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Carriers of negative electricity

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Introductory

In this lecture I wish to give an account of some investigations which have led to the conclusion that the carriers of negative electricity are bodies, which I have called corpuscles, having a mass very much smaller than that of the atom of any known element, and are of the same character from whatever source the negative electricity may be derived.

The first place in which corpuscles were detected was a highly exhausted tube through which an electric discharge was passing. When an electric discharge is sent through a highly exhausted tube, the sides of the tube glow with a vivid green phosphorescence. That this is due to something proceeding in straight lines from the cathode - the electrode where the negative electricity enters the tube - can be shown in the following way (the experiment is one made many years ago by Sir William Crookes): A Maltese cross made of thin mica is placed between the cathode and the walls of the tube. When the discharge is past, the green phosphorescence no longer extends all over the end of the tube, as it did when the cross was absent. There is now a well-defined cross in the phosphorescence at the end of the tube; the mica cross has thrown a shadow and the shape of the shadow proves that the phosphorescence is due to something travelling from the cathode in straight lines, which is stopped by a thin plate of mica. The green phosphorescence is caused by cathode rays and at one time there was a keen controversy as to the nature of these rays. Two views were prevalent: one, which was chiefly supported by English physicists, was that the rays are negatively electrified bodies shot off from the cathode with great velocity; the other view, which was held by the great majority of German physicists, was that the rays are some kind of ethereal vibration or waves.

The arguments in favour of the rays being negatively charged particles are primarily that they are deflected by a magnet in just the same way as moving, negatively electrified particles. We know that such particles, when a magnet is placed near them, are acted upon by a force whose direction is

at right angles to the magnetic force, and also at right angles to the direction in which the particles are moving.

Thus, if the particles are moving horizontally from east to west, and the magnetic force is horizontal from north to south, the force acting on the negatively electrified particles will be vertical and downwards.

When the magnet is placed so that the magnetic force is along the direction in which the particle is moving, the latter will not be affected by the magnet.

The next step in the proof that cathode rays are negatively charged particles was to show that when they are caught in a metal vessel they give up to it a charge of negative electricity. This was first done by Perrin. This experiment was made conclusive by placing the catching vessel out of the path of the rays, and bending them into it by means of a magnet, when the vessel became negatively charged.

Electric deflection of the rays

If the rays are charged with negative electricity they ought to be deflected by an electrified body as well as by a magnet. In the earlier experiments made on this point no such deflection was observed. The reason of this has been shown to be that when cathode rays pass through a gas they make it a conductor of electricity, so that if there is any appreciable quantity of gas in the vessel through which the rays are passing, this gas will become a conductor of electricity and the rays will be surrounded by a conductor which will screen them from the effect of electric force, just as the metal covering of an electroscope screens off all external electric effects.

By exhausting the vacuum tube until there was only an exceedingly small quantity of air left in to be made a conductor, I was able to get rid of this effect and to obtain the electric deflection of the cathode rays. This deflection had a direction which indicated a negative charge on the rays.

Thus, cathode rays are deflected by both magnetic and electric forces, just as negatively electrified particles would be.

Hertz showed, however, that cathode particles possess another property which seemed inconsistent with the idea that they are particles of matter, for he found that they were able to penetrate very thin sheets of metal, e.g. pieces of gold leaf, and produce appreciable luminosity on glass behind them. The idea of particles as large as the molecules of a gas passing through

a solid plate was a somewhat startling one, and this led me to investigate more closely the nature of the particles which form the cathode rays.

The principle of the method used is as follows: When a particle carrying a charge e is moving with velocity v across the lines of force in a magnetic field, placed so that the lines of magnetic force are at right angles to the motion of the particle, then, if H is the magnetic force, the moving particle will be acted on by a force equal to Hev. This force acts in the direction which is at right angles to the magnetic force and to the direction of motion of the particle. If also we have an electric field of force X, the cathode ray will be acted upon by a force Xe. If the electric and magnetic fields are arranged so that they oppose each other, then, when the force Hev due to the magnetic field is adjusted to balance the force due to the electric field Xe, the green patch of phosphorescence due to the cathode rays striking the end of the tube will be undisturbed, and we have

$$Hev = Xe$$

or
$$v = \frac{X}{H}$$

Thus if we measure, as we can do without difficulty, the values of X and H when the rays are not deflected, we can determine the value of v, the velocity of the particles. In a very highly exhausted tube this may be $1/3$ the velocity of light, or about 60,000 miles per second; in tubes not so highly exhausted it may not be more than 5,000 miles per second, but in all cases when the cathode rays are produced in tubes their velocity is much greater than the velocity of any other moving body with which we are acquainted. It is, for example, many thousand times the average velocity with which the molecules of hydrogen are moving at ordinary temperatures, or indeed at any temperature yet realized.

