The Discovery of Subatomic Particles

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W. H. Freeman and Company
NEW YORK

Staff and students at the Cavendish Laboratory, 1933.

Top row: W. J. Henderson, W. E. Duncanson, P. Wright, G. E. Pringle, H. Miller.

Second row: C. B. O. Mohr, N. Feather, C. W. Gilbert, D. Shoenberg, D. E. Lea, R. Witty, —— Halliday, H. S. W. Massey, E. S. Shire.

Third row: B. B. Kinsey, F. W. Nicoll, G. Occhialini, E. C. Allberry, B. M. Crowther, B. V. Bowden, W. B. Lewis, P. C. Ho, E. T. S. Walton, P. W. Burbidge, F. Bitter.

Fourth row: J. K. Roberts, P. Harteck, R. C. Evans, E. C. Childs, R. A. Smith, G. T. P. Tarrant, L. H. Gray, J. P. Gott, M. L. Oliphant, P. I. Dee, J. L. Pawsey, C. E. Wynn-Williams.

Seated row: —— Sparshott, J. A. Ratcliffe, G. Stead, J. Chadwick, G. F. C. Searle, Professor Sir J. J. Thomson, Professor Lord Rutherford, Professor C. T. R. Wilson, C. D. Ellis, Professor Kapitza, P. M. S. Blackett, —— Davies.

2

The Discovery of the Electron

This century has seen the gradual realization that all matter is composed of a few types of elementary particles—tiny units that apparently cannot be subdivided further. The list of elementary particle types has changed many times during the century, as new particles have been discovered and old ones have been found to be composed of more elementary constituents. At latest count, there are some sixteen known types of elementary particles. But through all these changes, one particle type has always remained on the list: the electron.

The electron was the first of the elementary particles to be clearly identified. It is also by far the lightest of the elementary particles (aside from a few types of electrically neutral particles that appear to have no mass at all) and one of the few that does not decay into other particles. As a consequence of its lightness, charge, and stability, the electron has a unique importance to physics, chemistry, and biology. An electrical current in a wire is nothing but a flow of electrons. Electrons participate in the nuclear reactions that produce the heat of the sun. Even more important, every normal atom in the universe consists of a dense core, (the nucleus) surrounded by a cloud of electrons. The chemical differences between one element and another depend almost entirely on the number of electrons in the atom, and the chemical forces that hold atoms together in all substances are due to the attraction of the electrons in each atom for the nuclei of the other atoms.

The discovery of the electron is usually and justly credited to the English physicist Sir Joseph John Thomson (1856–1940). Thomson went up to the University of Cambridge as a scholarship student in 1876. After placing second in the competitive mathematical "tripos" examination in 1880, he earned a fellowship at Trinity, the old Cambridge college of Isaac Newton, and remained a fellow of Trinity for the following 60 years of his life. Thomson's early work was chiefly mathematical, and not outstandingly important; so he was somewhat surprised when in 1884 he was elected to the Cavendish Professorship of Experimental Physics. It was in his experimental researches and his leadership of the Cavendish Laboratory from 1884 to 1919 that Thomson made his greatest contributions to physics. He was actually not skillful in the execution of experiments; one of his early assistants recalled that "J.J. was very awkward with his fingers, and I found it necessary not to encourage him to handle the instruments." His talent—one that is for both theorists and experimentalists the most important—lay instead in knowing at every moment what was the next problem to be attacked.

J. J. Thomson.

From what is written about him, I gather that Thomson was greatly loved by his colleagues and students. It is certain that he was greatly honored: by the Nobel Prize in 1906, a knighthood in 1908, and the Presidency of the Royal Society in 1915. He served Britain in World War I as a member of the Board of Investigation and Research, and in 1918 was appointed Master of Trinity College, a post he held until shortly before his death. He was buried in Westminster Abbey, not far from Newton and Rutherford.

Shortly after assuming the Cavendish Professorship, Thomson began his investigation of the nature of discharges of electricity in rarefied gases, and in particular the type of discharge known as cathode rays. These spectacular phenomena were interesting enough in themselves, but their study led Thomson to an even more interesting problem: that of the nature of electricity itself.

His conclusion, that electricity is a flow of the particles that are today known as electrons, was published in three papers in 1897.[1] But before we take up Thomson's investigations, let us review earlier efforts to understand the nature of electricity.

Flashback: The Nature of Electricity*

It has been known since early times that a piece of amber, when rubbed with fur, will acquire the power to attract small bits of hair and other materials. Plato refers in his dialogue *Timaeus* to the "marvels concerning the attraction of amber."[2] By the early Middle Ages, it had become known that this power is shared by other materials, such as the compressed form of coal known as jet. The earliest written observation of this property of jet seems to be that of the Venerable Bede (673–735), the English monk who also studied the tides, calculated the dates of Easter for centuries to come, and wrote one of the world's great works of history, *The Ecclesiastical History of the English*. In his history, Bede notes of jet that "like amber, when it is warmed by friction, it clings to whatever is applied to it."[3] (Bede exhibits here a confusion about the cause of electric attraction, between friction itself and the warmth it produces—a confusion that was often to recur until the eighteenth century.) Other substances, such as glass, sulfur, wax, and gems, were found to have similar properties by the English physician William Gilbert (1544–1603), president of the Royal College of Surgeons and court physician to Elizabeth I and James I. It was Gilbert who introduced the term *electric* (in his Latin text, *electrica*), after the Greek word *electron* (ηλεκτρον) for amber.[4]

The observation of electrical attraction in so many different substances led naturally to the idea that electricity is not an intrinsic property of the substances themselves, but is instead some sort of fluid (to Gilbert, an "effluvium") that is produced or transferred when bodies are rubbed together and spreads out to draw in nearby objects. This picture was supported by the discovery by Stephen Gray (1667–1736) of electrical conduction. In 1729, while a "poor brother" of the Charterhouse in London, Gray reported in a letter to some fellows of the Royal Society that "the Electrick Virtue" of a rubbed glass tube may be transmitted to other bodies, either by direct contact or via a thread connecting them, so "as to give them the same Property of attracting and repelling light Bodies as the Tube does."[5] It was clear that, whatever electricity might be, it could be separated from the body in which it was produced. But the problem of the nature of electricity became more complicated when it was found that electrified bodies could either attract or repel other electrified bodies, raising the question whether there was one kind of electricity or two.

Among those who first observed electric repulsion were Niccolo Cabeo (1586–1650)[6] and Francis Hauksbee (1666–1713), a paid demonstrator of scientific experiments at the Royal Society of London. In a communication to the Royal Society in 1706 Hauksbee reported that, when a glass tube was electrified by rubbing, it would at first attract bits of brass leaf, but that after the bits of brass came in contact with the tube they would be repelled by it.

Further complications were discovered in France by one of the most versatile scientists of the eighteenth century, Charles-François de Cisternay Du Fay (1698–1739). Chemist at the Académie des Sciences and administrator of the Jardin Royal des Plantes, Du Fay wrote papers on almost every conceivable scientific subject, including geometry, fire pumps, artificial gems, phosphorescence, slaked lime, plants, and dew. In 1733 he learned of Stephen Gray's experiments and began to work on electricity. Soon he observed that bits of metal that had been in contact with an electrified glass tube would repel each other (as observed by Cabeo and Hauksbee) but would *attract* bits of metal that had been in contact with an electrified piece of a resin, copal. Du Fay concluded that "there are two electricities, very different from each other; one of these I call vitreous electricity; the other resinous electricity."[7] "Vitreous" electricity (from the Latin *vitreus*, glassy) is produced when substances like glass, crystal, or gems are rubbed, especially with silk. "Resinous" electricity is produced when resins like amber or copal are rubbed, especially with fur. At the same time, the silk used to rub the glass picks up resinous electricity, and the fur used to rub the resin picks up vitreous electricity. Both vitreous and resinous electricity were assumed to attract ordinary matter, and vitreous electricity was assumed to attract resinous electricity, but bodies carrying vitreous electricity were assumed to repel each other, and likewise for resinous electricity. That is, unlike types of electricity attract each other, but like types repel. A bit of metal that had come into contact with the rubbed glass tube would pick up some of the tube's vitreous electricity, and would therefore be repelled by it; and a bit of metal that had been in contact with a rubbed amber or copal rod would pick up some of the rod's resinous electricity, and so again would be repelled by it, but the two bits of metal would attract each other, because they would be carrying electricity of two different types.

