until this falls below about 1·27; for expansions smaller than this the number of nuclei caught falls off rapidly with the expansion. We conclude from this that for expansions greater than 1·33 all the ions positive as well as negative are caught by the cloud; then when the expansion is smaller than 1·33 and greater than 1·29 some, but not all, of the positive ions and all the negative ions; for expansions from 1·29 to 1·27 all the negative but none of the positive ions are caught in the cloud; and that when the expansion falls below 1·27 only a fraction of the negative ions are caught.

The values of the numbers given in the third column of the preceding table were calculated by the following method: let q be the volume of water deposited through the expansion per unit volume of the expanded gas (this was calculated by the method given in the earlier paper), n' the number of drops per unit volume of the expanded gas, a the radius of one of these drops; then $q = n' \frac{4\pi}{3} a^3$.

If v is the rate at which the drops fall, then

$$v = \frac{2}{9} \frac{ga^2}{\mu},$$

where μ is the coefficient of viscosity of the gas. In the case of air $\mu = 1.8 \times 10^{-4}$ and v is therefore equal to $121 \times 10^4 a^2$; hence

$$n' = \frac{3q}{4\pi} 1331 \times 10^6 v^{-\frac{2}{3}}.$$

The number of drops reckoned per unit volume of the gas before expansion is $n' \times$ expansion. The velocity of the drops was determined by measuring the time taken by the top of the cloud to fall through two consecutive centimetres. With the drops used, these times were very approximately equal to each other; with clouds consisting of very fine drops which fall slowly, the time taken to fall through the second centimetre is often considerably greater than that for the first, owing to the diminution produced by evaporation in the size of the drops.

To facilitate the measurement of the velocity the inside of

the cloud-chamber was lined with damped black silk, a narrow slit being left to allow the cloud to be observed. The bottom of the chamber was a plane piece of glass, and the fog was illuminated by a vertical beam of light reflected from a mirror. The top of the cloud-chamber was made of sheet aluminium .3 mm. thick, this allowed the rays from the radium to pass through. Two different samples of radium were used: the one called B was placed at a distance of 15 cms. above the top of the cloud-chamber, the other (a weaker specimen), A, was 10 cms. above it. The radium was spread over surfaces measuring 7 cms. by 5 cms., and was kept in its place by a thin sheet of mica.

The electrical part of the apparatus included a guard-ring condenser, the upper plate of which was a circular piece of aluminium of the same thickness and cut from the same plate as that forming the top of the cloud-chamber; the lower part of the condenser consisted of a circular plate of aluminium 2.47 cms. in radius in one piece of apparatus, 4.55 in another, surrounded by a guard-ring also of aluminium; the distance between the upper and lower plates of the condenser was 1 cm. The radium was placed above the upper plate of the condenser and at the same distance from it as in the cloud experiments, *i. e.* the sample A was placed 10 cms. and the sample B 15 cms. above the plate. The lower circular plate was connected with one pair of quadrants of a Dolezalek electrometer, the wire making the connexion being led through a metal tube connected with the earth. The radium was surrounded by lead guards so as to confine its radiation to the neighbourhood of the condenser. The radium, the guard-ring condenser, and a second condenser used to determine the capacity of the system were placed inside a box lined with metal. The top plate of the condenser was maintained at a constant potential; the lower plate, which was in connexion with the electrometer, was initially put to earth. When the earth connexion was then broken, a current of electricity passed between the plates through the air ionized by the radium; this current charged up the electrometer, and the needle was deflected. Knowing the deflexion of the electrometer produced in a given time, the quantity of electricity received by the lower plate in that time can be calculated, if we know the capacity of the electrometer and its connexions.

If u is the mean velocity of the positive and negative ions under the electric field applied to the air between the plates, n the number of ions (positive and negative) per c.c. of the air, e the charge on an ion, A the area of the lower plate, the quantity of electricity received by the lower plate in unit

time is neA . If C is the capacity of the electrometer and its connexions, this quantity of electricity will produce a potential-difference of neA/C between the quadrants, the deflexion of the electrometer is proportional to this difference of potential; hence to deduce the value of ne from the readings of the electrometer, we require to know the value of C . This was found by connecting with the lower plate of the condenser another condenser of known capacity C' , and again measuring the difference of potential between the plates after the current has been flowing for one second; this is equal to $neA/(C + C')$; hence if δ_1, δ_2 are the deflexions of the electrometer before and after C' was inserted, we have

