GREAT EXPERIMENTS IN PHYSICS
"Firsthand Accounts from
Galileo to Einstein."

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J. J. Thomson

1856-1940

The Electron

NEW DISCOVERIES in science often lead to developments in the most unexpected quarters. We have seen how Roentgen's discovery of x-rays led Becquerel to the investigations from which he chanced upon his discovery of radioactivity. The discovery of x-rays led as well to increased activity in the field of gas discharges. The atomic theory of matter was, by that time, firmly established on the strength of chemical evidence and the kinetic theory of gases. The electrical nature of matter was also readily apparent. But the actual connection between electrical and atomic properties was not clearly recognized. No doubt those who investigated the passage of electricity through gases believed that their studies might provide the essential link between these phenomena. At least this was the goal that induced J. J. Thomson to undertake research in gas discharges during the last decade of the nineteenth century. There were others who preceded him, notably J. W. Hittorf (1824–1914), Sir William Crookes (1832–1919), Eugen Goldstein (1850–1930), and Jean Baptiste Perrin (1870–1942), but their investigations added chiefly to the qualitative aspects of gas discharge phenomena.

The technique was generally the same in each case; a glass tube with platinum electrodes was gradually evacuated while a (large) potential difference was applied between the electrodes. The visible discharge was then studied as a function of pressure, electric field, and nature of the gas. There were several significant advances prior to the discovery of x-rays. It was known, for example, that in these discharges a radiation emanated from the cathode or negative electrode which exhibited certain interesting properties. Perhaps the most significant of these was the green fluorescence that was produced in the glass walls wherever the radiation fell upon them. In 1869 Hittorf showed the rectilinear propagation of the radiation by placing

obstacles between the cathode and glass walls and showing that "optical" shadows were formed. This was confirmed several years later by Goldstein, who introduced the name *cathode rays*, and who held, in common with many of his colleagues, that the radiation was a wave phenomenon, similar to light. On the other hand, Crookes, who showed that the radiation could be deflected by a magnetic field, and Perrin, who found that an insulated conductor assumed a negative charge when cathode rays fell upon it, believed the radiation to be corpuscular. A spirited controversy continued for many years until Thomson proved conclusively that the radiation consisted of material particles originating in the vicinity of the cathode.

The discovery of x-rays contributed indirectly but significantly to Thomson's solution of the problem. When Roentgen showed that x-rays rendered the air conducting, Thomson saw in this a means of investigating the mechanism of conduction in gases, from which he found that the currents were carried by positive and negative *ions*, such as would be expected if the x-rays disrupted the molecules of gas. Proceeding from these observations Thomson had the necessary insight to devise telling experiments on the electric discharges in rarefied gases, and from these to identify the electron as the unit of electric charge.

Joseph J. Thomson was born near Manchester, England, on December 18, 1856, the son of a publisher and bookseller. As he recollected when writing his autobiography,

> . . . both time and place were fortunate, for the period between now and then has been one of the most eventful in the history of the world. From the beginning to the end, and especially in the latter half, there has been a quick succession of one stupendous event after another. Monarchies have fallen, and have been replaced by Republics and Dictatorships. Free trade, which as a Manchester man I naturally regarded for long as essential to the prosperity of the country, has gone too. . . . When I was a boy there were no bicycles, no motor cars, no aeroplanes, no electric light, no telephones, no wireless, no gramophones, no electrical engineering, no x-ray photographs, no cinemas, and no germs, at least none recognized by the doctors.[1]

Among his contemporaries were Hertz, Roentgen, and Becquerel, each of whom made substantial contributions to the *modern age of physics*, and who, like Thomson, were awarded Nobel prizes for their extraordinary grasp and elucidation of physical phenomena.

Thomson was educated at a private school until he was fourteen, when he entered Owens College, a small school in Manchester which had a great

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[1] J. J. Thomson, *Recollections and Reflections* (London: Macmillan, 1937), p. 1.

influence on his choice of career. He had intended to be an engineer, which in those days required an apprenticeship, and while waiting for an opening at the particular company to which he had applied, it was decided that he should attend the local college. There he developed an interest in pure science, and in 1876 entered Trinity College, Cambridge, on a small scholarship. He achieved an outstanding record at Trinity, where, on the basis of a thesis on the transformation of energy, he was elected a fellow in 1880. In the following year Thomson published the first of many papers that were to show his deep insight into physical problems. This was a theoretical paper (*Phil. Mag.*, vol. xi) on the inertia of electric charge, a study that proved of great value to him in his subsequent experimental work.

