TABLE IV.—Selected Fusing and Boiling Points on the Proposed British Association Scale.

Substance.	F.P.	Substance.	B.P.
Tin	231·9°	Aniline	184·1
Bismuth	269·2	Naphthalene	218·0
Cadmium	320·7	Benzophenone	305·8
Lead	327·7	Mercury	356·7
Zinc	419·0	Sulphur	414·5
Antimony	629·5	Cadmium	756
Aluminium	654·5	Zinc	916

My thanks are due to several Members of the Electrical Standards Committee of the British Association and others, who have kindly revised the proofs of this article.

LVIII. *On the Masses of the Ions in Gases at Low Pressures.* *By* J. J. THOMSON, *M.A., F.R.S., Cavendish Professor of Experimental Physics, Cambridge**.

IN a former paper (Phil. Mag. Oct. 1897) I gave a determination of the value of the ratio of the mass, *m*, of the ion to its charge, *e*, in the case of the stream of negative electrification which constitutes the cathode rays. The results of this determination, which are in substantial agreement with those subsequently obtained by Lenard and Kaufmann, show that the value of this ratio is very much less than that of the corresponding ratio in the electrolysis of solutions of acids and salts, and that it is independent of the gas through which the discharge passes and of the nature of the electrodes. In these experiments it was only the value of *m*/*e* which was determined, and not the values of *m* and *e* separately. It was thus possible that the smallness of the ratio might be due to *e* being greater than the value of the charge carried by the ion in electrolysis rather than to the mass *m* being very much smaller. Though there were reasons for thinking that the charge *e* was not greatly different from the electrolytic one, and that we had here to deal with masses smaller than the atom, yet, as these reasons were somewhat indirect, I desired if possible to get a direct measurement of either *m* or *e* as well as of *m*/*e*. In the case of cathode rays I did not

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* Communicated by the Author: read at the Meeting of the British Association at Dover.

see my way to do this; but another case, where negative electricity is carried by charged particles (*i. e.* when a negatively electrified metal plate in a gas at low pressure is illuminated by ultra-violet light), seemed more hopeful, as in this case we can determine the value of e by the method I previously employed to determine the value of the charge carried by the ions produced by Röntgen-ray radiation (Phil. Mag. Dec. 1898). The following paper contains an account of measurements of m/e and e for the negative electrification discharged by ultra-violet light, and also of m/e for the negative electrification produced by an incandescent carbon filament in an atmosphere of hydrogen. I may be allowed to anticipate the description of these experiments by saying that they lead to the result that the value of m/e in the case of the ultra-violet light, and also in that of the carbon filament, is the same as for the cathode rays; and that in the case of the ultra-violet light, e is the same in magnitude as the charge carried by the hydrogen atom in the electrolysis of solutions. In this case, therefore, we have clear proof that the ions have a very much smaller mass than ordinary atoms; so that in the convection of negative electricity at low pressures we have something smaller even than the atom, something which involves the splitting up of the atom, inasmuch as we have taken from it a part, though only a small one, of its mass.

The method of determining the value of m/e for the ions carrying the negative electrification produced by ultra-violet light is as follows:—Elster and Geitel (Wied. *Ann.* xli. p. 166) have shown that the rate of escape of the negative electrification at low pressures is much diminished by magnetic force if the lines of magnetic force are at right angles to the lines of electric force. Let us consider what effect a magnetic force would have on the motion of a negatively electrified particle. Let the electric force be uniform and parallel to the axis of x, while the magnetic force is also uniform and parallel to the axis of z. Let the pressure be so low that the mean free path of the particles is long compared with the distance they move while under observation, so that we may leave out of account the effect of collisions on the movements of the particles.

If m is the mass of a particle, e its charge, X the electric force, H the magnetic force, the equations of motion are:—

$$m\frac{d^2x}{dt^2}=\mathrm{X}e-\mathrm{H}e\frac{dy}{dt},$$

$$m\frac{d^2y}{dt^2}=\mathrm{H}e\frac{dx}{dt}.$$

Eliminating x we have :—

$$m\frac{d^3y}{dt^3}=\frac{\mathrm{H}e}{m}\left(\mathrm{X}e-\mathrm{H}e\frac{dy}{dt}\right).$$

The solutions of these equations, if x, y, dx/dt, dy/dt all vanish when $t=0$, is expressed by

$$y=\frac{\mathrm{X}m}{e\mathrm{H}^2}\left\{\frac{e}{m}\mathrm{H}t-\sin\left(\frac{e}{m}\mathrm{H}t\right)\right\},$$

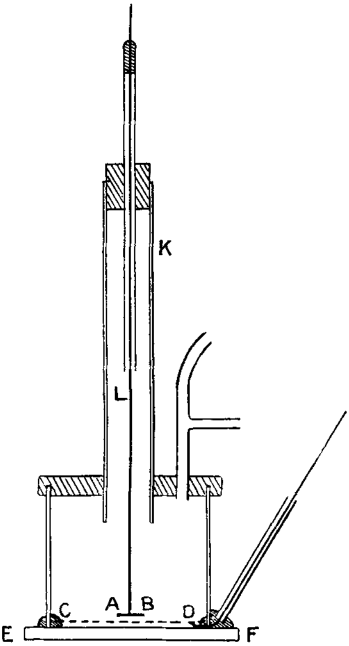
$$x=\frac{\mathrm{X}m}{e\mathrm{H}^2}\left\{1-\cos\left(\frac{e}{m}\mathrm{H}t\right)\right\}.$$

The equations show that the path of the particle is a cycloid, the generating circle of which has a diameter equal to $2\mathrm{X}m/e\mathrm{H}^2$, and rolls on the line $x=0$.

