Physics 1906

JOSEPH JOHN THOMSON

<< in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases>>

Physics 1906

Presentation Speech by Professor]. P. Klason, President of the Royal Swedish Academy of Sciences

Your Majesty, Your Royal Highnesses, Ladies and Gentlemen.

Every day that passes witnesses electricity obtaining an ever-increasing importance in practical life. The conceptions, which a few decades ago were the subject of investigation in the quiet studies or laboratories of sundry learned men, have by this time become the property of the public at large, who will soon be as familiar with them as with their ordinary weights and measures. Still greater however are the revolutions brought about by electricians' labours in the sphere of science. Immediately after Örsted's epochmaking discovery of the influence of the electric current on a magnetic needle(1820), Ampere, the ingenious French investigator, promulgated a theory explaining magnetic phenomena as results of electrical agencies. The investigations of Maxwell, the brilliantly gifted Scotch physicist (1873), were still more far-reaching in their effect, for by them the phenomenon of light was proved to be dependent upon electromagnetic undulatory movements in the ether. There is reason to believe that the grand discoveries of the last few years respecting the discharge of electricity through gases will prove to be of equally great, or perhaps still greater, importance, throwing as they do a great deal of light upon our conception of matter. In this domain Professor J. J. Thomson of Cambridge, this year's Prize-winner in Physics, has made most valuable contributions through his investigations and researches, which he has assiduously pursued for many years past.

By Faraday's great discovery in the year 1834 it had been shown that every atom carries an electric charge as large as that of the atom of hydrogen gas, or else a simple multiple of it corresponding to the chemical valency of the atom. It was, then, natural to speak, with the immortal Helmholtz, of an elementary charge or, as it is also called, an atom of electricity, as the quantity of electricity inherent in an atom of hydrogen gas in its chemical combinations.

Faraday's law may be expressed thus, that a gram of hydrogen, or a quantity equivalent thereto of some other chemical element, carries an electric charge of $28,950 \times 10^{10}$ electrostatic units. Now if we only knew how

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many hydrogen atoms there are in a gram, we could calculate how large a charge there is in every hydrogen atom. The kinetic gas-theory, a field of investigation as popular as any among the scientists of the century recently ended, is based upon the assumption that the gases consist of freely moving molecules, the impact of which on the walls of the encompassing vessel is recognizable as the pressure of the gas. From this the velocity of the gas molecules could be calculated with great accuracy. From the velocity with which one gas diffuses in another, and from other closely allied phenomena, it was further possible to calculate the volume of space occupied by the molecules, and by that means the investigator was enabled to form an idea of the mass of the molecules and consequently of the number of molecules to be found in one gram of a chemical substance, such as, e.g. hydrogen. The figures thus obtained could not however lay claim to any great amount of accuracy and were regarded by many scientists as purely conjectural. If it had been possible to calculate the number of molecules in a drop of water by the aid of an exceedingly powerful microscope, the case would of course have been quite otherwise. But there was not the remotest hope of the investigator ever being successful in doing that, and thus the existence of the molecules was regarded as very problematical. If from the figures quoted by the champions of the kinetic gas-theory as the most probable ones for the sizes of molecules and atoms we calculate how large a quantity of electricity is carried by one hydrogen atom, we arrive at the conclusion that the atom charge lies between 1.3 x 10⁻¹⁰ and 6.1 x 10⁻¹⁰ electrostatic units.

What no one regarded as probable has however been achieved by J.J. Thomson by devious methods. Richard von Helmholtz found out, as long ago as 1887, that electrically charged small particles possess the remarkable property of condensing steam around them. J. J. Thomson and his pupil C. T.R. Wilson took up the study of this phenomenon. By the aid of Röntgen rays they procured some electrically charged small particles in air. Thomson assumes that each of those particles carries an electrical unit charge. By electrical measurements he was able to determine how great the electric charge was in a given quantity of air. Then, by means of a sudden expansion of the air, which was saturated with steam, he effected a condensation of the steam on the electrically charged small particles, the size of which he could calculate from the velocity with which they sank. Now as he knew the amount of water condensed and the size of each drop, it was not difficult to calculate the number of drops. That number was the same as that of the electrically charged small particles. Having before determined the total quan-

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tity of electricity in the vessel, he could easily reckon out what quantity there was in each drop or, previously, in every small particle, that is to say the atomic charge. That was thus found to be 3.4×10^{-10} electrostatic units. This value is very close to the mean of the values previously obtained by the kinetic gas-theory, rendering the correctness of these different measurements and the accuracy of the reasoning employed in their determination in a very high degree probable.