In 1882 Thomson was appointed a lecturer in mathematics at Trinity, and in the following year became a university lecturer. In 1894 he succeeded Lord Rayleigh as Cavendish professor of experimental physics. For some time prior to this he had been investigating the properties of electrical discharges in gases, but it was not until 1895 that he found himself on the right track and in 1897 he discovered the electron. His discovery immediately opened wide avenues for further study; the electron had to be fitted into the scheme of things. The atomic theory of matter, as well as older branches of physics such as physical optics, electricity, and magnetism had to be re-examined in the light of the new discovery. In all this Thomson played an active and major role. He pioneered the field of mass spectroscopy and discovered *isotopes*. He calculated the scattering of x-rays by the electrons bound to atoms, from which it appeared that the number of electrons in a heavy atom was roughly one half its atomic weight. All this contributed greatly to the gradual evolution of our modern theories of atomic and nuclear structure.

Thomson was president of the Royal Society from 1915 to 1920, during the war years, and was heavily engaged at the same time in defense activities for various government agencies. In 1918 he became master of Trinity College, but the Cavendish Laboratory remained his primary interest throughout his long and active life. He had been instrumental in building there one of the greatest research laboratories in the world, and to it he returned at every opportunity. He was appointed professor of natural philosophy at the Royal Institution in 1905, received the Nobel prize in 1906, and was knighted two years later. He resigned his chair at the Cavendish Laboratory and the Royal Institution in 1919 and 1920 respectively, but until his death in 1940 continued his duties as master of Trinity. The honors that came to him are too numerous to mention. He received all that one might imagine could be awarded a scientist; even so, they could not begin to measure his contributions to science.

The extract which follows is taken from his paper on cathode rays (*Philosophical Magazine*, vol. 44, Series 5, 1897, page 293), containing his account of the discovery of the electron.

Thomson's Experiment

The experiments* discussed in this paper were undertaken in the hope of gaining some information as to the nature of the cathode rays. The most diverse opinions are held as to these rays; according to the almost unanimous opinion of German physicists they are due to some process in the ether to which—inasmuch as in a uniform magnetic field their course is circular and not rectilinear—no phenomenon hitherto observed is analogous:■ another view of these rays is that, so far from being wholly ethereal, they are in fact wholly material, and that they mark the paths of particles of matter charged with negative electricity. It would seem at first sight that it ought not to be difficult to discriminate between views so different, yet experience shows that this is not the case, as amongst the physicists who have most deeply studied the subject can be found supporters of either theory.

It appears that opinion on the nature of cathode rays was divided almost along national lines, most of those holding the view that it was a wave phenomenon being from the German school, while the adherents to the corpuscular view were, like Thomson, English. The division stemmed from traditions in science in these two countries rather than differences in political thought.

The electrified-particle theory has for purposes of research a great advantage over the ethereal theory, since it is definite and its consequences can be predicted; with the etherial theory it is impossible to predict what will happen under any given circumstances, as on this theory we are dealing with hitherto unobserved phenomena in the ether, of whose laws we are ignorant.

The following experiments were made to test some of the consequences of the electrified-particle theory.

CHARGE CARRIED BY THE CATHODE RAYS

If these rays are negatively electrified particles, then when they enter an enclosure they ought to carry into it a charge of negative electricity. This has been proved to be the case by Perrin,■ who placed in front of a plane cathode two coaxial metallic cylinders which were insulated from

Comptes Rendus, vol. 121 (1895), page 1130.

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* Some of these experiments have already been described in a paper read before the Cambridge Philosophical Society (*Proceedings*, vol. ix, 1897); and in a Friday Evening Discourse at the Royal Institution ("Electrician," May 21, 1897).

each other: the outer of these cylinders was connected with the earth, the inner with a gold-leaf electroscope. These cylinders were closed except for two small holes, one in each cylinder, placed so that the cathode rays could pass through them into the inside of the inner cylinder. Perrin found that when the rays passed into the inner cylinder the electroscope received a charge of negative electricity, while no charge went to the electroscope when the rays were deflected by a magnet so as no longer to pass through the hole.