Suppose now that we have a metal plate AB exposed to ultra-violet light, placed parallel to a larger metal plate CD perforated so as to allow the light to pass through it and fall upon the plate AB. Then, if CD is at a higher electric potential than AB, all the negatively electrified particles which start from AB will reach CD if this plate is large compared with AB, the particles travelling along the lines of electric force. Let us now suppose that a uniform magnetic force equal to H, and at right angles to the electric force, acts on the particles; these particles will now describe cycloids and will reach a distance $2\mathrm{X}m/e\mathrm{H}^2$ from the place from which they start, and after reaching this distance they will again approach the plate. Thus if the plate CD is distant from AB by less than $2\mathrm{X}m/e\mathrm{H}^2$, every particle which leaves AB will reach CD provided CD stretches forward enough to prevent the particles passing by on one side. Now the distance parallel to y through which the particle has travelled when it is at the greatest distance from AB is $\pi\mathrm{X}m/e\mathrm{H}^2$: hence if CD stretches beyond AB by this distance at least, all the particles will be caught by CD and the magnetic field will produce no diminution in the rate of leak between AB and CD. If, on the other hand, the distance between the plates is greater than $2\mathrm{X}m/e\mathrm{H}^2$, then a particle starting from AB will turn back before it reaches CD: it will thus never reach it, and the rate at which CD acquires negative electrification will be diminished by the magnetic force. Hence, if this view of the action of the magnetic field is correct, if we begin with the plates very near together and gradually increase the distance between them, we should expect that, at first with the plates quite close together, the rate at which CD received a negative charge would not be affected by the magnetic force, but as soon as the distance between the plates was equal to $2\mathrm{X}\,m\,e\mathrm{H}^2$ the magnetic force would greatly diminish the rate at which CD received a negative charge, and would in fact reduce the rate almost to zero if all the negatively electrified particles came from the surface of AB. Hence, if we measure the distance between the plates when the magnetic force first diminishes the rate at which CD receives a negative charge, we shall determine the value of $2\mathrm{X}m/e\mathrm{H}^2$; and as we can easily determine X and H, we can deduce the value of m/e.

The way in which this method was carried into practice was as follows, the apparatus being shown in fig. 1.

Fig. 1.



AB is a carefully polished zinc plate about 1 centim. in diameter, while CD is a grating composed of very fine wires crossing each other at right angles, the ends being soldered into a ring of metal; the wires formed a network with a mesh about 1 millim. square. This was placed parallel to AB on the quartz plate EF, which was about 4 millim. thick. The grating was very carefully insulated. The system was enclosed in a glass tube which was kept connected with a mercury-pump provided with a McLeod gauge. The ultra-violet light was supplied from an arc about 3 millim. long between zinc terminals. The induction-coil giving the arc was placed in a metal box, and the light passed through a window cut in the top of the box; over this window the quartz base of the vessel was placed, a piece of wire gauze connected with the earth being placed between the quartz and the window. The plate AB was carried by the handle L which passed through a sealing-wax stopper in the tube K. The magnet used was an electromagnet of the horseshoe type. The magnetic force due to the magnet was determined by observing the deflexion of a ballistic galvanometer when an exploring coil, of approximately the same vertical dimension as the distance between the plates AB and CD, was withdrawn from between its poles. The coil was carefully placed so as to occupy the same part of the magnetic field as that occupied by the space between AB and CD when the magnet was used to affect the rate of leak of electricity between AB and CD. In this way the intensity of the magnetic field between the poles of the magnet was determined for a series of values of the current through the magnetizing-coils of the electromagnet ranging between 1 and 4·5 amperes, and a curve was drawn which gave the magnetic force when the magnetizing-current (observed by an amperemeter) was known.

The pressure of the gas in the tube containing the plate was reduced by the mercury-pump to 1/100 of a millim. of mercury. As the mean free path of hydrogen molecules at atmospheric pressure and 0° C. is $1{\cdot}85 \times 10^{-5}$ centim. (Emil Meyer, *Kinetische Theorie der Gase*, p. 142), and of air 10^{-5} centim., the mean free paths of these gases at the pressure of 1/100 of a millim. of mercury are respectively 14 and 7·6 millim., and are consequently considerably greater than the greatest distance, 4 millim., through which the electrified particles have to travel in any of the experiments. These are the free paths for molecules of the gas; if, as we shall see reason to believe, the actual carriers of the negative electrification are much smaller than the molecules, the free paths of these carriers will be larger than the numbers we have quoted.