Gray and Du Fay did not write of electricity as a fluid, but rather as a condition that could be induced in matter. It was the Abbé Jean-Antoine Nollet

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*This is an often-told story, and my recount of it here is based almost entirely on secondary sources. I review it here because it gives a good idea of what was known and what was not known about electricity when the experiments on cathode rays began.

(1700–1770), preceptor to the French royal family and professor at the University of Paris, who interpreted Du Fay's two types of electricity specifically as two distinct types of electrical fluid, one vitreous and the other resinous.

The two-fluid theory was consistent with all experiments that could be carried out in the eighteenth century. But physicists' passion for simplicity does not let them rest with a complicated theory when a simpler one can be found. The two-fluid theory of electricity was soon to be challenged by a one-fluid theory, proposed first by the London physician and naturalist William Watson (1715–1787) and then more comprehensively and influentially by the Philadelphia savant Benjamin Franklin (1706–1790).

Franklin became interested in electricity when in 1743, on a visit to Boston, he happened to witness electrical experiments carried out by a Dr. Adam Spencer, a popular lecturer from Scotland. Soon Franklin received some glass tubes and instructions from a correspondent in London, the manufacturer and naturalist Peter Collinson, and began his own experiments and speculations, which he reported in a series of letters to Collinson. In brief, Franklin concluded that electricity consisted of a single kind of fluid, consisting of "extremely subtile particles," which could be identified with what Du Fay had called vitreous electricity. (Franklin did not know of Du Fay's work, and did not use his terminology.) Franklin supposed ordinary matter to hold electricity like a "kind of spunge." When a glass tube is rubbed with a silk cloth, some of the electricity from the silk is transferred to the glass, leaving a deficiency in the silk. It is this deficiency of electricity that is to be identified with what Du Fay called resinous electricity. Similarly, when an amber rod is rubbed with fur, some electricity is transferred, but this time from the rod to the fur, leaving a deficiency of electricity in the rod; again, the deficiency of electricity in the rod and the excess in the fur are to be identified with Du Fay's resinous and vitreous electricity, respectively. Franklin referred to a deficiency of electricity as *negative* electricity and to an excess as *positive* electricity; the amount of electricity (positive or negative) in any body he called the electric *charge* of the body. These terms are the ones that are still in general use today.

Franklin also introduced the fundamental hypothesis of the conservation of charge. Electricity is never created or destroyed, but only transferred. Hence, when a glass rod is rubbed with silk, the positive electric charge on the rod is exactly equal numerically to the negative charge on the silk; balancing positive and negative, the total charge remains zero.

What about attraction and repulsion? Franklin supposed that electricity repels itself but attracts the matter that holds it. Thus, the repulsion that Cabeo observed between pieces of brass leaf that had been in contact with a rubbed glass rod could be understood because these bits of metal all contained an

Benjamin Franklin in 1762. Notice the apparatus behind him; the position of the two balls indicates that a charged cloud is overhead.

excess of electricity, while the attraction that Du Fay observed between such bits of metal and others that had been in contact with a rubbed rod of resin could be understood because the latter bits had a deficiency of electricity, so that the attraction between their matter and the former bits' electricity would dominate. This neatly accounted for the repulsion observed between two bodies each carrying the "vitreous" electricity, and for the attraction observed between a body carrying "resinous" electricity and one carrying "vitreous" electricity.

But then what about the repulsion between two bodies carrying resinous electricity, such as bits of metal that had been in contact with a rubbed amber rod? This gap in Franklin's one-fluid theory was filled by Franz Ulrich Theodosius Aepinus (1724–1802), director of the astronomical observatory in St. Petersburg. After learning of Franklin's ideas, Aepinus in 1759 suggested that, in the absence of a counterbalancing quantity of electricity, ordinary matter repels itself.[8] Thus, the repulsion between bodies that had been supposed to carry resinous electricity was explained in terms of the repulsion between the matter of the bodies when it was stripped of some of its normal accompaniment of electricity. With this emendation, the one-fluid theory of Franklin was thus able to account for all the phenomena that had been explained by the two-fluid theory of Du Fay and Nollet.

Franklin's letters were assembled by Collinson into a book, which by 1776 had gone through ten editions, some in English and others in Italian, German, and French.[9] Franklin became a celebrity; he was elected to the Royal Society of London and the French Académie des Sciences, and his work influenced all later studies of electricity in the eighteenth century. Indeed, Franklin's fame was a great asset to the thirteen American colonies when, during the revolutionary war, Franklin served as the American minister to France. However, despite Franklin's enormous prestige, the question of one fluid or two continued to divide physicists until well into the nineteenth century, and it was only really settled with the discovery of the electron.

For readers who cannot wait until we come to the discovery of the electron to learn whether the one-fluid or the two-fluid theory is correct—the answer is that they were both correct. Under normal circumstances, electricity is carried by the particles called electrons, which as Franklin supposed possess electricity of only one type. But Franklin guessed wrong as to which type of electricity it was. In fact, electrons carry electricity of the type that Du Fay had called "resinous," not the "vitreous" type. (Physicists continue to follow Franklin's lead in calling vitreous electricity positive and resinous electricity negative, so we are stuck in the unfortunate position of saying that the most common carriers of electricity carry negative electrical charge.) Thus, when a

glass tube is rubbed with silk, the tube picks up vitreous electricity and the silk acquires resinous electricity, because electrons are transferred from the tube to the silk. On the other hand, when an amber rod is rubbed with fur, electrons are transferred from the fur to the rod.

In the atoms of ordinary matter, electrons are bound to dense atomic nuclei, which contain most of the mass of any substance and are normally immobile in solids. As Franklin supposed, electrons repel electrons, and electrons and nuclei attract each other; and as Aepinus supposed, atomic nuclei repel other nuclei. But it is convenient to think of the positive or vitreous charge of matter as residing in the nuclei, and not as merely an absence of electrons. Indeed, by dissolving solids like salt in water it is possible to shake the atomic nuclei loose (though they will almost always be accompanied by some electrons), and in this case it is possible to have a flow of particles carrying positive (or vitreous) electricity. Furthermore, there exist other particles, called positrons, that are identical to electrons in almost every respect except that they carry positive electric charge. Thus, in a deep sense Du Fay was correct in taking a symmetrical view of the two types of electric charge: Positive and negative (or resinous and vitreous) electricity are equally fundamental.

The reader may well also wonder why when amber is rubbed with fur the electrons go from the fur to the amber, but when glass is rubbed with silk the electrons go from the glass to the silk? Oddly enough, we still don't know. The question involves the physics of surfaces of complex solids such as silk or hair, and this branch of physics has still not reached a point where we can make definite predictions with any certainty. In a purely empirical way, there has been developed a list of substances called the triboelectric sequence, part of which goes as follows[10]:

rabbit's fur/lucite/glass/quartz/wool/cat's fur/silk/cotton/wood/amber/resins/metals/teflon.

Substances near the beginning of the list tend to lose electrons, and those near the end of the list tend to collect them. Thus, if two objects are rubbed together, the one closer to the beginning of the list will tend to pick up a positive, or vitreous, electric charge and the one closer to the end will tend to pick up a negative, or resinous, charge. The electrification is most intense for objects that are well separated in the triboelectric sequence. For example, it is easier to electrify amber by rubbing with fur than it is to electrify glass by rubbing with silk. The triboelectric sequence is not well understood theoretically, and even a change in the weather can affect the relative placement of various substances.

It is ironic that we still do not have a detailed understanding of frictional electrification, even though it was the first of all electrical phenomena to be studied scientifically. But that is often the way science progresses—not by solving every problem presented by nature, but by selecting problems that are as free as possible from irrelevant complications and that therefore provide opportunities to get at the fundamental principles that underlie physical phenomena. The study of the electricity produced by friction played a great role in letting us know that there is such a thing as electricity and that it can exert attractive and repulsive forces, but the actual process of electrification by rubbing is just too complicated to provide further insights into the quantitative properties of electricity. By the end of the eighteenth century, the attention of physicists was already beginning to focus on other electrical phenomena.