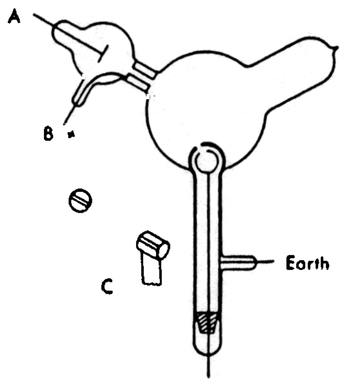


FIG. 1

This experiment proves that something charged with negative electricity is shot off from the cathode, traveling at right angles to it, and that this something is deflected by a magnet; it is open, however, to the objection that it does not prove that the cause of the electrification in the electroscope has anything to do with the cathode rays. Now the supporters of the ethereal theory do not deny that electrified particles are shot off from the cathode; they deny, however, that these charged particles have any more to do with the cathode rays than a rifle ball has with the flash when a rifle is fired. I have therefore repeated Perrin's experiment in a form which is not open to this objection. The arrangement used was as follows: Two coaxial cylinders (Fig. 1) with slits in them are placed in a bulb connected with the discharge tube; the cathode rays from the cathode *A* pass into the bulb through a slit in a metal plug fitted into the neck of the tube; this plug is connected with the anode and is put to earth. The cathode rays thus do not fall upon the cylinders unless they are deflected by a magnet.■ The outer cylinder is connected with the earth, the inner with the electrometer. When the cathode rays (whose path was traced by the phosphorescence on the glass) did not fall on the slit, the electrical charge sent to the electrometer when the induction coil producing the rays was set in action was small and irregular;■ when, however, the rays were bent by a magnet so as to fall on the slit there was a large charge of negative electricity sent to the electrometer. I was surprised at the magnitude of the charge; on some occasions enough negative electricity went through the narrow slit into the inner cylinder in one second to alter the potential of a capacity of 1.5 microfarads by 20 volts.■ If the rays were so much bent by the magnet that they overshot the slits in the cylinder, the charge passing into the cylinder fell again to a very small fraction of its value when the aim was true. Thus this experiment shows that however we twist and deflect the cathode rays by magnetic forces, the negative electrification follows the same path as the rays, and that this negative electrification is indissolubly connected with the cathode rays.

The objection to Perrin's experiment stemmed from the fact that the anode of his discharge tube served also as the outer cylinder. Thus, deflecting the charged particles away proved nothing, according to the supporters of the wave picture.

Generally, several thousand volts were required to initiate such discharges; hence the use of an induction coil.

This corresponds to a current of 30 microamperes.

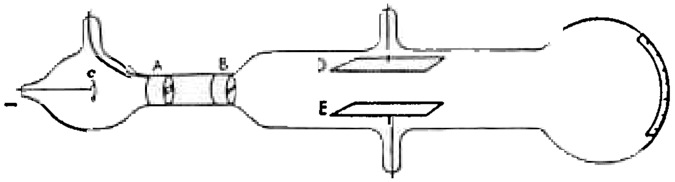
When the rays are turned by the magnet so as to pass through the slit into the inner cylinder, the deflection of the electrometer connected with this cylinder increases up to a certain value, and then remains stationary although the rays continue to pour into the cylinder. This is due to the fact that the gas in the bulb becomes a conductor of electricity when the cathode rays pass through it, and thus, though the inner cylinder is perfectly insulated when the rays are not passing, yet as soon as the rays pass through the bulb the air between the inner cylinder and the outer one becomes a conductor, and the electricity escapes from the inner cylinder to the earth. Thus the charge within the inner cylinder does not go on continually increasing; the cylinder settles down into a state of equilibrium in which the rate at which it gains negative electricity from the rays is equal to the rate at which it loses it by conduction through the air. If the inner cylinder has initially a positive charge it rapidly loses that charge and acquires a negative one; while if the initial charge is a negative one, the cylinder will leak if the initial negative potential is numerically greater than the equilibrium value.

DEFLECTION OF THE CATHODE RAYS BY AN ELECTROSTATIC FIELD

An objection very generally urged against the view that the cathode rays are negatively electrified particles, is that hitherto no deflection of the rays has been observed under a small electrostatic force, and though the rays are deflected when they pass near electrodes connected with sources of large differences of potential, such as induction coils or electrical machines, the deflection in this case is regarded by the supporters of the etherial theory as due to the discharge passing between the electrodes, and not primarily to the electrostatic field. Hertz■ made the rays travel between two parallel plates of metal placed inside the discharge tube, but found that they were not deflected when the plates were connected with a battery of storage cells; on repeating this experiment I at first got the same result, but subsequent experiments showed that the absence of deflection is due to the conductivity conferred on the rarefied gas by the cathode rays. On measuring this conductivity it was found that it diminished very rapidly as the exhaustion increased; it seemed then that on trying Hertz's experiment at very high exhaustions there might be a chance of detecting the deflection of the cathode rays by an electrostatic force.