The rate of leak of negative electricity to CD when AB was exposed to ultra-violet light was measured by a quadrant-electrometer. The zinc plate was connected with the negative pole of a battery of small storage-cells, the positive pole of which was put to earth. One pair of the quadrants of the electrometer was kept permanently connected with the earth, the other pair of quadrants was connected with the wire gauze CD. Initially the two pairs of quadrants were connected together, the connexion was then broken, and the ultra-violet light allowed to fall on the zinc plate; the negative charge received by the wire gauze in a given time is proportional to the deflexion of the electrometer in that time. By this method the following results were obtained: when the difference of potential between the illuminated plate and the wire gauze was greater than a certain value, depending upon the intensity of the magnetic force and the distance between AB and CD, no diminution in the deflexion of the electrometer was produced by the magnetic field, in fact in some cases the deflexion was just a little greater in the magnetic field. The theory just given indicates that the deflexion ought to be the same: the small increase (amounting to not more than 3 or 4 per cent.) may be due to the obliquity of the path of the particles in the magnetic field, causing more of them to be caught by the wires of the grating than would be the case if the paths of the particles were at right angles to the plane of the gauze. When the difference of potential is reduced below a certain value, the deflexion of the electrometer is very much reduced by the magnetic field; it is not, however, at once entirely destroyed when the potential-difference passes through the critical value. The simple theory just given would indicate a very abrupt transition from the case when the magnetic force produces no effect, to that in which it entirely stops the flow of negative electricity to CD. In practice, however, I find that the transition is not abrupt: after passing a certain difference of potential the diminution in the electric charge received by CD increases gradually as the potential-difference is reduced, and there is not an abrupt transition from zero effect to a complete stoppage of the leak between AB and CD. I think this is due to the ionization not being confined to the gas in contact with the illuminated plate, but extending through a layer of gas whose thickness at very low pressures is quite appreciable. The existence of a layer of this kind is indicated by an experiment of Stoletow's. Stoletow found that the maximum current between two plates depended at low pressures to a considerable extent upon the distance between the plates, increasing as the distance between the plates was increased. Now the maximum current is the one that in one second uses up as many ions as are produced in that time by the ultra-violet light. If all the ions are produced close to the illuminated plate, increasing the distance between the plates will not increase the number of ions available for carrying the current; if, however, the ions are produced in a layer of sensible thickness, then, until the distance between the plates exceeds the thickness of this layer, an increase in the distance between the plates will increase the number of ions, and so increase the maximum current. If this layer has a sensible thickness, then the distance d which has to be traversed by the ions before reaching the gauze connected with the electrometer ranges from the distance between the plates to the difference between this distance and the thickness of the layer. The first ions to be stopped by the magnetic field will be those coming from the surface of the illuminated plate, as for these d has the greatest value: hence we may use the equation

$$d=\frac{2\mathrm{X}m}{e\mathrm{H}^2}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

if d represents the distance between the plates, X the value of the electric field when the rate of leak first begins to be affected by the magnetic force H. Assuming that the field is uniform,

$$X = V/d,$$

where V is the potential-difference between the plates ; and equation (1) becomes

$$d^2 = \frac{2Vm}{eH^2}.$$

The negative ions travelling between the plates will disturb to some extent the uniformity of the field between the plates ; but if the intensity of the ultra-violet light is not too great, so that the rate of leak and the number of ions between the plates is not large, this want of uniformity will not be important. A calculation of the amount of variation due to this cause showed that its effect was not large enough to make it worth while correcting the observations for this effect, as the variation in the intensity of the ultra-violet light was sufficient to make the errors of experiments much larger than the correction.

The following is a specimen of the observations :—

Distance between the plates ·29 centim.
Strength of magnetic field 164. Pressure 1/100 millim.

Potential-difference between Plates, in volts.	Deflexion of Electrometer in 30 secs.	
	Magnet off.	Magnet on.
240	180	190
120	160	165
80	160	140
40	130	75

These observations showed that the critical value of the potential-difference was about 80 volts. A series of observations were then made with potential-differences increasing from 80 volts by 2 volts at a time, and it was found that 90 volts was the largest potential-difference at which any effect due to the magnet could be detected. The results of a number of experiments are given in the following table :—

d (in cm.).	H.	V in absolute measure.	e/m.
·18	170	40×10^8	$8·5\times10^6$
·19	170	30×10^8	$5·8\times10^6$
·20	181	46×10^8	$7·0\times10^6$
·29	167	84×10^8	$7·1\times10^6$
·29	164	90×10^8	$7·6\times10^6$
·30	160	86×10^8	$7·4\times10^6$
·45	100	80×10^8	$7·9\times10^6$

giving a mean value for e/m equal to $7·3\times10^6$. The value I found for e/m for the cathode rays was 5×10^6; the value found by Lenard was $6·4\times10^6$. Thus the value of e/m in the case of the convection of electricity under the influence of ultra-violet light is of the same order as in the case of the cathode rays, and is very different from the value of e/m in the case of the hydrogen ions in ordinary electrolysis when it is equal to 10^4. As the measurements of e, the charge carried by the ions produced by ultra-violet light to be described below, show that it is the same as e for the hydrogen ion in electrolyis, it follows that the mass of the carrier in the case of the convection of negative electricity under the influence of ultra-violet light is only of the order of 1/1000 of that of the hydrogen atom. Thus with ultra-violet light, as with cathode rays, the negative electrification at low pressures is found associated with masses which are exceedingly small fractions of the smallest mass hitherto known—that of the hydrogen atom.

I have examined another case in which we have convection of electricity at low pressures by means of negatively electrified particles—that of the discharge of electricity produced by an incandescent carbon filament in an atmosphere of hydrogen. In this case, as Elster and Geitel (Wied. *Ann.* xxxviii. p. 27) have shown, we have negative ions produced in the neighbourhood of the filament, and the charge on a positively electrified body in the neighbourhood of the filament is discharged by these ions, while if the body is negatively electrified it is not discharged. If the filament is negatively, and a neighbouring body positively electrified, there will be a current of electricity between the filament and the body, while there will be no leak if the filament is positively and the body negatively electrified. Elster and Geitel (Wied.