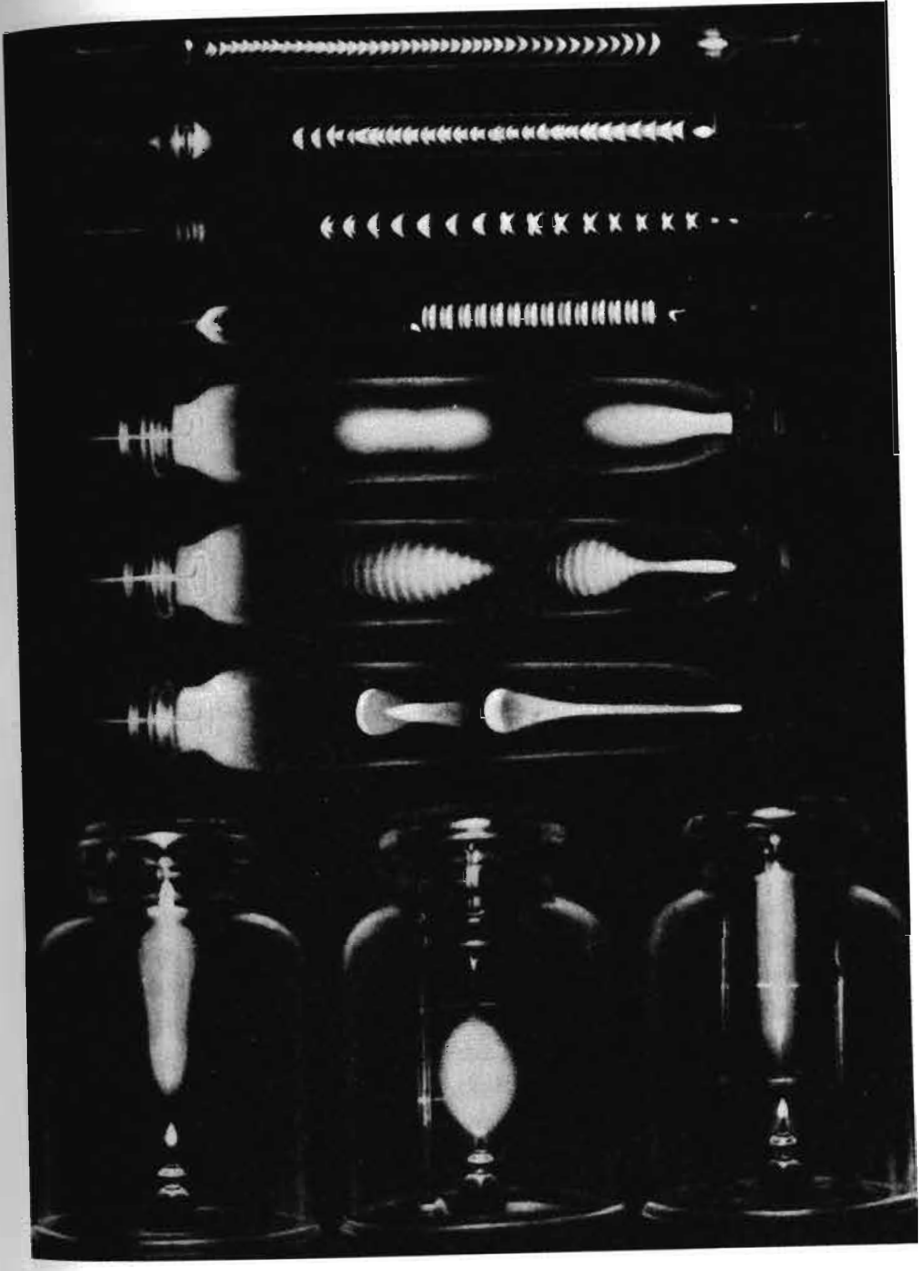
Electric Discharges and Cathode Rays

The study of electricity widened after Franklin to take in the quantitative details of electrical attraction and repulsion and the connection of electricity with magnetism and chemistry. We will have much to do with these matters later on; but for now, let us follow one line of discoveries, concerning the discharge of electricity through rarefied gases and empty space.

The earliest-known and most spectacular sort of electric discharge is of course lightning. Although the nature of lightning as a current of electricity was demonstrated in 1752 in a celebrated experiment suggested by Franklin, lightning is so sporadic and uncontrollable that its study could reveal little about the nature of electricity. But by the eighteenth century, a more controllable sort of electric discharge was becoming available for scientific study.

In 1709 Hauksbee observed that when the air inside a glass vessel was pumped out until its pressure was about $\frac{1}{60}$ normal air pressure and the vessel was attached to a source of frictional electricity, a strange light would be seen inside the vessel. Flashes of similar light had already been noticed in the partial vacuum above the mercury in barometers. In 1748 Watson described the light in a 32-inch evacuated tube as an "arch of lambent flame." Other observations were recorded by the Abbé Nollet, by Gottfried Heinrich Grummont (1719–1776), and by the great Michael Faraday, about whom more later.

The nature of this light was not understood at first, but today we know that it is a secondary phenomenon. When an electric current flows through a gas, the electrons knock into gas atoms and give up some of their energy, which is then reemitted as light. Today's fluorescent lights and neon signs are

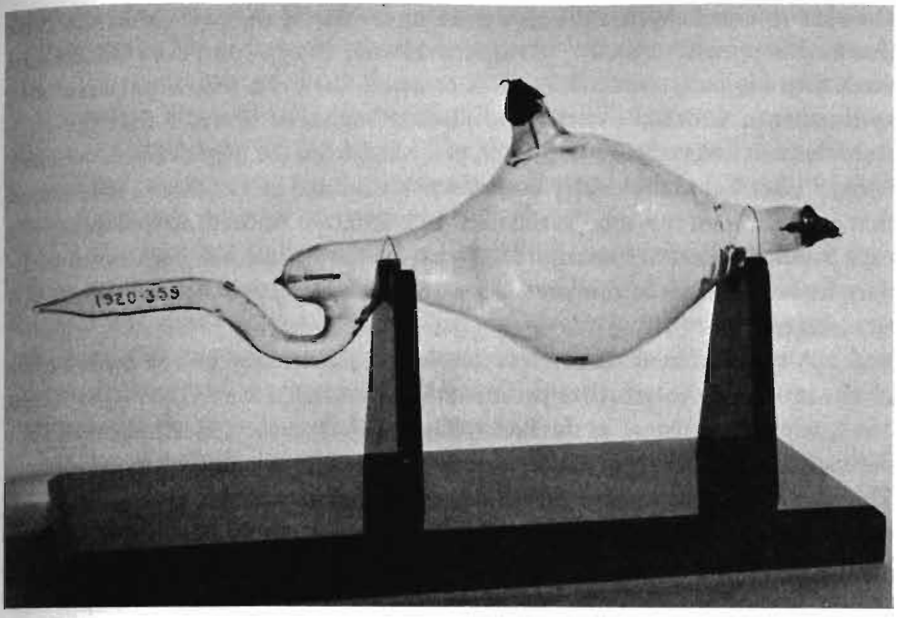


Electrical discharges in gases at low pressure.

based on the same principle, with their color determined by the color of light that is preferentially emitted by the gas atoms: orange for neon, pinkish-white for helium, greenish-blue for mercury, and so on. The importance of the phenomenon for the history of electrical science lay, however, not in the light given off in electric discharges, but in the electric current itself. When electricity collects on an amber rod, or an electric current flows through a copper wire, properties of the electricity are hopelessly mixed up with those of the solid integument of amber or copper. For instance, it would be impossible even today to determine the weight of a given quantity of electricity by weighing an amber rod before and after it is electrified; the weight of the electrons is just too tiny compared with that of the rod. What was needed was to get electricity off by itself, away from the solid or liquid matter that normally carries it. The study of electric discharges in gases was a step in the right direction, but even at $\frac{1}{60}$ atmospheric pressure the air interfered too much with the flow of electrons to allow their nature to be discovered. Real progress became possible only when the gas itself could be removed and scientists could study the flow of pure electricity through nearly empty space.

The turning point came with the invention of really effective air pumps. Early pumps had leaked air through the gaskets around their pistons. In 1885 Johann Heinrich Geissler (1815–1879) invented a pump that used columns of mercury as pistons and consequently needed no gaskets. With Geissler's pump, it became possible to evacuate the air in a glass tube until its pressure was a few ten-thousandths that of normal air at sea level. Geissler's pump was used in 1858–59 in a series of experiments on the conduction of electricity in gases at very low pressure, carried out by Julius Plücker (1801–1868), Professor of Natural Philosophy at the University of Bonn. In Plücker's arrangement, metal plates inside a glass tube were connected by wires to a powerful source of electrcity. (Following Faraday's terminology, the plate attached to the source of positive electricity is called the *anode* and the plate attached to the source of negative electricity is called the *cathode*.) Plücker observed that when almost all air was evacuated from the tube, the light disappeared through most of the tube, but a greenish glow appeared on the glass tube near the cathode. The position of the glow did not seem to depend on where the anode was placed. It appeared that something was coming out of the cathode, traveling through the nearly empty space in the tube, hitting the glass, and then being collected by the anode. A few years later, Eugen Goldstein (1850–1930) introduced a name for this mysterious phenomenon: *Cathodenstrahlen*, or cathode rays.