Hertz was a supporter of the etherial view—perhaps understandably so in view of his main interests.

The apparatus used is represented in Figure 2.



Fɪɢ. 2

The rays from the cathode *C* pass through a slit in the anode *A*, which is a metal plug fitting tightly into the tube and connected with the earth; after passing through a second slit■ in another earth-connected metal plug *B*, they travel between two parallel aluminium plates about 5 cm long by 2 broad and at a distance of 1.5 cm apart; they then fall on the end of the tube and produce a narrow well-defined phosphorescent patch. A scale pasted on the outside of the tube serves to measure the deflection of this patch. At high exhaustions the rays were deflected when the two aluminum plates were connected with the terminals of a battery of small storage cells; the rays were depressed when the upper plate was connected with the negative pole of the battery, the lower with the positive, and raised when the upper plate was connected with the positive, the lower with the negative pole. The deflection was proportional to the difference of potential between the plates, and I could detect the deflection when the potential-difference was as small as two volts. It was only when the vacuum was a good one that the deflection

took place, but that the absence of deflection is due to the conductivity of the medium is shown by what takes place when the vacuum has just arrived at the stage at which the deflection begins. At this stage there is a deflection of the rays when the plates are first connected with the terminals of the battery, but if this connection is maintained the patch of phosphorescence gradually creeps back to its undeflected position. This is just what would happen if the space between the plates were a conductor, though a very bad one, for then the positive and negative ions between the plates would slowly diffuse, until the positive plate became coated with negative ions, the negative plate with positive ones; thus the electric intensity between the plates would vanish and the cathode rays be free from electrostatic force. Another illustration of this is afforded by what happens when the pressure is low enough to show the deflection and a large difference of potential, say 200 volts, is established between the plates; under these circumstances there is a large deflection of the cathode rays, but the medium under the large electromotive force breaks down every now and then and a bright discharge passes between the plates;■ when this occurs the phosphorescent patch produced by the cathode rays jumps back to its undeflected position. When the cathode rays are deflected by the electrostatic field, the phosphorescent band breaks up into several bright bands separated by comparatively dark spaces; the phenomena are exactly analogous to those observed by Birkeland when the cathode rays are deflected by a magnet, and called by him the magnetic spectrum.

To define the beam more precisely.

That is, the residual air between the plates breaks down under the high electric field.

A series of measurements of the deflection of the rays by the electrostatic force under various circumstances will be found later on in the part of the paper which deals with the velocity of the rays and the ratio of the mass of the electrified particles to the charge carried by them.■ It may, however, be mentioned here that the deflection gets smaller as the pressure diminishes,■ and when in consequence the potential-difference in the tube in the neighborhood of the cathode increases.

See page 228. Since the velocity of the cathode rays increases with increase in mean free path.

Probably the current decreased at the same time because less gas was available for ionization.

■......................................

As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter. The question next arises, what are these particles? are they atoms, or molecules, or matter in a still finer state of subdivision? To throw some light on this point, I have made a series of measurements of the ratio of the mass of these

Some measurements on the conductivity of gases and on the behavior of the cathode rays in magnetic fields are omitted.

particles to the charge carried by it. To determine this quantity, I have used two independent methods. The first of these is as follows: Suppose we consider a bundle of homogeneous cathode rays. Let m be the mass of each of the particles, e the charge carried by it. Let N be the number of particles passing across any section of the beam in a given time; then Q the quantity of electricity carried by these particles is given by the equation.

$$Ne = Q$$

We can measure Q if we receive the cathode rays in the inside of a vessel connected with an electrometer.■ When these rays strike against a solid body, the temperature of the body is raised; the kinetic energy of the moving particles being converted into heat; if we suppose that all this energy is converted into heat, then if we measure the increase in the temperature of a body of known thermal capacity caused by the impact of these rays, we can determine W, the kinetic energy of the particles, and if v is the velocity of the particles,

As in Thomson's first experiment.

$$(\tfrac{1}{2})Nmv^2 = W$$

If ρ is the radius of curvature of the path of these rays in a uniform magnetic field H, then

$$\frac{mv}{e} = H\rho = I$$

where I is written for $H\rho$ for the sake of brevity. From these equations we get

Replacing N by $\frac{Q}{e}$

$$\frac{m}{2e}\, v^2 = \frac{W}{Q}$$

$$v = \frac{2W}{QI}$$

$$\frac{m}{e} = \frac{I^2Q}{2W}$$

Thus, if we know the values of Q, W, and I, we can deduce the values of v and $\frac{m}{e}$.