Ann. xxxviii. p. 27) showed that the rate of leak from a negatively electrified filament was at low pressures diminished by the action of the magnetic field. On the theory of charged ions, the effect of the magnet in diminishing the rate of leak could be explained in the same way as the effect on the convection due to ultra-violet light. A series of experiments were made which showed that the effects due to the magnetic field were consistent with this explanation, and led to a determination of e/m for the carriers of the negative electricity.

The apparatus was of the same type as that used in the preceding experiments. The wire gauze and the zinc plate were replaced by two parallel aluminium disks about 1·75 centim. in diameter; between these disks, and quite close to the upper disk, there was a small semicircular carbon filament which was raised to a red heat by the current from four storage-cells. The carbon filament was placed close to the axis of the disks; the object of the upper disk was to make the electric field between the disks more uniform. The lower plate was connected with the electrometer. The plates and filaments were enclosed in a glass tube which was connected with a mercury-pump, by means of which the pressure, after the vessel had been repeatedly filled with hydrogen, was reduced to ·01 millim. of mercury. Great difficulty was found at first in getting any consistent results with the incandescent carbon filament: sometimes the filament would discharge positive as well as negative electricity; indeed sometimes it would discharge positive and not negative. Most of these irregularities were traced to gas given out by the incandescent filament; and it was found that by keeping the filament almost white-hot for several hours, and continually pumping and refilling with hydrogen, and then using the filament at a much lower temperature than that to which it had been raised in this preliminary heating, the irregularities were nearly eliminated, and nothing but negative electrification was discharged from the filament. When this state was attained, the effect of magnetic force showed the same characteristics as in the case of ultra-violet light. When the difference of potential between the filament and the lower plate was small, the effect of the magnetic force was very great, so much so as almost to destroy the leak entirely; when, however, the potential-difference exceeded a certain value, the magnetic force produced little or no effect upon the leak. An example of this is shown by the results of the following experiment:—

The distance between the carbon filament and the plate connected with the electrometer was 3·5 millim., the strength of the magnetic field 170 C.G.S. units.

Difference of Potential between wire and plate, in volts.	Leak in 5 seconds.		Ratio of leaks.
	Without magnetic field.	With magnetic field.	
40	43	1	·023
80	170	50	·29
120	300	250	·83
140	345	345	1·0
160	400	430	1·07

Taking 140 volts as the critical value of the potential-difference, we find by equation (1) that

$$\frac{e}{m}=7{\cdot}8\times10^{6}.$$

The results of this and similar experiments are given in the following table; V denoting the critical potential-difference in C.G.S. units, and H the magnetic force:

d.	V.	H.	*e/m.*
·35	140×10^{3}	170	$7{\cdot}8\times10^{6}$
·35	220×10^{3}	220	$7{\cdot}5\times10^{6}$
·35	170×10^{3}	170	$9{\cdot}6\times10^{6}$
·35	130×10^{3}	170	$7{\cdot}2\times10^{6}$
·35	120×10^{3}	120	$11{\cdot}3\times10^{6}$

giving $8{\cdot}7\times10^{6}$ as the mean value of *e/m.* This value does not differ much from that found in the case of ultra-violet light. In the case of the incandescent filament the ions are only produced at a small part of the plate, and not over the whole surface as in the case of ultra-violet light, so the conditions do not approximate so closely to those assumed in the theory. We conclude that the particles which carry the negative electrification in this case are of the same nature as those which carry it in the cathode rays and in the electrification arising from the action of ultra-violet light.

The unipolar positive leak which occurs from an incandescent platinum wire in air or oxygen, and in which the moving bodies are positively electrified, was found not to be affected by a magnetic field of the order of that used in the experiments on the negative leak. This had already been observed by Elster and Geitel (Wied. *Ann.* xxxviii. p. 27).

On the theory of the effect given in this paper, the absence of magnetic effect on the positively charged carriers indicates that e/m is much smaller or m/e much larger for the positive ions than it is for the negative. I am engaged with some experiments on the effect of the magnetic field on the convection of electricity by positive ions, using very strong magnetic fields produced by a powerful electromagnet kindly lent to me by Professor Ewing. From the results I have already got, it is clear that m/e for the positive ions produced by an incandescent wire must be at least 1000 times the value for the negative ions, and this is only an inferior limit.

The positive and negative ions produced by incandescent solids show the same disproportion of mass as is shown by the positive and negative ions in a vacuum-tube at low pressures. W. Wien (Wied. *Ann.* lxv. p. 440) and Ewers (Wied. *Ann.* lxix. p. 187) have measured the ratio of m/e for the positive ions in such a tube, and found that it is of the same order as the value of m/e in ordinary electrolysis; Ewers has shown that it depends on the metal of which the cathode is made. Thus the carriers of positive electricity at low pressures seem to be ordinary molecules, while the carriers of negative electricity are very much smaller.

Measurement of the Charge on the Ion produced by the Action of Utra-Violet Light on a Zinc Plate.