We know now that these rays are streams of electrons. They are projected from the cathode by electrical repulsion, coast through the nearly empty space within the tube, strike the glass, depositing energy in its atoms which is then reemitted as visible light, and finally are drawn to the anode, via which they return to the source of electricity. But this was far from obvious to nineteenth-century physicists. Many different clues were discovered, and for a long time they seemed to point in different directions.



A Crookes tube, made in 1879, devised for studying cathode rays.

Plücker himself was misled by the fact that when the cathode was of platinum, a film of platinum was found deposited on the walls of the glass bulb. He thought that the rays might consist of small pieces of cathode material. We now know that the electrical repulsion felt by the cathode material does indeed cause pieces of the cathode's surface to be torn off (a phenomenon known as sputtering), but this really has nothing to do with cathode rays in general. In fact, Goldstein showed in the 1870s that the properties of cathode rays do not depend on the material of which the cathode is made.

Plücker also observed that the position of the glow on the walls of the tube could be moved by placing a magnet near the tube. As we shall see, this was a sign that the rays consist of electrically charged particles of some sort. Plücker's student J. W. Hittorf (1824–1914) observed that solid bodies placed near a small cathode would cast shadows on the glowing walls of the tube. From this he deduced that the rays travel from the cathode in straight lines. The same phenomena were observed in 1878–79 by the English physicist, chemist, and spiritualist Sir William Crookes (1832–1919), and this led

Crookes to conclude that the rays were molecules of the gas within the tube that had happened to pick up a negative electric charge from the cathode and were then violently repelled by it. (Cromwell Varley, a fellow physicist and spiritualist in Crookes's circle, had already suggested in 1871 that the rays were "attenuated particles of matter, projected from the negative pole by electricity.") But Crookes's theory was effectively refuted by Goldstein, who noted that in a cathode-ray tube evacuated to 1/100,000 normal air pressure, the rays traveled at least 90 centimeters, whereas the typical free path of an ordinary molecule in air at this pressure would be expected to be only about 0.6 centimeters.

A very different theory was developed in Germany on the basis of the observations of the gifted experimentalist Heinrich Hertz (1857–1894). In 1883, while an assistant at the Berlin Physical Laboratory, Hertz showed that the cathode rays were not appreciably deflected by electrified metal plates. This seemed to rule out the possibility that the cathode rays were electrically charged particles, for in that case the ray particles should have been repelled by the plate carrying like charge and attracted to the plate carrying unlike charge. Hertz concluded that the rays were some sort of wave, like light. It was not clear why such a wave should be deflected by a magnet, but the nature of light was then not well understood, and a magnetic deflection did not seem impossible. In 1891 Hertz made a further observation that seemed to support the wave theory of cathode rays: The rays could penetrate thin foils of gold and other metals, much as light penetrates glass.

But the rays were not a form of light. In his doctoral research, the French physicist Jean Baptiste Perrin (1870–1942) showed in 1895 that the rays deposit negative electric charge on a charge collector placed inside the cathode-ray tube. We now know that the reason Hertz had not observed any attraction or repulsion of the rays by electrified plates is that the ray particles were traveling so fast, and the electric forces were so weak, that the deflection was just too small to observe. (As Hertz recognized, the electric charge on his plates was partly canceled by effects of the residual gas molecules in the tube. These molecules were broken up by the cathode rays into charged particles, which were then attracted to the plate of opposite charge.) But as Goldstein has shown, if the rays are charged particles, these particles cannot be ordinary molecules. So what were they?

It is at this point that J. J. Thomson enters the story. Thomson first attempted to measure the speed of the rays. In 1894 he obtained a value of 200 kilometers per second (1/1,500 the speed of light), but his method was faulty and he later abandoned this result. Then in 1897 Thomson succeeded where Hertz had failed: He detected a deflection of the cathode rays by electric forces between the rays and electrified metal plates. His success in this was due largely to the use of better vacuum pumps, which lowered the pressure inside the cathode-ray tube to the point where effects of the residual gas within the tube became negligible. (Some evidence for electrical deflection was found at about the same time by Goldstein.) The deflection was toward the positively charged plate and away from the negatively charged one, confirming Perrin's conclusion that the rays carry negative electric charge.

The problem now was to learn something quantitative about the nature of the mysterious negatively charged particles of the cathode rays. Thomson's method was direct: He exerted electric and magnetic forces on the rays and measured the amount by which the rays were deflected.* To understand how Thomson analyzed these measurements, we must first consider how bodies move under the influence of forces in general.

Flashback: Newton's Laws of Motion

The laws of motion of classical physics were set out by Sir Isaac Newton at the beginning of his great work, the *Principia*.[11] Of these, the key principle is contained in the Second Law, which can be paraphrased as the statement that the force required to give an object of definite mass a certain acceleration is proportional to the product of the mass and the acceleration. To understand what this law means, we have to understand what are meant by acceleration, mass, and force.

Acceleration is the rate of change of velocity. That is, just as the velocity is the ratio of the distance traveled by a moving body to the time that elapses in the motion, acceleration is the ratio of the change in velocity of an accelerating body to the time elapsed during the acceleration. The units in which acceleration is measured are therefore the units of velocity per time, or distance-per-time per time. For instance, falling bodies near the surface of the earth fall with an acceleration of 9.8 meters-per-second per second. This means that after the first second a body dropped from rest in a vacuum will be falling at a

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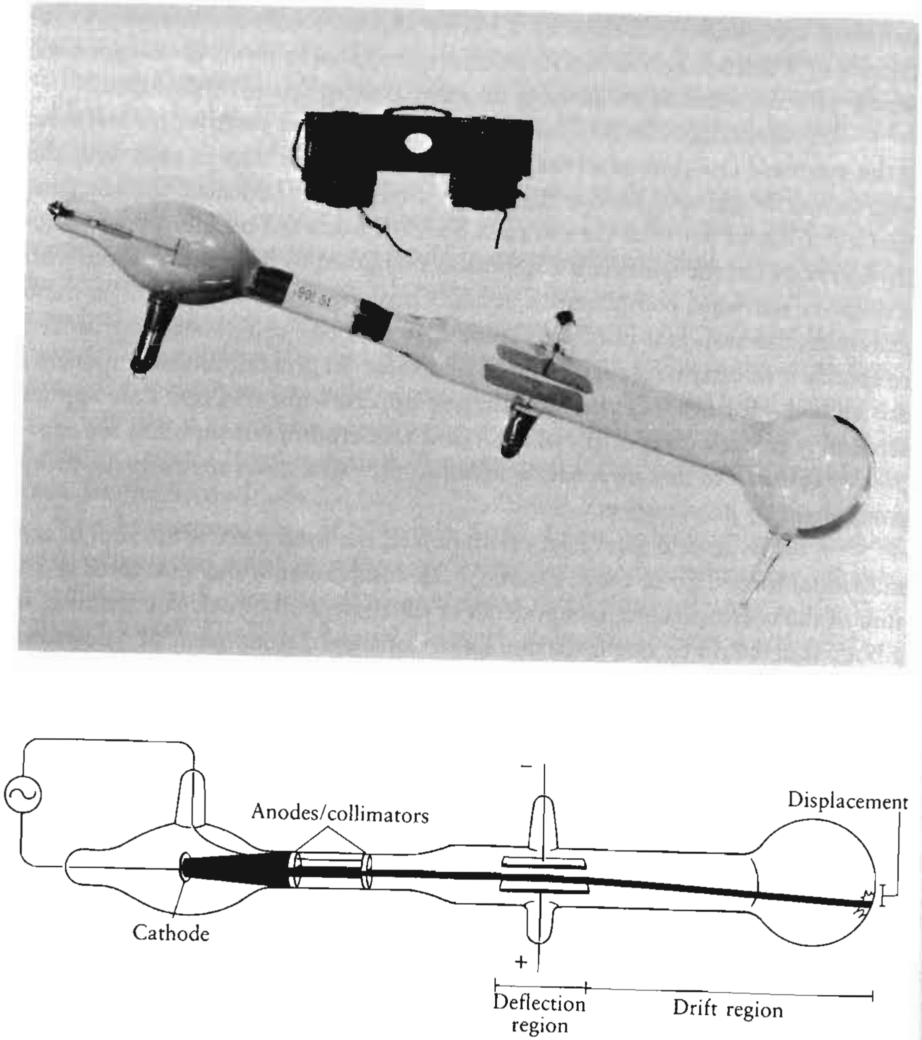
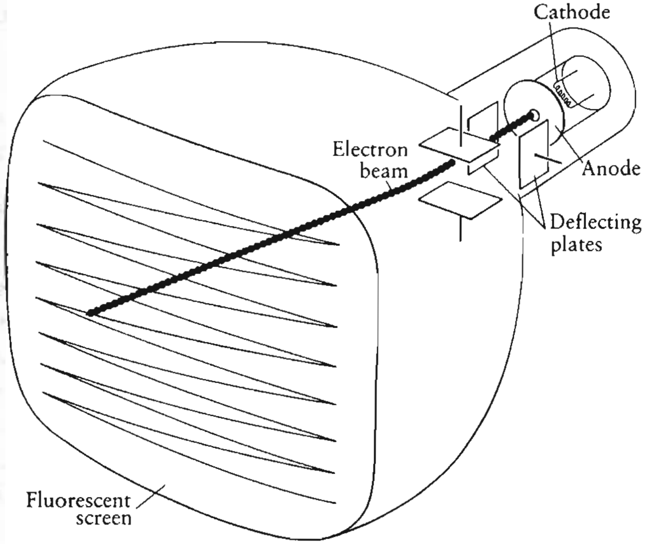
*Thomson also used an alternative experimental method, in which he measured the heat energy and electric charge deposited at the end of the tube by the cathode-ray particle and thus avoided the difficult measurement of the deflection of the ray by electric forces. This method was actually more accurate than the one based on the electric and magnetic deflection of the cathode ray. I am describing the electric/magnetic deflection method here first, not because it was historically more important, but because it presents an occasion for a review of electric forces, which I will need to pin down the definition of electric charge. Thomson's other method I will describe below, after a review of the concepts of energy and heat.