$$\frac{\delta_1}{\delta_2} = \frac{C + C'}{C},$$

or

$$C = \frac{\delta_2 C'}{\delta_1 - \delta_2}.$$

The effective capacity of the Dolezalek electrometer depends mainly upon the charge on the needle, and may therefore vary considerably from time to time, thus in these experiments C ranged from 200 to 900 cms.: it is therefore very necessary to determine the value of C for each observation. The proceeding adopted was to take, say, six consecutive readings with the condenser C' (whose capacity was $\cdot 001$ microfarad) out (in three of these the upper plate was at a higher potential than the lower plate; in the other three the sign of the potential-difference was reversed); then six with it in, and then another six with it out.

The high effective capacity of the Dolezalek electrometer makes it less sensitive for measuring small quantities of electricity than for potential-differences.

The value of n in the electrical experiments is the number of ions per c.c. of the gas when exposed to the electric field; in the cloud experiments the value found for n is the number when there is no electric field. The electric field tends to drive the ions out of the gas, so that the number in the electric field will be less than the other; when the field is strong the difference is very marked, but with the weak fields (about $\frac{1}{3}$ of a volt per cm.) used in these experiments the difference is inappreciable; we can test whether the field is weak enough to ensure this by measuring the currents under different electric fields: since u the velocity of the ion is proportional to the electric force, if the electrometer deflexion is also proportional to this force, n will be constant, *i.e.* will not alter with the force. The electric force was reduced to

one-half its value, *i. e.* $\frac{1}{6}$ of a volt per cm., and the electrometer deflexions again determined: as these were found to be just half the value with the double force, it was concluded that with the weak fields used in these experiments the value of n was sensibly the same as that without fields.

To test whether the secondary ionization due to the incidence of the radiation on the aluminium was appreciable, the observations were repeated with the lower plate covered with wet tissue-paper. It was found, however, that the results obtained with the wet paper were the same as those without.

The following are the results of experiments made to determine the number of ions per c.c. due (1) to a specimen of radium A placed 10 cms. above the top of the chamber in

Expansions greater than 1.33.

Pressure of atmosphere.	Temp.	Difference in pressure before and after expansion.	Expansion.	Time taken by cloud to fall 1 cm.		Ions per c.c.	
				Radium A.	Radium B.	Radium A.	Radium B.
773	19.5° C.	193	1.343	9.65 sec.	18.6 sec.	6.3×10^4	17×10^4
753	19	185	1.335	10	...	6.65×10^4	
749.5	19	184	1.336	10.25	...	6.8×10^4	
761	19	185	1.33	10	18.25	6.66×10^4	16.3×10^4
772	19	193	1.343	9.5	17.25	6.3×10^4	15.5×10^4
768	19.5	193	1.344	9.75	18.5	6.4×10^4	16.9×10^4
					Mean ...	6.5×10^4	16.42×10^4
Expansions less than 1.33.						Negative ions per c.c.	
768	19.5	163	1.277	7	13	3.3×10^4	8.6×10^4
773	19.5	163	1.276	6	13.5	2.6×10^4	8.9×10^4
772	19	167	1.28	7.125	12.5	3.3×10^4	8.2×10^4
					Mean ...	3.0×10^4	8.5×10^4

which the cloud was produced, (2) to another specimen (B) placed at a height of 15 cms. above the cloud-chamber. The first table contains the number of positive and negative ions caught by expansions greater than 1.33, the second the number of negative ions caught by expansions less than 1.33.

If we take the mean of the results, we find the radium A produces at a distance of 10 cms. 6.25×10^4 ions per c.c., while radium B produces 16.75×10^4 .

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The results of the determinations of ne , where n is the number of ions per c.c., and e the charge in electrostatic measure on an ion, are given in the following table. D is the deflexion of the electrometer in scale-divisions for the potential-difference of 1 volt, C is the capacity of the electrometer and its connexions, δ_1 the mean of the positive and negative deflexions in one minute of the electrometer when there was a potential-difference of $\frac{1}{3}$ of a volt between the plates of the condenser, the gas between the plates being exposed to the radiation from the radium A at a distance of 10 cms., δ_2 the same quantity when the gas was exposed to the radiation from B at a distance of 15 cms. The values of ne are deduced as follows: if A is the area of the plate attached to the electrometer, u the mean velocity of the positive and negative ions under a potential-gradient of a volt per cm., the quantity of electricity given to this plate in unit time under $\frac{1}{3}$ of a volt per cm. is equal to $\frac{1}{3}neuA$, this produces a potential-difference of $\frac{1}{3}neuA/C$ in electrostatic measure between the plates; the potential-difference in volts is, however, $\delta_1/60D$, hence we have

$$\frac{1}{3} \frac{neuA}{C} = \frac{\delta_1}{60D} \times \frac{1}{300}.$$

From Zeleny's experiments u for moist air is 1.4 cm./sec., $A=19.1$; we have thus the data for determining ne :—