This charge was determined by the method used by me to measure the charge on the ions produced by the action of Röntgen rays on a gas (Phil. Mag. Dec. 1898); for the details of the method I shall refer to my former paper, and here give only an outline of the principle on which the method is based. Mr. C. T. R. Wilson (Phil. Trans. 1898) discovered that the ions produced by ultra-violet light act like those produced by Röntgen rays, in forming nuclei around which water will condense from dust-free air when the supersaturation exceeds a certain definite value.

Suppose, then, we wish to find the number of ions produced by ultra-violet light in a cubic centimetre of air. We cool the air by a sudden expansion until the supersaturation produced by the cooling is sufficient to form a cloud round the ions: the problem of finding the number of ions per cub. centim. is now reduced to finding the number of drops per cub. centim. in this cloud. We can do this in the following way:—If we know the amount of the expansion we can calculate the amount of water deposited per cub. centim. of the cloud; this water is deposited as drops, and if the drops are of equal size, the number of drops per cub. centim. will be equal to the volume of water per cub. centim. divided by the volume of one of the drops. Hence, if we know the size of the drops, we can calculate the number. The size of the drops in the cloud was determined by observing v, the velocity with which they fall under gravity, and then deducing a, the radius of the drop, by means of the equation

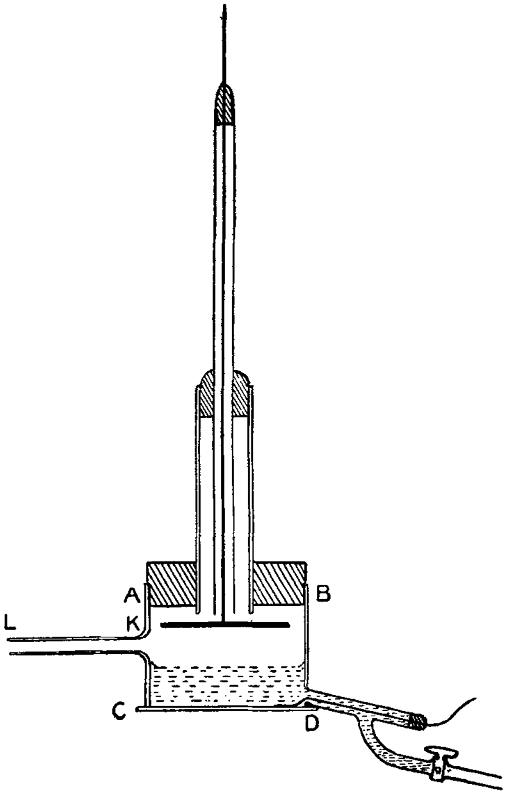
$$v=\frac{2}{9}\frac{ga^2}{\mu},$$

where μ is the coefficient of viscosity of the gas through which the drop falls.

In this way we can determine n the number of ions per cub. centim.: if e is the charge on an ion, v the velocity with which it moves under a known electric force, the quantity of electricity which crosses unit area in unit time under this force is equal to neu. We can determine this quantity if we allow the negative ions to fall on a plate connected with a condenser of known capacity and measure the rate at which the potential falls. We thus determine the product neu, and we already know n; u has been determined by Mr. Rutherford (Proc. Camb. Phil. Soc. ix. p. 401); for air at atmospheric pressure u is proportional to the potential gradient, and when this is one volt per centim., u is 1·5 centim. per second; for hydrogen at atmospheric pressure u is 4·5 centim. per second for the same potential gradient. Hence, as in the known product neu we know n and u, we can deduce the value of e the charge on the ion.

There are some features in the condensation of clouds by ultra-violet light which are not present in the clouds formed by the Röntgen rays. In the first place, the cloud due to the ultra-violet light is only formed in an electric field. When there is no electric field, the ions remain close to the surface of the illuminated plate, and are not diffused through the region in which the cloud has to be formed; to get the negative ions into this region we must electrify the plate negatively; when this is done, expansion produces a cloud. Again, if the ultra-violet light is very strong, Mr. C. T. R. Wilson has shown (Phil. Trans. 1899) that large nuclei are produced in the gas through which the light passes; these are distinct from those produced near a metal plate on which the light falls, and they can produce a cloud with very little supersaturation; these nuclei are not ions, for they do not move in an electric field, and the drops formed round these nuclei ought therefore not to be counted in estimating the number of negative ions. For this reason it is necessary to use ultra-violet light of small intensity, and there are in addition other reasons which make it impossible to work with strong light. I found when working with the ions produced by Röntgen rays, that it was impossible to get good results unless the rays were weak and the clouds therefore thin. If the rays were strong, one expansion was not sufficient to bring down all the ions by the cloud; sometimes as many as five or six expansions were required to remove the ions from the vessel. Another

Fig. 2.



reason why the strong rays do not give good results is that there are slight convection-currents in the vessel after the expansion, for the walls of the vessel are warmer than the gas; this gives rise to convection-currents in the gas, the gas going up the sides and down the middle of the vessel. The velocity of the convection-current is added on to the velocity of the ions due to gravity; and if the velocity of the ions is very small, as it is when the rays are strong and the drops numerous, a very small convection-current will be sufficient to make the actual rate of fall of the drops very different from that of a drop of the same size falling through air at rest. All the reasons are operative in the case of ultra-violet light, and it is only when the intensity of the light is small that I have got consistent results.