Above: One of the tubes with which J. J. Thomson measured the mass-to-charge ratio of the electron. Below: A schematic view of Thomson's apparatus. The cathode is connected by a wire through the glass tube to a generator that supplies it with negative electric charge; the anode and collimator are connected to the generator by another wire so that negative electric charge can flow back to the generator. The deflection plates are connected to the terminals of a powerful electric battery, and are thereby given strong negative and positive charges. The invisible cathode rays are repelled by the cathode; some of them pass through the slits in the anode and collimator, which only admit a narrow beam of rays. The rays are then deflected by electric forces as they pass between the plates; they then travel freely until they finally hit the glass wall of the tube, producing a spot of light. (This figure is based on a drawing of Thomson's cathode-ray tube in Figure 2 of his article "Cathode Rays," *Phil. Mag.* 44(1897), 293. For clarity, the magnets used to deflect the rays by magnetic forces are not shown here.)



A schematic view of a more familiar cathode-ray tube, the modern television picture tube. As we have seen, Thomson used the position of the glowing spot where the cathode ray hit the end of the tube to tell him about the path taken by the ray, which was invisible as it passed through the vacuum of his tube. Since Thomson's time, this glowing spot has become much more familiar to all of us as the basis of television. A television picture tube is essentially just a cathode-ray tube aimed at the viewer. In it, the cathode ray is steered by electric forces so that it passes regularly back and forth over the end of the tube. When the ray hits the screen of specially coated glass at the end of the tube, a spot of light appears. The television signal controls the strength of the cathode ray as it strikes each spot on the screen, so that a pattern of light and dark appears successively on the screen. The eye and brain respond slowly, and see this pattern as an instantaneous picture.

(See the schematic diagram of Thomson's apparatus.) Thomson's formula states that

$$\begin{matrix}\text{Displacement of ray}\\ \text{at end of tube}\end{matrix} = \frac{\begin{matrix}\text{Force on}\\ \text{ray particle}\end{matrix} \times \begin{matrix}\text{Length of}\\ \text{deflection region}\end{matrix} \times \begin{matrix}\text{Length of}\\ \text{drift region}\end{matrix}}{\begin{matrix}\text{Mass of}\\ \text{ray particle}\end{matrix} \times \begin{pmatrix}\text{Velocity of}\\ \text{ray particle}\end{pmatrix}^2}$$

To take an illustration using numbers that are more or less realistic, suppose that the force exerted on the ray particles is 10^{-16} newtons, the length of the deflection region is 0.05 meters, the length of the drift region is 1.1 meters, the mass of the cathode-ray particles is 9×10^{-31} kilograms, and the

The important point for Thomson was that, because the magnetic force is proportional to the velocity, the magnetic deflection depends on a different combination of the charge, mass, and velocity of the ray particles than does the electric deflection.

Thomson's Results

Now we will put the theory that has been developed in previous sections together with Thomson's experimental results to learn something about the cathode-ray particles. First, recall the main results we obtained above. Electric or magnetic fields at right angles to the cathode ray in the "deflection region" will produce a displacement of the ray when it hits the glass wall of the tube at the end of the "drift region," by an amount given by the formulas

$$\begin{matrix}\text{Electric}\\ \text{deflection}\end{matrix} = \frac{\begin{matrix}\text{Charge of}\\ \text{ray}\\ \text{particle}\end{matrix} \times \begin{matrix}\text{Electric}\\ \text{field}\end{matrix} \times \begin{matrix}\text{Length of}\\ \text{deflection}\\ \text{region}\end{matrix} \times \begin{matrix}\text{Length of}\\ \text{drift}\\ \text{region}\end{matrix}}{\begin{matrix}\text{Mass of}\\ \text{ray particle}\end{matrix} \times \begin{pmatrix}\text{Velocity of}\\ \text{ray particle}\end{pmatrix}^2}$$

and

$$\begin{matrix}\text{Magnetic}\\ \text{deflection}\end{matrix} = \frac{\begin{matrix}\text{Charge of}\\ \text{ray}\\ \text{particle}\end{matrix} \times \begin{matrix}\text{Magnetic}\\ \text{field}\end{matrix} \times \begin{matrix}\text{Length of}\\ \text{deflection}\\ \text{region}\end{matrix} \times \begin{matrix}\text{Length of}\\ \text{drift}\\ \text{region}\end{matrix}}{\begin{matrix}\text{Mass of}\\ \text{ray particle}\end{matrix} \times \begin{matrix}\text{Velocity of}\\ \text{ray particle}\end{matrix}}$$

Thomson knew the values of the electric and magnetic fields in the tube and the length of the deflection and drift regions, and he measured the deflections produced by the electric or magnetic forces. What, then, could he deduce about the cathode-ray particles? It is immediately clear that there was no way Thomson or anyone else could use these formulas to learn anything separately about the charge or the mass of the cathode-ray particles, since in both formulas it is only the *ratio* of these quantities that appears. Never mind—this ratio is interesting in its own right. (We will come back in Chapter 3 to the separate measurement of the electron's mass and charge.) Another problem is that neither formula could be used by itself to learn even the ratio of the charge and the mass of the cathode-ray particles, because Thomson did not know the particles' velocity. However, as has already been mentioned, this problem could be surmounted by measuring both the electric and the magnetic deflection. For

Table 2.1. Results of Thomson's experiments on electric and magnetic deflection of cathode rays.