Determination of e/m

Having found the velocity of the rays, let us now subject them to the action of the electric field alone. Then the particles forming the rays are acted upon by a constant force and the problem is like that of a bullet projected horizontally with a velocity v and falling under gravity. We know that in time

t, the bullet will fall a depth equal to *1/2gt²,* where g is the acceleration due to gravity. In our case the acceleration due to the electric field is equal to *Xe/m,* where *m* is the mass of the particle. The time *t = l/v,* where *l* is the length of path, and *v* the velocity of projection.

Thus the displacement of the patch of phosphorescence where the rays strike the glass is equal to

$$\frac{1}{2} \frac{Xe}{m} \cdot \frac{l^2}{v^2}$$

We can easily measure this displacement *d,* and we can thus find *e/m* from the equation

$$\frac{e}{m} = \frac{2d}{X} \cdot \frac{v^2}{l^2}$$

The results of the determinations of the values of *e/m* made by this method are very interesting, for it is found that, however the cathode rays are produced, we always get the same value of *e/m* for all the particles in the rays. We may, for example, by altering the shape of the discharge tube and the pressure of the gas in the tube, produce great changes in the velocity of the particles, but unless the velocity of the particles becomes so great that they are moving nearly as fast as light, when other considerations have to be taken into account, the value of *e/m* is constant. The value of *e/m* is not merely independent of the velocity. What is even more remarkable is that it is independent of the kind of electrodes we use and also of the kind of gas in the tube. The particles which form the cathode rays must come either from the gas in the tube or from the electrodes; we may, however, use any kind of substance we please for the electrodes and fill the tube with gas of any kind and yet the value of *e/m* will remain unaltered.

This constant value, when we measure *e/m* in the c.g.s. system of magnetic units, is equal to about 1.7 x 10⁷. If we compare this with the value of the ratio of the mass to the charge of electricity carried by any system previously known, we find that it is of quite a different order of magnitude. Before the cathode rays were investigated, the charged atom of hydrogen met with in the electrolysis of liquids was the system which had the greatest known value of *e/m*, and in this case the value is only 10⁴, hence for the corpuscle in the cathode rays the value of *e/m* is 1,700 times the value of the correspond-

ing quantity for the charged hydrogen atom. This discrepancy must arise in one or other of two ways: either the mass of the corpuscle must be very small compared with that of the atom of hydrogen, which until quite recently was the smallest mass recognized in physics, or else the charge on the corpuscle must be very much greater than that on the hydrogen atom. Now it has been shown by a method which I shall shortly describe, that the electric charge is practically the same in the two cases; hence we are driven to the conclusion that the mass of the corpuscle is only about $1/1,700$ of that of the hydrogen atom. Thus the atom is not the ultimate limit to the subdivision of matter; we may go further and get to the corpuscle, and at this stage the corpuscle is the same from whatever source it may be derived.

Corpuscles very widely distributed

It is not only from what may be regarded as a somewhat artificial and sophisticated source, viz. cathode rays, that we can obtain corpuscles. When once they had been discovered, it was found that they are of very general occurrence. They are given out by metals when raised to a red heat; indeed any substance when heated gives out corpuscles to some extent. We can detect the emission of them from some substances, such as rubidium and the alloy of sodium and potassium, even when they are cold; and it is perhaps allowable to suppose that there is some emission by all substances, though our instruments are not at present sufficiently delicate to detect it unless it is unusually large.

Corpuscles are also given out by metals and other bodies, but especially by the alkali metals, when these are exposed to light.