The vessel in which the expansion took place is shown in fig. 2. AB is a glass tube about 3·6 cm. in diameter; the base CD is a quartz plate about ·5 cm. thick; on the top of this there is a layer of water in electrical connexion with the earth about 1 cm. in thickness; the illuminated zinc plate was 3·2 cm. in diameter, and was 1·2 cm. above the surface of the water. The ultra-violet light was produced by an arc about ·3 cm. long, between zinc terminals connected with an induction-coil; the arc was about 40 cm. below the lower face of the quartz plate. The space between the zinc plate and the water surface was illuminated by an arc-light so as to allow the rate of fall of the drops to be accurately measured. The tube LK connected this vessel with the apparatus used in the previous experiments; a figure of this is given in the Phil. Mag. Dec. 1898.

To observe the current of electricity through the gas, the illuminated plate was connected with one pair of quadrants of an electrometer, the other pair of quadrants being kept connected with the earth. The capacity C of the system, consisting of the plate, connecting wires and quadrants of the electrometer, was determined. The plate was then charged to a negative potential, and the deflexion of the electrometer-needles observed. The induction-coil was now set in action, and the ultra-violet light allowed to fall on the zinc plate: the deflexion of the electrometer-needle immediately began to decrease; the rate at which it decreased was determined by measuring the diminution of the deflexion in 30 seconds.

Let D be the original deflexion of the electrometer, let this correspond to a potential-difference equal to αD between the plate and the earth. If b is the distance between the zinc plate and the surface of the water, the potential gradient is $\alpha D/b$. If A is the area of the plate, n the number of ions per cub. centim., e the charge on an ion, u_0 the velocity of the ion under unit potential gradient, then the quantity of negative electricity lost by the plate in one second is

$$\mathrm{A}neu_0\alpha\mathrm{D}/b.$$

But the plate is observed to fall in potential by αb per second, and the capacity of the system attached to the plate is C: hence the loss of electricity by the plate per second is

$$\mathrm{C}\alpha d.$$

Equating these two expressions for the loss of electricity, we get

$$\mathrm{A}neu_0\alpha\mathrm{D}/b=\mathrm{C}\alpha d$$

or

$$e=\frac{b}{nu_0}\,\frac{\mathrm{C}}{\mathrm{A}}\,\frac{d}{\mathrm{D}}.$$

Hence knowing b, C, A, and u_0, if we measure n and d/D we can determine e.

To calculate n we begin by finding the volume of water deposited in consequence of the expansion in each cub. centim. of the expansion. In my previous paper I show how this can be determined if we know the ratio of the final to the initial volumes and the temperature before expansion. In the present experiments the final volume was 1·36 times the initial volume, and the temperature before expansion was 18°·5 C. It follows from this that 50×10^{-7} cub. centim. of water were deposited in each cub. centim. of the expansion chamber.

If a is the radius of one of the drops, the volume of a drop is $4\pi a^3/3$, and hence $n'=\dfrac{3\times50\times10^{-7}}{4\pi a^2}$; here n' is the number of ions per cub. centim. of the expanded gas.

If v is the velocity of fall

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

Since for air $\mu=1{\cdot}8\times10^{-4}$, we find

$$a=\frac{v^{\frac{1}{2}}}{1{\cdot}1\times10^{3}},$$

and

$$\frac{4}{3}\pi a^3=3{\cdot}14\,v^{\frac{3}{2}}\times10^{-9},$$

$$n'=\frac{5000}{3{\cdot}14\,v^{\frac{3}{2}}}.$$

This is the number in 1 cub. centim. of the expanded gas; the number in 1 cub. centim. of the gas before expansion is $1{\cdot}36\,n'$. To find n the number of ions we must subtract from $1{\cdot}36\,n'$ the number of drops which are formed when the ultra-violet light does not fall on the plate. With an expansion as large as 1·36, Mr. Wilson has shown that a few drops are always formed in dust-free air, even when free from the influence of Röntgen rays or ultra-violet light. If V be the velocity with which these drops formed in the absence of the light fall, then the number of drops due to these nuclei is

$$\frac{1{\cdot}36\times 5000}{3{\cdot}14\,\mathrm{V}^{\frac{3}{2}}}.$$

Subtracting this from $1{\cdot}36\,n'$, we find

$$n=2{\cdot}07\times 10^{3}\left\{\frac{1}{v^{\frac{3}{2}}}-\frac{1}{\mathrm{V}^{\frac{3}{2}}}\right\}.$$

In making this correction we have assumed that the clouds form round these nuclei even when the negative ions due to the ultra-violet light are present. If the cloud formed more readily about the negative ions than about the nuclei, the ions would rob the nuclei of their water, and we should not need the correction. The following table gives the result of some experiments; in making the observation on the cloud the same potential-difference between the plate and the water was used as when observing the value of d/D: u_0 was determined by Prof. Rutherford as $1{\cdot}5\times 3\times 10^2$, and A was $\pi(1{\cdot}6)^2$ throughout the experiments.

b.	C.	*d*/D.	*v.*	V.	$e\times 10^{10}$.
1·2	62	·0017	·13	·3	7·9
1·2	62	·0019	·11	·3	7·3
·9	50	·0012	·14	·3	5·3
1·2	65	·0035	·08	·3	7·3
1·2	50	·0018	·11	·3	6
1·2	40	·0018	·14	·3	7

The mean value of e is $6{\cdot}8\times 10^{-10}$. The values differ a good deal, but we could not expect a very close agreement unless we could procure an absolutely constant source of ultra-violet light, as these experiments are very dependent on the constancy of the light; since the electrical part of the experiment measures the average intensity of the light over 30 seconds, while the observations on the cloud measure the intensity over an interval of a small fraction of a second.