Gas in cathode-ray tube	Material of cathode	Electric field (*N/C*)	Electric deflection (*m*)	Magnetic field (*N/amp-m*)	Magnetic deflection (*m*)	Deduced velocity of ray particles (*m/sec*)	Deduced ratio of particle mass to charge (*kg/C*)
Air	Aluminum	1.5×10^4	0.08	5.5×10^{-4}	0.08	2.7×10^7	1.4×10^{-11}
Air	Aluminum	1.5×10^4	0.095	5.4×10^{-4}	0.095	2.8×10^7	1.1×10^{-11}
Air	Aluminum	1.5×10^4	0.13	6.6×10^{-4}	0.13	2.2×10^7	1.2×10^{-11}
Hydrogen	Aluminum	1.5×10^4	0.09	6.3×10^{-4}	0.09	2.4×10^7	1.6×10^{-11}
Carbon dioxide	Aluminum	1.5×10^4	0.11	6.9×10^{-4}	0.11	2.2×10^7	1.6×10^{-11}
Air	Platinum	1.8×10^4	0.06	5.0×10^{-4}	0.06	3.6×10^7	1.3×10^{-11}
Air	Platinum	1.0×10^4	0.07	3.6×10^{-4}	0.07	2.8×10^7	1.0×10^{-11}

The electric deflections vary even for entries with the same electric field, because of differing cathode-ray velocities in the different cases. The magnetic deflections are the same here as the electric deflections, because in each case Thomson adjusted the magnetic field to give the same deflection as the electric field. I have calculated the results given in the last two columns from the data published by Thomson. Some of them differ by one unit in the last decimal place from the calculated values given by Thomson. I presume this is because the experimental data published by Thomson were rounded off from his actual data, and it was his actual data that Thomson used in his calculations.

instance, suppose we take the ratio of these two equations. The mass, the charge, and both lengths then cancel on the right-hand side, but the velocity does not cancel because it appears in one formula squared and in the other unsquared. This yields the simple result

$$\frac{\text{Magnetic deflection}}{\text{Electric deflection}} = \frac{\text{Magnetic field}}{\text{Electric field}} \times \text{Velocity} .$$

Since both field strengths were known and the corresponding deflections were measured, it was possible for Thomson to solve for the velocity. Then, treating the velocity as a known quantity, he could determine the ratio of charge to mass (or mass to charge) of the cathode-ray particles from either one of the formulas for the deflection of the ray, either electric or magnetic.

Now to the data. Thomson measured the electric and magnetic deflection of cathode rays for a number of different cases characterized by different values of the electric and magnetic fields, different low-pressure gases in the tube, different cathode materials, and different cathode-ray velocities. His results are shown in Table 2.1, which is adapted from his 1897 article in the *Philosophical Magazine*.[15] In all these cases, Thomson used a cathode ray in which the distance traveled by the ray while under the influence of electric and magnetic forces (the length of the deflection region) was 0.05 meters, and the distance that it subsequently traveled freely before striking the end of the tube (the length of the drift region) was 1.1 meters.

The two rightmost columns of Table 2.1 show values of the cathode-ray particle's velocity and mass/charge ratio deduced from Thomson's measurement of the electric and magnetic deflections. The formulas for calculating these quantities are worked out in Appendix B. Here, let us just check one set of results to see if they have been calculated correctly. Look at the first row in Table 2.1. For this run of the experiment, the electric and magnetic fields were 1.5×10^4 newtons per coulomb and 5.5×10^{-4} newtons per ampere-meter, the deduced value of the cathode-ray velocity was 2.7×10^7 meters per second, and the deduced ratio of particle mass to charge was 1.4×10^{-11} kilograms per coulomb (equivalent to a ratio of charge to mass of 7×10^{10} coulombs per kilogram). Using the formulas at the beginning of this section, we find the following deflections:

$$\text{Electric deflection} = \frac{(7 \times 10^{10}\ \text{C/kg}) \times (1.5 \times 10^4\ \text{N/m}) \times 0.05\ \text{m} \times 1.1\ \text{m}}{(2.7 \times 10^7\ \text{m/sec})^2}$$

$$= 0.08\ \text{m},$$

$$\text{Magnetic deflection} = \frac{(7 \times 10^{10}\ \text{C/kg}) \times (5.5 \times 10^{-4}\ \text{N/amp m}) \times 0.05\ \text{m} \times 1.1\ \text{m}}{2.7 \times 10^7\ \text{m/sec}}$$

$$= 0.08\ \text{m}.$$

This is in agreement with the measured deflections, which confirms that the velocity and the mass/charge ratio were calculated correctly. Incidentally, the deflection came out the same here for both electric and magnetic fields (as in the other experimental runs) for a reason of no great importance; it is just that Thomson found it convenient to adjust the magnetic field in each run until it gave the same deflection as the electric field.

The last column of Table 2.1 shows reasonable consistency. Even though the gas in the cathode-ray tube and the material of the cathode were varied from run to run, and the velocity of the cathode-ray particles varied by almost a factor of 2, the mass/charge ratios of the supposed cathode-ray particles came fairly close in all cases. This was (at least to Thomson) convincing evidence that cathode rays consisted of a single kind of particle, with a unique value of mass and charge, independent of the material of the cathode from which they were emitted.

An average of Thomson's results for the mass/charge ratio of the cathode-ray particles gives a value of 1.3×10^{-11} kilograms per coulomb. Thomson did not publish estimates of the uncertainties in his individual measurements (a failing that would cause his paper to be returned to him by any good physics journal to which it might be submitted today). However, from the spread in his values of the mass/charge ratio, we can conclude that these values must have been subject to a statistical uncertainty (in either direction) of about 0.2×10^{-11} kg/C.

Thomson's result, of a mass/charge ratio probably between 1.1×10^{-11} and 1.5×10^{-11} kg/C, can be compared with the modern value of 0.56857×10^{-11} kg/C. Evidently, Thomson did not come very close. Because his results have a fair degree of internal consistency, one suspects that there was some large systematic error in Thomson's measurements of electric and magnetic fields that pervaded all his experimental runs, but after eighty years who can tell? Thomson was not very good in handling apparatus. In fact, however, Thomson did not rely solely on his measurements of electric and magnetic deflections to determine the mass/charge ratio of the cathode-ray particles. He also employed another method, based on measurements of the heat energy deposited at the end of the tube. We will come back to this method after reviewing the concept of energy.

4.184 joules of heat energy. When mechanical energy is turned into heat energy, as in the boring of cannon barrels, or when heat energy is turned into mechanical energy, as in a steam engine, the total energy remains conserved. The beauty of this idea is that it allows us to derive precise predictions for a great many phenomena whose nature is not entirely understood. For instance, the falling of a heavy weight into a bucket of water is a pretty complicated affair, and no one would be able to work out all the details of the splashes and ripples, but the conservation of energy can be used to predict the increase of the temperature of the water with complete confidence. It is said that Joule spent time on his honeymoon verifying the predicted increase in the temperature of water after it had passed over a waterfall.

Energy Relations in Thomson's Experiment

Now we are in a position to tie up the last loose ends in our discussion of Thomson's experiment.

First, how did Thomson know the value of the electric field between the charged aluminum plates in his cathode-ray tube? In his first five experimental runs, the electrically charged aluminum plates that produced the field were connected to a 225-volt battery. This means that the work done in carrying any electric charge from one plate to the other was 225 joules per coulomb of charge. The distance between the plates was 0.015 meters. Since work is force times distance, the electric force per coulomb times 0.015 meters was 225 joules per coulomb. Dividing by the distance, we get a force per coulomb of

$$\frac{225\ \text{J/C}}{0.015\ \text{m}} = 1.5 \times 10^4\ \text{J/C m} = 1.5 \times 10^4\ \text{N/C}.$$

(Recall that the joule is one newton-meter.) This force per coulomb is just the electric field, as entered in the first five rows of Table 2.1. (The different electric fields in the last two experimental runs were obtained with batteries of 270 volts and 150 volts instead of 225 volts.)

This little calculation suggests a different way that Thomson's experiment could have been done. If the cathode and anode are attached to the terminals of a battery or generator of known voltage, then the cathode-ray particles passing from the cathode to the anode acquire a known kinetic energy per coulomb that is just equal to this voltage.* The kinetic energy is half the mass of the particles times the square of their velocity, so dividing by the charge we have

$$\text{Voltage between cathode and anode} = \frac{\frac{1}{2} \times \text{Mass of particles} \times \left(\text{Velocity of particles}\right)^2}{\text{Charge of particles}}.$$

Note that the combination of ray-particle parameters that appears on the right-hand side here is just the same as the combination of parameters that appears in the formula for electric deflection on p. 42, except that numerator and denominator are interchanged. Thus, in principle, the difficult measurement of deflection by electric forces could be replaced by a measurement of the voltage between the cathode and the anode.