D.	C.	δ_1 .	δ_2 .	ne for radium A.	ne for radium B.
7400	483	63	170	25.2×10^{-6}	68×10^{-6}
6550	640	30	...	20.7×10^{-6}	
7600	900	25.5	71.5	19×10^{-6}	53×10^{-6}
8800	930	28	78	18.5×10^{-6}	52×10^{-6}
			Mean ...	20.8×10^{-6}	57.6×10^{-6}

Thus, since for radium A $ne=20.8 \times 10^{-6}$ and $n=6.25 \times 10^4$, the value of $e=3.3 \times 10^{-10}$:

For radium B $ne=57.6 \times 10^{-6}$ and $n=16.75 \times 10^4$, thus $e=3.5 \times 10^{-10}$.

The mean of these values gives 3.4×10^{-10} as the charge in electrostatic units of the gaseous ion. This is only about half the value 6.5×10^{-10} I found in the earlier experiments. The difference is, as I have already explained, due to the expansions in the earlier experiments practically catching only the negative ions; this made the calculated value of n little

more than half the true value, while it made the value of e twice as great as it ought to have been.

If we know the value of e , we can at once deduce the number of molecules in a c.c. of gas at 0° C. and 760 mm. pressure. For if N is this number, then, since e is the same as the charge on the hydrogen ion in the electrolysis of solutions,

$$Ne = 1.22 \times 10^{10}$$

since $e = 3.4 \times 10^{-10}$, $N = 3.6 \times 10^{19}$.

This number is well within the limits of the various determinations made by the methods of the kinetic theory. The above method for determining N has the advantage of not involving a knowledge of the shape of the molecules, or any assumption as to the nature of the effects produced when two molecules come into collision.

In making the experiments described in this paper, I have had the help of my assistant Mr. Everett.

XXXIV. *On the Effect of Absorption on the Resolving Power of Prism Trains, and on Methods of Mechanically Compensating this Effect.* By F. L. O. WADSWORTH*.

[Plate VIII.]

IN previous investigations † of the resolving-power of prism spectroscopes, it has been generally assumed, 1st, that the illumination is uniform over the wave-front passing

* Communicated by the Author. The general investigation on resolving-power, of which the present paper forms a part, was begun nearly eight years ago, but the work has been much interrupted and delayed by other more imperative and immediate demands upon the writer's time and attention. The publication of various parts of the work has therefore been more scattered and irregular than might otherwise have been the case. Since this paper was written, Prof. Campbell, with whom I fortunately had an opportunity of discussing it, has called my attention to a paper on the same subject that was published about a year ago by Dr. Reese of the Lick Observatory Staff. On examining this paper (*Astrophys. Journ.* xiii. p. 199, April 1901) I find that Dr. Reese has deduced the general equation corresponding to (11) of this paper (for $\delta_1 = 0$), but has confined his investigations of the effects of absorption to the particular case where the value of β is very small. Hence his conclusion (p. 206) "that the resolving power of the Mills Spectrograph is diminished by less than one half of one per cent. by the absorption of the prisms" is incomplete, and for that reason erroneous and misleading as a general conclusion. I have therefore allowed my own paper to stand as it was originally written, acknowledging Dr. Reese's priority of publication as above.

† See Rayleigh, *Phil. Mag.* vol. viii. pp. 261-264; vol. ix. pp. 49-56; vol. xlii. p. 167; *Enc. Brit.* vol. xxiv. pp. 430-439; Schuster, *ibid.* vol. xxii. pp. 373-374; also papers by the writer, *Astrophysical Journal*, vol. i. p. 52; vol. iii. pp. 176 and 321; vol. iv. p. 54; vol. vi. p. 27; vol. xvi. p. 1; *Phil. Mag.* vol. xliii. p. 317.