The value of e found by me previously for the ions produced by Röntgen rays was $6 \cdot 5 \times 10^{-8}$: hence we conclude that e for the ions produced by ultra-violet light is the same as e for the ions produced by the Röntgen rays; and as Mr. Townsend has shown that the charge on these latter ions is the same as the charge on an atom of hydrogen in electrolysis, we arrive at the result previously referred to, that the charge on the ion produced by ultra-violet light is the same as that on the hydrogen ion in ordinary electrolysis.

The experiments just described, taken in conjunction with previous ones on the value of m/e for the cathode rays (J. J. Thomson, Phil. Mag. Oct. 1897), show that in gases at low pressures negative electrification, though it may be produced by very different means, is made up of units each having a charge of electricity of a definite size; the magnitude of this negative charge is about 6×10^{-10} electrostatic units, and is equal to the positive charge carried by the hydrogen atom in the electrolysis of solutions.

In gases at low pressures these units of negative electric charge are always associated with carriers of a definite mass. This mass is exceedingly small, being only about $1 \cdot 4 \times 10^{-3}$ of that of the hydrogen ion, the smallest mass hitherto recognized as capable of a separate existence. The production of negative electrification thus involves the splitting up of an atom, as from a collection of atoms something is detached whose mass is less than that of a single atom. We have not yet data for determining whether the mass of the negative atom is entirely due to its charge. If the charge is e, the apparent mass due to the charge supposed to be collected on a sphere of radius a is $\frac{1}{3}e^2/\mu a$: hence m/e in this case is $e/3\mu a$. Substituting the values of m/e and e found above, we find that a would be of the order 10^{-13} centim.

We have no means yet of knowing whether or not the mass of the negative ion is of electrical origin. We could probably get light on this point by comparing the heat produced by the bombardment by these negatively electrified particles of the inside of a vessel composed of a substance transparent to Röntgen rays, with the heat produced when the vessel was opaque to those rays. If the mass was "mechanical," and not electrical, the heat produced should be same in the two cases. If, on the other hand, the mass were electrical, the heat would be less in the first case than in the second, as part of the energy would escape through the walls.

Hitherto we have been considering only negative electrification; as far as our present knowledge extends positive electrification is never associated with masses as small as those which invariably accompany negative electrification in gases at low pressures. From W. Wien's experiments on the ratio of the mass to the electric charge for the carriers of positive electrification in a highly exhausted vacuum-tube (Wied. *Ann.* lxv. p. 440), it would seem that the masses with which positive electrification is associated are comparable with the masses of ordinary atoms. This is also in accordance with the experiments of Elster and Geitel (Wied. *Ann.* xxxviii. p. 27), which show that when positive ions are produced by an incandescent platinum wire in air they are not affected to anything like the same extent as negative ions produced by an incandescent carbon filament in hydrogen.

It is necessary to point out that the preceding statements as to the masses of the ions are only true when the pressure of the gas is very small, so small that we are able to determine the mass of the carriers before they have made many collisions with the surrounding molecules. When the pressure is too high for this to be the case, the electric charge, whether positive or negative, seems to act as a nucleus around which several molecules collect, just as dust collects round an electrified body, so that we get an aggregate formed whose mass is larger than that of a molecule of a gas.

The experiments on the velocities of the ions produced by Röntgen or uranium rays, by ultra-violet light, in flames or in the arc, show that in gases at pressures comparable with the atmospheric pressure, the electric charges are associated with masses which are probably several times the mass of a molecule of the gas, and enormously greater than the mass of a carrier of negative electrification in a gas at a low pressure.

There are some other phenomena which seem to have a very direct bearing on the nature of the process of ionizing a gas. Thus I have shown (Phil. Mag. Dec. 1898) that when a gas is ionized by Röntgen rays, the charges on the ions are the same whatever the nature of the gas: thus we get the same charges on the ions whether we ionize hydrogen or oxygen. This result has been confirmed by J. S. Townsend ("On the Diffusion of Ions," Phil. Trans. 1899), who used an entirely different method. Again, the ionization of a gas by Röntgen rays is in general an additive property; *i. e.*, the ionization of a compound gas AB, where A and B represent the atoms of two elementary gases, is one half the sum of the ionization of A_2 and B_2 by rays of the same intensity, where

A_2 and B_2 represent diatomic molecules of these gases (Proc. Camb. Phil. Soc. vol. x. p. 9). This result makes it probable that the ionization of a gas in these cases results from the splitting up of the atoms of the gas, rather than from a separation of one atom from the other in a molecule of the gas.

These results, taken in conjunction with the measurements of the mass of the negative ion, suggest that the ionization of a gas consists in the detachment from the atom of a negative ion; this negative ion being the same for all gases, while the mass of the ion is only a small fraction of the mass of an atom of hydrogen.

From what we have seen, this negative ion must be a quantity of fundamental importance in any theory of electrical action; indeed, it seems not improbable that it is the fundamental quantity in terms of which all electrical processes can be expressed. For, as we have seen, its mass and its charge are invariable, independent both of the processes by which the electrification is produced and of the gas from which the ions are set free. It thus possesses the characteristics of being a fundamental conception in electricity; and it seems desirable to adopt some view of electrical action which brings this conception into prominence. These considerations have led me to take as a working hypothesis the following method of regarding the electrification of a gas, or indeed of matter in any state.