This latter method was used in 1896–98 by Walter Kaufmann (1871–1947) of the Berlin Physics Institute to measure the mass/charge ratio of cath-

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*There is a unit of energy that is naturally adapted to this sort of experiment: the electron volt, the energy gained or lost by an electron (or any other particle carrying the same charge) in moving through an electrical-potential difference of one volt. For instance, if the cathode and the anode of the cathode-ray tube in Thomson's or Kaufmann's experiment were connected to the negative and positive terminals of a 300-volt battery, then each electron accelerated from the cathode to the anode would pick up a kinetic energy of 300 electron volts. Unfortunately, it was not possible to relate the electron volt to ordinary units of energy like the joule or the erg without knowing the electric charge of the electron. By the definition of the volt, the work in joules is the voltage times the charge in coulombs, so the electron volt in joules just equals the electronic charge in coulombs. Since the work of Millikan (discussed in Chapter 3) we have known that the electronic charge is 1.6×10^{-19} coulombs, so the electron volt is 1.6×10^{-19} joules (more precisely, 1.602×10^{-19} joules). We could use any unit we like for elementary particle energies, but the electron volt (abbreviated eV) has become the traditional energy unit. All physicists know that the energy required to pull the electron out of the hydrogen atom is 13.6 electron volts, the energy required to pull a proton or a neutron out of a typical medium-weight nucleus is about 8 million electron volts (MeV), and so on. The cathode-ray tubes of the 1890s produced electron beams with kinetic energies of hundreds of eV. The first accelerators, developed in the 1930s by Cockcroft and Walton at the Cavendish Laboratory and by E. O. Lawrence at Berkeley, produced proton kinetic energies of the order of 10^5–10^6 eV. Energies over 10^8 eV were reached in the late 1940s, and 10^9 eV (a GeV) was attained in the 1950s. Today there are two accelerators in the world that produce proton energies over 10^{11} eV. However, no manmade accelerator matches the highest energies found in cosmic rays. These rays consist of protons and other particles that crash into our atmosphere from interstellar or perhaps intergalactic space, carrying energies up to about 10^{21} eV. Unfortunately, the high-energy cosmic rays are infrequent and interact in complicated ways with the earth's atmosphere, so they cannot substitute for manmade accelerators.

ode rays. His result for the mass/charge ratio was 0.54×10^{-11} kilograms per coulomb—quite good in comparison with the modern value of 0.5687×10^{-11} kg/C. However, as we will see in the next section, Kaufmann held back from drawing conclusions about the nature of cathode-ray particles.

Finally, we come to the method Thomson used in 1897 to obtain his most reliable value for the mass/charge ratio. In this method, the cathode ray was directed into a small metal collector that would capture the electric charge of the ray particles and would also capture their kinetic energy, converting it to heat. The ratio of the heat energy and electric charge deposited in the collector then gives the ratio of the kinetic energy and charge of *each* ray particle:

$$\frac{\text{Heat energy deposited}}{\text{Charge deposited}} = \frac{\frac{1}{2} \times \begin{array}{c}\text{Mass of}\\ \text{particles}\end{array} \times \left(\begin{array}{c}\text{Velocity of}\\ \text{particles}\end{array}\right)^2}{\text{Electric charge of particles}}.$$

Once again, the combination of ray parameters on the right-hand side is just the same as the combination in the formula for electric deflection on p. 42 (except for the interchange of numerator and denominator), so this combination of parameters can be determined by measuring the ratio of heat to charge deposited, rather than the deflection due to electric fields, or the voltage between cathode and anode. This is another nice example of the power of the principle of conservation of energy. Thomson had no idea at all of the detailed physical processes that occur when a cathode ray hits a metal collector, but he could be confident that the increase in heat energy of the collector had to be precisely equal to the kinetic energy lost by the cathode-ray particles when they were stopped by the collector.

Thomson's results for three different cathode-ray tubes are given in Table 2.2. The second column gives the ratio of the measured heat energy to the electric charge deposited in the collector during the time (about a second) that the cathode ray was on. The third column gives the value of the mass times the velocity divided by the charge of the cathode-ray particles, as determined according to the equation on p. 52 from the measured deflection of the cathode ray by a magnetic field. The last two columns give the values of the velocity and the mass/charge ratio of the cathode-ray particles deduced from the foregoing measured quantities. The formulas for calculating the mass-to-charge ratio and velocity are worked out in Appendix E; for now let us just check that one result comes out right. If we use the deduced values of the velocity and the

Table 2.2. Results of Thomson's experiments[17] on ratio of heat to charge deposited by cathode ray and magnetic deflection of ray.

Gas in cathode-ray tube	Measured ratio of heat energy to charge deposited (*J/C*)	$\frac{\text{Mass} \times \text{Velocity}}{\text{Electric charge}}$ (*kg-m/sec-C, measured by magnetic deflection*)	Deduced velocity (*m/sec*)	Deduced mass/charge ratio (*kg/C*)
Tube 1:				
Air	4.6×10^3	2.3×10^{-4}	4×10^7	0.57×10^{-11}
Air	1.8×10^4	3.5×10^{-4}	10^8	0.34×10^{-11}
Air	6.1×10^3	2.3×10^{-4}	5.4×10^7	0.43×10^{-11}
Air	2.5×10^4	4.0×10^{-4}	1.2×10^8	0.32×10^{-11}
Air	5.5×10^3	2.3×10^{-4}	4.8×10^7	0.48×10^{-11}
Air	10^4	2.85×10^{-4}	7×10^7	0.4×10^{-11}
Air	10^4	2.85×10^{-4}	7×10^7	0.4×10^{-11}
Hydrogen	6×10^4	2.05×10^{-4}	6×10^7	0.35×10^{-11}
Hydrogen	2.1×10^4	4.6×10^{-4}	9.2×10^7	0.5×10^{-11}
Carbon dioxide	8.4×10^3	2.6×10^{-4}	7.5×10^7	0.4×10^{-11}
Carbon dioxide	1.47×10^4	3.4×10^{-4}	8.5×10^7	0.4×10^{-11}
Carbon dioxide	3×10^4	4.8×10^{-4}	1.3×10^8	0.39×10^{-11}
Tube 2:				
Air	2.8×10^3	1.75×10^{-4}	3.3×10^7	0.53×10^{-11}
Air	4.4×10^3	1.95×10^{-4}	4.1×10^7	0.47×10^{-11}
Air	3.5×10^3	1.81×10^{-4}	3.8×10^7	0.47×10^{-11}
Hydrogen	2.8×10^3	1.75×10^{-4}	3.3×10^7	0.53×10^{-11}
Air	2.5×10^3	1.60×10^{-4}	3.1×10^7	0.51×10^{-11}
Carbon dioxide	2×10^3	1.48×10^{-4}	2.5×10^7	0.54×10^{-11}
Air	1.8×10^3	1.51×10^{-4}	2.3×10^7	0.63×10^{-11}
Hydrogen	2.8×10^3	1.75×10^{-4}	3.3×10^7	0.53×10^{-11}
Hydrogen	4.4×10^3	2.01×10^{-4}	4.4×10^7	0.46×10^{-11}
Air	2.5×10^3	1.76×10^{-4}	2.8×10^7	0.61×10^{-11}
Air	4.2×10^3	2×10^{-4}	4.1×10^7	0.48×10^{-11}
Tube 3:				
Air	2.5×10^3	2.2×10^{-4}	2.4×10^7	0.9×10^{-11}
Air	3.5×10^3	2.25×10^{-4}	3.2×10^7	0.7×10^{-11}
Hydrogen	3×10^3	2.5×10^{-4}	2.5×10^7	1.0×10^{-11}

mass/charge ratio given in the first row in Table 2.2, then the formula on p. 64 gives a ratio of heat energy to charge of

$$\tfrac{1}{2} \times (0.57 \times 10^{-11}\ \text{kg/C}) \times (4 \times 10^{7}\ \text{m/sec})^{2} = 4.6 \times 10^{3}\ \text{J/C},$$

which is indeed Thomson's measured value. (Incidentally, in this experiment the electric charge deposited in the collector was typically a few hundred-thousandths of a coulomb per second, that is, a few hundred-thousandths of an ampere, so the heat energy deposited was a few hundredths of a joule per second—enough to raise the temperature of the small collector by a few degrees Celsius per second.)

Evidently this method worked much better than the one based on the measurement of electric as well as magnetic deflection. The results for the first two cathode-ray tubes show a high degree of uniformity, and yield average values for the mass/charge ratio of 0.49×10^{-11} kilograms per coulomb—not far from the modern value of 0.5687×10^{-11} kg/C. Oddly, Thomson preferred the results obtained with his third tube, which gave a value almost two times too large. It may be that Thomson preferred the larger value of the mass/charge ratio because it agreed more closely with the result he obtained by measuring electric as well as magnetic deflection. Be that as it may, for some years Thomson made a practice of quoting the mass/charge ratio as about 10^{-11} kilograms per coulomb.