Now, even if Thomson has not actually beheld the atoms, he has nevertheless achieved work commensurable therewith, by having directly observed the quantity of electricity carried by each atom. By the aid of this observation the number has been determined of the molecules in a cubic centimetre of gas at a temperature of zero and under the pressure of one atmosphere; that is to say, there has been thereby calculated what is perhaps the most fundamental natural constant in the material world. That number amounts to not less than forty trillions (40 x 10¹⁸). By means of a series of exceedingly ingenious experiments, Professor Thomson, aided by his numerous pupils, has determined the most important properties (such as mass and velocity under the influence of a given force), of these electrically charged small particles, which are produced in gases by various methods, e.g. by Röntgen rays, Becquerel rays, ultraviolet light, needle-point discharge and incandescent metals. The most remarkable of these electrically charged small particles are those constituting the cathode rays in highly rarefied gases. These small particles are called electrons and have been made the object of very thorough-going researches on the part of a large number ofinvestigators, foremost of whom are Lenard, last year's Nobel Prize winner in Physics, and J.J.Thomson. These small particles are to be met with also in the so-called β-rays, emitted by certain radioactive substances. Assuming, on the basis of Thomson's above-mentioned work, that they carry the negative unit charge, we are led to the result that they possess about a thousand times less mass than the least atoms hitherto known, viz. the atoms of hydrogen gas.

On the other hand, the least *positively* charged small particles we know are, according to Thomson's, Wien's and other investigators' calculations, of the same order in mass as ordinary atoms. Now, seeing that all substances yet examined are capable of giving off negatively charged electrons, Thomson was led by these circumstances to assume that the negative charge in the electrons has a real existence, whereas the charge of the positive small particles arises from a neutral atom losing one or more negative electrons with

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their charges. Thomson has herewith given an actual physical import to the view put forward in 1747 by Benjamin Franklin that there is only one kind of electricity, a view eagerly championed too by Edlund. The actually existing electricity is negative electricity, according to Thomson.

As early as 1892 Thomson had shown that a charged body moving forward is thereby in possession of an electromagnetic energy, which produces the effect of the mass of the body being increased. From experiments carried out by Kaufmann regarding the velocity of β -rays from radium, Thomson concluded that the negative electrons do not possess any real, but only an apparent, mass due to their electric charge.

It might now be considered reasonable to assume that all matter is built up of negative electrons, and that consequently mass in matter was apparent and really depended on the effect of electric forces. An experiment of very great interest has moreover been made in this direction by Thomson, but his investigations of most recent date in the present year(1906) seem to intimate that only about a thousandth part of the material is apparent and due to electric forces.

Professor Thomson. As you are aware, the Royal Swedish Academy of Sciences has decided to award you the Nobel Prize in Physics for this year.

I am at a loss to explain how it is, but somehow or another the contemplation of the work you have achieved has revived in my mind a passage in the famous essay on Socrates by Xenophon, a work which you too no doubt perused in your youth. The author tells us that every time conversation turned upon the elements of the Earth, Socrates would say <<of these matters we know nothing>>. Will the sagacity which Socrates displayed in this answer and which has been approved by all ages up to and including our own, continue to be acknowledged as the conclusion of the whole matter? Who shall say? One thing we all know, and that is, that every great period of Natural Philosophy has evolved elements of its own, and furthermore we seem to feel as though we might be at the threshold of a new such period with new elements.

In the name and on behalf of our Academy I congratulate you upon having bestowed upon the world some of the main works which are enabling the natural philosopher of our time to take up new enquiries in new directions. You have thus been worthily treading in the footsteps of your great and renowned compatriots, Faraday and Maxwell, men who set to the world of science the highest and noblest examples.