They are being continually given out in large quantities and with very great velocities by radioactive substances such as uranium and radium; they are produced in large quantities when salts are put into flames, and there is good reason to suppose that corpuscles reach us from the sun.

The corpuscle is thus very widely distributed, but wherever it is found, it preserves its individuality, e/m being always equal to a certain constant value.

The corpuscle appear to form a part of all kinds of matter under the most diverse conditions; it seems natural therefore to regard it as one of the bricks of which atoms are built up.

Magnitude of the electric charge carried by the corpuscle

I shall now return to the proof that the very large value of *e/m* for the corpuscle, as compared with that for the atom of hydrogen, is due to the smallness of *m* the mass, and not to the greatness of *e* the charge. We can do this by actually measuring the value of *e*, availing ourselves for this purpose of a discovery by C. T. R. Wilson, that a charged particle acts as a nucleus round which water vapour condenses and forms drops of water. If we have air saturated with water vapour and cool it, so that it would be supersaturated if there were no deposition of moisture, we know that if any dust is present, the particles of dust act as nuclei round which the water condenses and we get the familiar phenomena of fog and rain. If the air is quite dust-free, we can, however, cool it very considerably without any deposition of moisture taking place. If there is no dust, C. T. R. Wilson has shown that the cloud does not form until the temperature has been lowered to such a point that the supersaturation is about eightfold. When however this temperature is reached, a thick fog forms even in dust-free air.

When charged particles are present in the gas, Wilson showed that a much smaller amount of cooling is sufficient to produce the fog, a fourfold supersaturation being all that is required when the charged particles are those which occur in a gas when it is in a state in which it conducts electricity. Each of the charged particles becomes the centre round which a drop of water forms; the drops form a cloud, and thus the charged particles, however small to begin with, now become visible and can be observed.

The effect of the charged particles on the formation of a cloud can be shown very distinctly by the following experiment:

A vessel which is in contact with water is saturated with moisture at the temperature of the room. This vessel is in communication with a cylinder in which a large piston slides up and down. The piston to begin with is at the top of its travel; by suddenly exhausting the air from below the piston, the pressure of the air above it will force it down with great rapidity, and the air in the vessel will expand very quickly. When, however, air expands, it gets cool; thus the air in the vessel previously saturated is now supersaturated. If there is no dust present, no deposition of moisture will take place, unless the air is cooled to such a low temperature that the amount of moisture required to saturate it is only about 1/8 of that actually present.

Now the amount of cooling, and therefore of supersaturation, depends upon the travel of the piston; the greater the travel the greater the cooling.

Suppose the travel is regulated so that the supersaturation is less than eight-fold and greater than fourfold. We now free the air from dust by forming cloud after cloud in the dusty air; as the clouds fall they carry the dust down with them, just as in nature the air is cleared by showers. We find at last that when we make the expansion no cloud is visible.

The gas is now made in a conducting state by bringing a little radium near the vessel; this fills the gas with large quantities of both positively and negatively electrified particles. On making the expansion now an exceedingly dense cloud is formed. That this is due to the electrification in the gas can be shown by the following experiment:

Along the inside walls of the vessel we have two vertical insulated plates which can be electrified. If these plates are charged, they will drag the electrified particles out of the gas as fast as they are formed, so that in this way we can get rid of, or at any rate largely reduce, the number of electrified particles in the gas. If the expansion is now made with the plates charged before bringing up the radium, there is only a very small cloud formed.

We can use the drops to find the charge on the particles, for when we know the travel of the piston, we can deduce the amount of supersaturation, and hence the amount of water deposited when the cloud forms. The water is deposited in the form of a number of small drops all of the same size; thus the number of drops will be the volume of the water deposited divided by the volume of one of the drops. Hence, if we find the volume of one of the drops, we can find the number of drops which are formed round the charged particles. If the particles are not too numerous, each will have a drop round it, and we can thus find the number of electrified particles.

From the rate at which the drops slowly fall we can determine their size. In consequence of the viscosity or friction of the air small bodies do not fall with a constantly accelerated velocity, but soon reach a speed which remains uniform for the rest of the fall; the smaller the body the slower this speed. Sir George Stokes has shown that v, the speed at which a drop of rain falls, is given by the formula

$$v = \frac{2}{9} \times \frac{g\, a^2}{\mu}$$

where a is the radius of the drop, g the acceleration due to gravity, and μ the coefficient of viscosity of the air.