To measure these quantities, I have used tubes of three different types. The first I tried is like that represented in Figure 2, except that the plates E and D are absent, and two coaxial cylinders are fastened to the end of the tube. The rays from the cathode C fall on the metal plug B, which is connected with the earth, and serves for the anode; a horizontal slit is cut in this plug. The cathode rays pass through this slit, and then strike against the two coaxial cylinders at the end of the tube; slits are cut in these cylinders, so that the cathode rays pass into the inside of the inner cylinder. The outer cylinder is connected with the earth, the inner cylinder, which is insulated from the outer one, is connected with an electrometer, the deflection of which measures Q, the quantity of electricity brought into the inner cylinder by the rays. A thermoelectric couple is placed behind the slit in the inner cylinder; this couple is made of very thin strips of iron and copper fastened to very fine iron and copper wires. These wires passed through the cylinders, being insulated from them, and through the glass to the outside of the tube, where they were connected with a low-resistance galvanometer, the deflection of which gave data for calculating the rise of temperature of the junction produced by the impact against it of the cathode rays. The strips of iron and copper were large enough to ensure that every cathode ray which entered the inner cylinder struck against the junction. In some of the tubes the strips of iron and copper were placed end to end, so that some of the rays struck against the iron, and others against the copper; in others, the strip of one metal was placed in front of the other; no difference, however, could be detected between the results got with these two arrangements. The strips of iron and copper were weighed, and the thermal capacity of the junction calculated. In one set of junctions this capacity was 5×10^{-3}, in another 3×10^{-3}.■ If we assume that the cathode rays which strike against the junction give their energy up to it, the deflection of the galvanometer gives us W or $\tfrac{1}{2}Nmv^2$.

In calories per degree centigrade

The value of I, i.e., $H\rho$, where ρ is the curvature of the path of the rays in a magnetic field of strength H was found as follows: The tube was fixed between two large circular coils■ placed parallel to each other, and separated by a distance equal to the radius of either; these coils produce a uniform magnetic field, the strength of which is got by measuring with an ammeter the strength of the current passing through them. The cathode rays are thus in a uniform field, so that their path is circular. Suppose that the rays, when deflected by a magnet, strike against the glass of the tube at E (Fig. 3), then, if ρ is the radius of the circular path of the rays,

Known as *Helmholtz* coils.

$$2\rho = \frac{CE^2}{AC} + AC$$

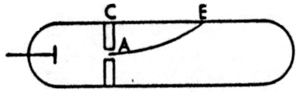


FIG. 3

From the expression relating the chord radius, and height of a segment of a circle.

thus, if we measure CE and AC we have the means of determining the radius of curvature of the path of the rays.

The determination of ρ is rendered to some extent uncertain, in consequence of the pencil of rays spreading out under the action of the magnetic field, so that the phosphorescent patch at E is several millimeters long;■ thus values of ρ differing appreciably from each other will be got by taking E at different points of this phosphorescent patch. Part

This would indicate a spread in velocity of the cathode rays.

of this patch was, however, generally considerably brighter than the rest; when this was the case, E was taken as the brightest point; when such a point of maximum brightness did not exist, the middle of the patch was taken for E. The uncertainty in the value of ρ thus introduced amounted sometimes to about 20 percent; by this I mean that if we took E first at one extremity of the patch and then at the other, we should get values of ρ differing by this amount.

The measurement of Q, the quantity of electricity which enters the inner cylinder, is complicated by the cathode rays making the gas through which they pass a conductor, so that though the insulation of the inner cylinder was perfect when the rays were off, it was not so when they were passing through the space between the cylinders; this caused some of the charge communicated to the inner cylinder to leak away so that the actual charge given to the cylinder by the cathode rays was larger than that indicated by the electrometer. To make the error from this cause as small as possible, the inner cylinder was connected to the largest capacity available, 1.5 microfarad, and the rays were only kept on for a short time, about 1 or 2 seconds, so that the alteration in potential of the inner cylinder was not large, ranging, in the various experiments from about .5 to 5 volts. Another reason why it is necessary to limit the duration of the rays to as short a time as possible, is to avoid the correction for the loss of heat from the thermoelectric junction by conduction along the wires;■ the rise in temperature of the junction was of the order 2° C; a series of experiments showed that with the same tube and the same gaseous pressure Q and W were proportional to each other when the rays were not kept on too long.