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Carriers of negative electricity

Nobel Lecture, December 11, 1906

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

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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 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

$$Hev = Xe$$
$$v = \frac{X}{H}$$

or

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 $1/2gt^2$, 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

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

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 10^7 . 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 10^4 , hence for the corpuscle in the cathode rays the value of e/m is 1,700 times the value of the correspond-

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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.

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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 dustfree, 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 in 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 super-saturated. 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 eightfold 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 *m* the coefficient of viscosity of the air.

If we substitute the values g and μ , we get

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

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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 wits 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.

Biography

John Joseph Thomson was born in Cheetham Hill, a suburb of Manchester on December 18, 1856. He enrolled at Owens College, Manchester in 1870 and in 1876 entered Trinity College, Cambridge as a minor scholar. He became a Fellow of Trinity College in 1880, when he was Second Wrangler and Second Smith's Prizeman, and he remained a member of the College for the rest of his life, becoming Lecturer in 1883 and Master in 1918. He was Cavendish Professor of Experimental Physics at Cambridge, where he succeeded Lord Rayleigh, from 1884 to 1918 and Honorary Professor of Physics, Cambridge and Royal Institution, London.

Thomson's early interest in atomic structure was reflected in his *Treatise on the Motion of Vortex Rings* which won him the Adams Prize in 1884. His *Application of Dynamics to Physics and Chemistry* appeared in 1886 and in 1892 he had *his Notes on Recent Researches in Electricity and Magnetism* published. This latter work covered results obtained subsequent to the appearance of James Clerk Maxwell's famous <<Treatise>> and it is often referred to as <<the third volume of Maxwell>>. Thomson co-operated with Professor J. H. Poynting in a four-volume textbook of physics, *Properties of Matter* and in 1895 he produced *Elements of the Mathematical Theory of Electricity and Magnetism*, the 5th edition of which appeared in 1921.

In 1896, Thomson visited America to give a course of four lectures, which summarised his current researches, at Princeton. These lectures were subsequently published as *Discharge of Electricity through Gases* (1897). On his return from America, he achieved the most brilliant work of his life-an original study of cathode rays culminating in the discovery of the electron, which was announced during the course of his evening lecture to the Royal Institution on Friday, April *30*, 1897. His book, *Conduction of Electricity through Gases*, published in 1903 was described by Lord Rayleigh as a review of <<Thomson's great days at the Cavendish Laboratory>>. A later edition, written in collaboration with his son, George, appeared in two volumes (1928 a n d 1 9 3 3).

Thomson returned to America in 1904 to deliver six lectures on electricity

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and matter at Yale University. They contained some important suggestions as to the structure of the atom. He discovered a method for separating different kinds of atoms and molecules by the use of positive rays, an idea developed by Aston, Dempster and others towards the discovery of many isotopes. In addition to those just mentioned, he wrote the books, *The Structure of Light* (1907), *The Corpuscular Theory of Mutter* (1907), *Rays of Positive Electricity* (1913), *The Electron in Chemistry* (1923) and his autobiography *Recollections and Reflections* (1936), among many other publications.

Thomson, a recipient of the Order of Merit, was knighted in 1908. He was elected Fellow of the Royal Society in 1884 and was President during 1916-1920: he received the Royal and Hughes Medals in 1894 and 1902 and the Copley Medal in 1914. He was awarded the Hodgkins Medal (Smithsonian Institute, Washington) in 1902; the Franklin Medal and Scott Medal (Philadelphia) 1923; the Mascart Medal (Paris) 1927; the Dalton Medal (Manchester) 1931; and the Faraday Medal (Institute of Civil Engineers) in 1938. He was President of the British Association in 1909 (and of Section A in 1896 and 1931) and he held honorary doctorate degrees from the Universities of Oxford, Dublin, London, Victoria, Columbia, Cambridge, Durham, Birmingham, Göttingen, Leeds, Oslo, Sorbonne, Edinburgh, Reading, Princeton, Glasgow, Johns Hopkins, Aberdeen, Athens, Cracow and Philadelphia.

In 1890, he married Rose Elisabeth, daughter of Sir George E. Paget, K.C.B. They had one son, now Sir George Paget Thomson, Emeritus Professor of Physics at London University, who was awarded the Nobel Prize for Physics in 1937, and one daughter.

Sir Joseph Thomson died on August 30, 1940.