I regard the atom as containing a large number of smaller bodies which I will call corpuscles; these corpuscles are equal to each other; the mass of a corpuscle is the mass of the negative ion in a gas at low pressure, *i. e.* about 3×10^{-26} of a gramme. In the normal atom, this assemblage of corpuscles forms a system which is electrically neutral. Though the individual corpuscles behave like negative ions, yet when they are assembled in a neutral atom the negative effect is balanced by something which causes the space through which the corpuscles are spread to act as if it had a charge of positive electricity equal in amount to the sum of the negative charges on the corpuscles. Electrification of a gas I regard as due to the splitting up of some of the atoms of the gas, resulting in the detachment of a corpuscle from some of the atoms. The detached corpuscles behave like negative ions, each carrying a constant negative charge, which we shall call for brevity the unit charge; while the part of the atom left behind behaves like a positive ion with the unit positive charge and a mass large compared with that of the negative ion. On this view, electrification essentially involves the splitting up of the atom, a part of the mass of the atom getting free and becoming detached from the original atom.

A positively electrified atom is an atom which has lost some of its "free mass," and this free mass is to be found along with the corresponding negative charge. Changes in the electrical charge on an atom are due to corpuscles moving from the atom when the positive charge is increased, or to corpuscles moving up to it when the negative charge is increased. Thus when anions and cations are liberated against the electrodes in the electrolysis of solutions, the ion with the positive charge is neutralized by a corpuscle moving from the electrode to the ion, while the ion with the negative charge is neutralized by a corpuscle passing from the ion to the electrode. The corpuscles are the vehicles by which electricity is carried from one atom to another.

We are thus led to the conclusion that the mass of an atom is not invariable: that, for example, if in the molecule of HCl the hydrogen atom has the positive and the chlorine atom the negative charge, then the mass of the hydrogen atom is less than half the mass of the hydrogen molecule H_2; while, on the other hand, the mass of the chlorine atom in the molecule of HCl is greater than half the mass of the chlorine molecule Cl_2.

The amount by which the mass of an atom may vary is proportional to the charge of electricity it can receive; and as we have no evidence that an atom can receive a greater charge than that of its ion in the electrolysis of solutions, and as this charge is equal to the valency of the ion multiplied by the charge on the hydrogen atom, we conclude that the variability of the mass of an atom which can be produced by known processes is proportional to the valency of the atom, and our determination of the mass of the corpuscle shows that this variability is only a small fraction of the mass of the original atom.

In the case of the ionization of a gas by Röntgen or uranium rays, the evidence seems to be in favour of the view that not more than one corpuscle can be detached from any one atom. For if more than one were detached, the remaining part of the atom would have a positive charge greater than the negative charge carried by each of the detached corpuscles. Now the ions, in virtue of their charges, act as nuclei around which drops of water condense when moist dust-free gas is suddenly expanded. If the positive charge were greater than the individual negative ones, the positive ions would be more efficient in producing cloudy condensation than the negative one, and would give a cloud with smaller expansion. As a matter of fact, however, the reverse is the case, as C. T. R. Wilson (Phil. Trans. 1899) has shown that it requires a considerably greater expansion to produce a cloud in dust-free air on positive ions than on negative ones when the ions are produced by Röntgen rays.

Though only a small fraction of the mass of an atom can be detached by any known process, it does not follow that the part left behind does not contain more corpuscles which could be detached by more powerful means than we have hitherto been able to use. For it is evident that it will require a greater expenditure of energy to tear two corpuscles from one atom than to tear two corpuscles one from each of two separate atoms; for when one corpuscle has been torn off from an atom the atom is positively electrified, and it will be more difficult to tear off a second negatively electrified corpuscle from this positively electrified atom, than it was to tear the first from the originally neutral atom. A reason for believing that there are many more corpuscles in the atom than the one or two that can be torn off, is afforded by the Zeeman effect. The ratio of the mass to the charge, as determined by this effect, is of the same order as that we have deduced from our measurements on the free corpuscles; and the charges carried by the moving particles, by which the Zeeman effect is explained, are all negatively electrified. Now, if there were only one or two of these corpuscles in the atom, we should expect that only one or two lines in the spectrum would show the Zeeman effect; for even if the coordinates fixing the position of the moving corpuscles were not "principal coordinates," though there might be a secondary effect on the periods of the other oscillations due to their connexion with these coordinates, yet we should expect this secondary effect to be of quite a different order from the primary one. As, however, there are a considerable number of lines in the spectrum which show Zeeman effects comparable in intensity, we conclude that there are a considerable number of corpuscles in the atom of the substance giving this spectrum.

I have much pleasure in thanking my assistant Mr. E. Everett for the help he has given me in making the experiments described in this paper.

LIX. *On Reflexion and Refraction of Elastic Waves.*

University of Edinburgh,
24th Oct., 1899.

To the Editors of the Philosophical Magazine.

Gentlemen,—The accompanying letter from Prof. T. Gray contains important corrections of some numbers I gave on page 68 of my paper on "Reflexion and Refraction of Elastic Waves" (Phil. Mag. July 1899). As explained in the footnote on page 67, I got part of the information from manuscript notes in Professor Milne's possession. Apparently I misunderstood them and deduced inaccurate conclusions from