The heat conduction would be proportional to the temperature difference.

Tubes of this kind gave satisfactory results, the chief drawback being that sometimes in consequence of the charging up of the glass of the tube, a secondary discharge started from the cylinder to the walls of the tube, and the cylinders were surrounded by glow; when this glow appeared, the readings were very irregular; the glow could, however, be got rid of by pumping and letting the tube rest for some time. The results got with this tube are given in the table■ under the heading Tube 1.

See page 227.

The second type of tube was like that used for photographing the path of the rays;■ double cylinders with a thermoelectric junction like those used in the previous tube were placed in the line of fire of the rays, the inside of the bell jar was lined with copper gauze connected with the earth. This tube gave very satisfactory results; we were never troubled with any glow round the cylinders, and the readings were most concordant; the only drawback was that as some of the connections had to be made with sealing wax,■ it was not possible to get the highest exhaustions with this tube, so that the range of pressure for this tube is less than that for Tube 1. The results got with this tube are given in the table under the heading Tube 2.

This was a bell jar with a projecting tube in which the discharge was produced. The rays caused visible paths in passing from the tube into the rarefied gas in the bell jar.

In the early days of vacuum practice, the use of sealing wax to fasten electrodes into tubes was fairly common. In fact, wax is still used to some extent for such purposes in research laboratories.

The third type of tube was similar to the first, except that the openings in the two cylinders were made very much smaller; in this tube the slits in the cylinders were replaced by small holes, about 1.5 mm in diameter. In consequence of the smallness of the openings, the magnitude of the effect was very much reduced; in order to get measurable results it was necessary to reduce the capacity of the condenser in connection with the inner cylinder to .15 microfarad,■ and to make the galvanometer exceedingly sensitive, as the rise in temperature of the thermoelectric junction was in these experiments only about .5° C on the average. The results obtained in this tube are given in the table under the heading Tube 3.

In order to increase the potential resulting from the reduced charge.

The results of a series of measurements with these tubes are given in the following table.

Gas	*Value of W/Q*	*m/e*	
	Tube 1.		
Air............	230	·57 × 10^{-7}	4 × 10^{9}
Air............	350	·34 × 10^{-7}	1 × 10^{10}
Air............	230	·43 × 10^{-7}	5·4 × 10^{9}
Air............	400	·32 × 10^{-7}	1·2 × 10^{10}
Air............	230	·48 × 10^{-7}	4·8 × 10^{9}
Air............	285	·4 × 10^{-7}	7 × 10^{9}
Air............	285	·4 × 10^{-7}	7 × 10^{9}
Hydrogen......	205	·35 × 10^{-7}	6 × 10^{9}
Hydrogen......	460	·5 × 10^{-7}	9·2 × 10^{9}
Carbonic acid■.	260	·4 × 10^{-7}	7·5 × 10^{9}
Carbonic acid..	340	·4 × 10^{-7}	8·5 × 10^{9}
Carbonic acid..	480	·39 × 10^{-7}	1·3 × 10^{10}
Air...........	175	·53 × 10^{-7}	3·3 × 10^{9}
Air...........	195	·47 × 10^{-7}	4·1 × 10^{9}
Air...........	181	·47 × 10^{-7}	3·8 × 10^{9}
Hydrogen.....	175	·53 × 10^{-7}	3·3 × 10^{9}
Air...........	160	·51 × 10^{-7}	3·1 × 10^{9}
Carbonic acid.	148	·54 × 10^{-7}	2·5 × 10^{9}
Air...........	151	·63 × 10^{-7}	2·3 × 10^{9}
Hydrogen.....	175	·53 × 10^{-7}	3·3 × 10^{9}
Hydrogen.....	201	·46 × 10^{-7}	4·4 × 16^{9}
Air...........	176	·61 × 10^{-7}	2·8 × 10^{9}
Air...........	200	·48 × 10^{-7}	4·1 × 10^{9}
Air......	220	·9 × 10^{-7}	2·4 × 10^{9}
Air.......	225	·7 × 10^{-7}	3·2 × 10^{9}
Hydrogen.	250	1·0 × 10^{-7}	2·5 × 10^{9}

Carbon dioxide.

It will be noticed that the value of $\frac{m}{e}$ is considerably greater for Tube 3, where the opening is a small hole, than for Tubes 1 and 2, where the opening is a slit of much greater area. I am of opinion that the values of $\frac{m}{e}$ got from Tubes 1 and 2 are too small,■ in consequence of the leakage from the inner cylinder to the outer by the gas being rendered a conductor by the passage of the cathode rays.