If we substitute the values g and μ, we get

$$v = 1.28 \times 10^6 \cdot a^2$$

Hence if we measure *v* we can determine *a,* the radius of the drop.

We can in this way find the volume of a drop, and may therefore, as explained above, calculate the number of drops and therefore the number of electrified particles.

It is a simple matter to find by electrical methods the total quantity of electricity on these particles; and hence, as we know the number of particles, we can deduce at once the charge on each particle.

This was the method by which I first determined the charge on the particle; H. A. Wilson has since used a simpler method founded on the following principles: C. T. R. Wilson has shown that the drops of water condense more easily on negatively electrified particles than on positively electrified ones. Thus, by adjusting the expansion, it is possible to get drops of water round the negative particles and not round the positive; with this expansion, therefore, all the drops are negatively electrified. The size of these drops and therefore their weight can, as before, be determined by measuring the speed at which they fall under gravity. Suppose now, that we hold above the drops a positively electrified body: then, since the drops are negatively electrified, they will be attracted towards the positive electricity, and thus the downward force on the drops will be diminished and they will not fall so rapidly as they did when free from electrical attraction. If we adjust the electrical attraction so that the upward force on each drop is equal to the weight of the drop, the drops will not fall at all, but will, like Mahornet's coffin, remain suspended between heaven and earth. If then we adjust the electrical force until the drops are in equilibrium and neither fall nor rise, we know that the upward force on each drop is equal to the weight of the drop, which we have already determined by measuring the rate of fall when the drop was not exposed to any electrical force. If X is the electrical force, *e* the charge on the drop, and *w* its weight, we have, when there is equilibrium,

$$X \, e \, = \, w$$

Since X can easily be measured and *w* is known, we can use this relation to determine *e*, the charge on the drop. The value of *e*, found by these methods, is 3.0×10^{-10} electrostatic units, or 10^{-20} electromagnetic units. This value is the same as that of the charge carried by a hydrogen atom in the electrolysis of dilute solutions, an approximate value of which has been long known.

It might be objected that the charge measured in the preceding experi-

ments is the charge on a molecule or collection of molecules of the gas, and not the charge on a corpuscle.

This objection does not, however, apply to another form in which I tried the experiment, where the charges on the corpuscles were got, not by exposing the gas to the effects of radium, but by allowing ultraviolet light to fall on a metal plate in contact with the gas. In this case, as experiments made in a very high vacuum show, the electrification, which is entirely negative, escapes from the metal in the form of corpuscles. When a gas is present, the corpuscles strike against the molecules of the gas and stick to them.

Thus, though it is the molecules which are charged, the charge on a molecule is equal to the charge on a corpuscle, and when we determine the charge on the molecules by the methods I have just described, we determine the charge carried by the corpuscle.

The value of the charge when the electrification is produced by ultraviolet light is the same as when the electrification is produced by radium.

We have just seen that e, the charge on the corpuscle, is in electromagnetic units equal to 10^{-20}, and we have previously found that e/m, m being the mass of a corpuscle, is equal to 1.7×10^{7}, hence $m = 6 \times 10^{-28}$ grammes.

We can realize more easily what this means if we express the mass of the corpuscle in terms of the mass of the atom of hydrogen.

We have seen that for the corpuscle $e/m = 1.7 \times 10^{7}$. If E is the charge carried by an atom of hydrogen in the electrolysis of dilute solutions, and M is the mass of the hydrogen atom, $E/M = 10^{4}$; hence $e/m = 1,700\ E/M$.

We have already stated that the value of e found by the preceding methods agrees well with the value of E which has long been approximately known. Townsend has used a method in which the value of e/E is directly measured, and has shown in this way also that e equal to E. Hence, since $e/m = 1,700\ E/M$, we have $M = 1,700\ m$, i.e. the mass of a corpuscle is only about $1/1,700$ part of the mass of the hydrogen atom.

In all known cases in which negative electricity occurs in gases at very low pressures, it occurs in the form of corpuscles, small bodies with an invariable charge and mass. The case is entirely different with positive electricity.