Not so; see below.

It will be seen from these tables that the value of $\frac{m}{e}$ is independent of the nature of the gas.■ Thus, for the first tube the mean for air is $.40 \times 10^{-7}$, for hydrogen $.42 \times 10^{-7}$, and for carbonic acid gas $.4 \times 10^{-7}$; for the second tube the mean for air is $.52 \times 10^{-7}$, for hydrogen $.50 \times 10^{-7}$, and for carbonic acid gas $.54 \times 10^{-7}$.

The value of $\frac{m}{e}$ for electrons is 0.569×10^{-8} emu per gram.

Experiments were tried with electrodes made of iron instead of aluminium; this altered the appearance of the discharge and the value of v at the same pressure, the values of $\frac{m}{e}$ were, however, the same in the two tubes; the effect produced by different metals on the appearance of the discharge will be described later on.

In all the preceding experiments, the cathode rays were first deflected from the cylinder by a magnet, and it was then found that there was no deflection either of the electrometer or the galvanometer, so that the deflections observed were entirely due to the cathode rays; when the glow mentioned previously surrounded the cylinders there was a deflection of the electrometer even when the cathode rays were deflected from the cylinder.■

Owing to the collection of charge from the ionized gas.

Before proceeding to discuss the results of these measurements I shall describe another method of measuring the quantities $\frac{m}{e}$ and v of an entirely different kind from the preceding; this method is based upon the deflection of the cathode rays in an electrostatic field. If we measure the deflection experienced by the rays when traversing a given length under a uniform electric intensity, and the deflection of the rays when they traverse a given distance under a uniform magnetic field, we can find the values of $\frac{m}{e}$ and v in the following way:

This is the well known Thomso experiment.

■Let the space passed over by the rays under a uniform electric intensity F be l, the time taken for the rays to traverse this space is $\frac{l}{v}$, the velocity in the direction of F is therefore

$$\frac{Fe}{m}\frac{l}{v}$$

so that θ, the angle through which the rays are deflected when they leave the electric field and enter a region free from electric force, is given by the equation

$$\theta = \frac{Fe}{m}\frac{l}{v^2}$$

If, instead of the electric intensity, the rays are acted on by a magnetic force H at right angles to the rays, and extending across the distance l, the velocity at right angles to the original path of the rays is

$$\frac{Hev}{m}\frac{l}{v}$$

so that ϕ, the angle through which the rays are deflected when they leave the magnetic field, is given by the equation

$$\phi = \frac{He}{m}\frac{l}{v}$$

From these equations we get

$$v = \frac{\phi}{\theta}\frac{F}{H}$$

and

$$\frac{m}{e} = \frac{H^2\theta l}{F\phi^2}$$

In actual experiments H was adjusted so that $\phi = \theta$; in this case the equations become

$$v = \frac{F}{H},$$

$$\frac{m}{e} = \frac{H^2 l}{F\theta}$$

The apparatus used to measure v and $\frac{m}{e}$ by this means is that represented in Figure 2. The electric field was produced by connecting the two aluminium plates to the terminals of a battery of storage cells. The phosphorescent patch at the end of the tube was deflected, and the deflection measured by a scale pasted to the end of the tube. As it was necessary to darken the room to see the phosphorescent patch, a needle coated with luminous paint was placed so that by a screw it could be moved up and down the scale; this needle could be seen when the room was darkened, and it was moved until it coincided with the phosphorescent patch. Thus, when light was admitted, the deflection of the phosphorescent patch could be measured.

The magnetic field was produced by placing outside the tube two coils whose diameter was equal to the length of the plates;■ the coils were placed so that they covered the space occupied by the plates, the distance between the coils was equal to the radius of either. The mean

So that the magnetic field acted over the same distance as the electric field. A Helmholtz pair was employed.

value of the magnetic force over the length l was determined in the following way: a narrow coil C whose length was l, connected with a ballistic galvanometer, was placed between the coils; the plane of the windings of C was parallel to the planes of the coils; the cross section of the coil was a rectangle 5 cm by 1 cm. A given current was sent through the outer coils and the kick α of the galvanometer observed when this current was reversed. The coil C was then placed at the center of two very large coils, so as to be in a field of uniform magnetic force: the current through the large coils was reversed and the kick β of the galvanometer again observed; by comparing α and β we can get the mean value of the magnetic force over a length l; this was found to be

$$60 \times i$$

where i is the current flowing through the coils.

Probably in emu (electromagnetic units).

A series of experiments was made to see if the electrostatic deflection was proportional to the electric intensity between the plates; this was found to be the case. In the following experiments the current through the coils was adjusted so that the electrostatic deflection was the same as the magnetic:

Gas	θ	H	F	l	m/e	v
Air.............	8/110	5·5	$1{\cdot}5 \times 10^{10}$	5	$1{\cdot}3 \times 10^{-7}$	$2{\cdot}8 \times 10^{9}$
Air.............	9·5/110	5·4	$1{\cdot}5 \times 10^{10}$	5	$1{\cdot}1 \times 10^{-7}$	$2{\cdot}8 \times 10^{9}$
Air.............	13/110	6·6	$1{\cdot}5 \times 10^{10}$	5	$1{\cdot}2 \times 10^{-7}$	$2{\cdot}3 \times 10^{9}$
Hydrogen........	9/110	6·3	$1{\cdot}5 \times 10^{10}$	5	$1{\cdot}5 \times 10^{-7}$	$2{\cdot}5 \times 10^{9}$
Carbonic acid....	11/110	6·9	$1{\cdot}5 \times 10^{10}$	5	$1{\cdot}5 \times 10^{-7}$	$2{\cdot}2 \times 10^{9}$
Air.............	6/110	5	$1{\cdot}8 \times 10^{10}$	5	$1{\cdot}3 \times 10^{-7}$	$3{\cdot}6 \times 10^{9}$
Air.............	7/110	3·6	1×10^{10}	5	$1{\cdot}1 \times 10^{-7}$	$2{\cdot}8 \times 10^{9}$

It appears that the earlier measurements gave results in better agreement with the known value for the electron.

The cathode in the first five experiments was aluminium, in the last two experiments it was made of platinum; in the last experiment Sir William Crookes's method of getting rid of the mercury vapor by inserting tubes of pounded sulphur, sulphur iodide, and copper filings between the bulb and the pump was adopted.■ In the calculation of $\frac{m}{e}$ and v no allowance has been made for the magnetic force due to the coil in the region outside the plates; in this region the magnetic force will be in the opposite direction to that between the plates, and will tend to bend the cathode rays in the opposite direction: thus the effective value of H will be smaller than the value used in the equations, so that the values of $\frac{m}{e}$ are larger, and those of v less than they would be if this correction were applied. This method of determining the values of $\frac{m}{e}$ and v is much less laborious and probably more accurate than the former method; it cannot, however, be used over so wide a range of pressures.

Apparently Thomson used a mercury pump, probably of the Sprengel or Toepler type. Mercury vapor reacts with the substances listed, resulting in compounds having lower vapor pressures.

From these determinations we see that the value of $\frac{m}{e}$ is independent of the nature of the gas, and that its value 10^{-7} is very small compared with the value 10^{-4}, which is the smallest value of this quantity previously known, and which is the value for the hydrogen ion in electrolysis.■

The mass of the hydrogen ion (proton) is approximately 1830 times the electron mass.

Thus for the carriers of the electricity in the cathode rays $\frac{m}{e}$ is very small compared with its value in electrolysis.■ The smallness of $\frac{m}{e}$ may be due to the smallness of m or the largeness of e, or to a combination of these two. That the carriers of the charges in the cathode rays are small compared with ordinary molecules is shown, I think, by Lenard's results as to the rate at which the brightness of the phosphorescence produced by these rays diminishes with the length of path traveled by the ray. If we regard this phosphorescence as due to the impact of the charged particles, the distance through which the rays must travel before the phosphorescence fades to a given fraction (say $\frac{1}{e}$, where $e = 2.71$) of its original intensity, will be some moderate multiple of the mean free path. Now Lenard found that this distance depends solely upon the density of the medium, and not upon its chemical nature or physical state.■ In air at atmospheric pressure the distance was about half a centimeter, and this must be comparable with the mean free path of the carriers through air at atmospheric pressure. But the mean free path of the molecules of air is a quantity of quite a different order.■ The carrier, then, must be small compared with ordinary molecules.

Where the carriers are ions.

It is essentially the mass of gas traversed that determines the absorption of the cathode rays (electrons).

It is much smaller.

The two fundamental points about these carriers seem to me to be (1) that these carriers are the same whatever the gas through which the discharge passes, (2) that the mean free paths depend upon nothing but the density of the medium traversed by these rays.

SUPPLEMENTARY READING

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