We will come back in Chapter 3 to the story of how the charge and mass of the cathode-ray particles were separately measured.

Electrons as Elementary Particles

All Thomson had done so far was to measure the mass/charge ratio of whatever particles make up the cathode rays. Yet he leaped to the conclusion that these particles are the fundamental constituents of all ordinary matter. In his own words,

> *. . . we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state: a state in which all matter—that is, matter derived from different sources such as hydrogen, oxygen, etc.—is of one and the same kind; this matter being the substance from which the chemical elements are built up.*[17]

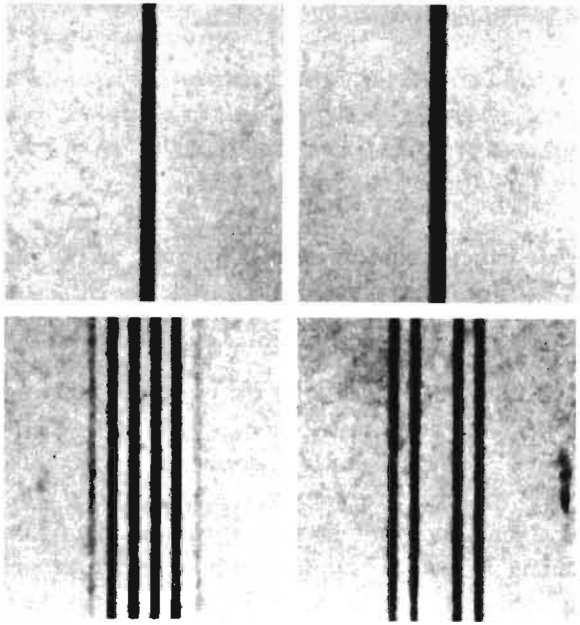
This was reaching very far. As Thomson recalled much later,

> *At first there were very few who believed in the existence of these bodies smaller than atoms. I was even told long afterwards by a distinguished physicist who had been present at my [1897] lecture at the Royal Institution that he thought I had been "pulling their legs."*[18]

Indeed, there was no way that the existence of smaller particles within the atom could be verified on the basis of Thomson's 1897 experiments. Thomson did not claim that he had proved it, but there were a number of hints that led Thomson toward his far-reaching conclusions.

The first of these hints was the universality of the measured ratios of mass to charge. The value of the mass/charge ratio of the cathode-ray particles did not seem to depend on any of the circumstances under which it was measured. For instance, as we saw in the preceding section, the value of this ratio was about the same for a tube containing carbon dioxide with an aluminum cathode as for a tube containing air with a platinum cathode (the fifth and sixth entries, respectively, in Table 2.1), even though the ray velocities were quite different. Thomson also quoted a result of the Dutch spectroscopist Pieter Zeeman (1865–1943) that indicated that similar values of the mass/charge ratio characterized the electric currents in atoms that are responsible for the emission and absorption of light.

(Zeeman had been studying the spectrum of the element sodium in a magnetic field. The spectrum of any element is the pattern of specific frequencies of the light that can be emitted or absorbed by atoms of that element. For instance, when a compound containing a given element is added to a flame and the light from the flame is broken up into its component colors by means of a prism or a diffraction grating, the band of colors will be found to be crossed with a number of bright lines at certain specific colors—colors corresponding to the frequencies of light being emitted by atoms of that element. The difference between light of one or another color is simply one of frequency; violet light has about twice the frequency of red light, and the other colors have intermediate frequencies. Similarly, when light from an unadulterated flame is passed through a cool vapor containing atoms of the element in question and is then broken up into its component colors, the band of colors will be crossed with a number of dark lines at precisely the same colors as the previous bright lines. These dark lines mark the frequencies at which light from the flame is being absorbed by atoms of the gas. The spectrum of sodium contains a pair of prominent lines known as the D lines, at nearby frequencies in orange light. It is these D lines that are responsible for the orange color of light from sodium



The Zeeman effect. A magnetic field splits the spectral lines of sodium into multiple sets.

lamps, used to illuminate many highways. Zeeman observed that these D lines, which are normally quite sharp, widen in a strong magnetic field, and that the widening in frequency is proportional to the magnetic field. It was the Dutch theorist Hendrick Antoon Lorentz (1853–1928) who, in 1896, used the numerical factor in this relation of proportionality to deduce a value for the mass/charge ratio of the carriers of electric charge in atoms. It is truly remarkable that Lorentz was able to carry through this calculation a year before Thomson's discovery of the electron, fifteen years before Rutherford discovered that atoms consist of a nucleus surrounded by orbiting electrons, and seventeen years before Bohr explained how the frequencies of the light emitted or absorbed by atoms are related to the energies of the orbiting electrons. Lorentz

made use of a theorem, devised by Sir Joseph Larmor, that the effect of a constant magnetic field on a system of charged particles, all of which have the same mass/charge ratio, is precisely the same as the effect that would be produced by observing the system from a coordinate system rotating at a definite frequency, now called the Larmor frequency. This frequency is proportional to the magnetic field and inversely proportional to the mass/charge ratio, but is otherwise independent of the nature of the particles, their state of motion, or the other forces that might act on them. For instance, a particle that is subjected only to magnetic forces will spiral around the lines of magnetic field at the Larmor frequency, which is just the same motion as would be seen if the particle were subject to no forces and traveled in a straight line at constant speed and if the observer's frame of reference rotated at the Larmor frequency around the direction of the magnetic-field lines. If a particle is subjected to other forces that in the absence of a magnetic field would cause it to move periodically at some natural frequency, then in the presence of a magnetic field its motion will be the superposition of three periodic motions, with frequencies equal to the natural frequency, or the natural frequency plus or minus the Larmor frequency, so the splitting in frequencies will be twice the Larmor frequency. Lorentz assumed that the frequencies of the light emitted or absorbed by atoms are equal to the frequencies of these motions, so that the splitting of the frequencies in a magnetic field would be twice the Larmor frequency for that field and hence could be used to calculate the mass/charge ratio of the carriers of electric currents in atoms. In fact, this interpretation of the frequencies at which light is emitted or absorbed by atoms is not correct, and happens to work only in certain special cases, *not* including the sodium D lines. Lorentz was lucky; although the frequencies of the two D lines of sodium are actually split by a magnetic field not into two frequencies each, but into four and six frequencies, respectively, and although the splittings among these various frequencies are not at all given by Lorentz's theory, Zeeman had not been able to resolve these separate frequencies, and by chance their overall frequency spread *is* approximately given by twice the Larmor frequency.)

Zeeman's measurements had provided a rough estimate of the mass-to-charge ratio of whatever it is that carries electric currents in atoms, and Thomson's work on cathode rays showed that these charge carriers are not just part of the architecture of the atom, but have a separate existence of their own outside as well as inside the atom. Thus it seemed that, whatever else ordinary matter might contain, it contained at least one common constituent, which could be emitted from metals as a cathode ray. The universality of these particles was soon to be verified when the so-called beta rays that were observed to be emitted by radioactive substances were found (by methods similar to Thomson's) to have the same mass/charge ratio as the cathode-ray particles. Thomson himself showed in 1899 that the negatively charged particles that are emitted in the photoelectric effect or from incandescent metal surfaces have the same mass/charge ratio as cathode rays.

The smallness of the particle mass indicated by Thomson's experiment also supported the idea that these were subatomic particles. It was already known in Thomson's time that the so-called ions that carry electric currents in solutions like salt water have various mass/charge ratios, but never a ratio less than about 10^{-8} kilograms per coulomb. (This will be discussed in some detail in the next chapter.) Thomson's result for the ratio in cathode rays was strikingly small compared with this. Of course, this might have meant either that the mass of the cathode-ray particles is smaller than the masses of ions or that their charge is greater, and for a while Thomson considered the possibility that both are true. However, it seemed more natural to suppose that ions are just ordinary atoms or molecules that become charged when they lose or gain a few units of electric charge, and if these units of charge were to be identified with the cathode-ray particles the charge of the ions would have to be comparable to the charge of the cathode-ray particles. It followed, then, that the mass of the cathode-ray particles would have to be less than the mass of the ions (and hence less than that of ordinary atoms) by a factor of about

$$\frac{10^{-11}\ \mathrm{kg/C}}{10^{-8}\ \mathrm{kg/C}} = 10^{-3}.$$

Thomson noted that this idea of very light cathode-ray particles fitted well with the observations of Phillip Lenard (1862–1947), who observed in 1894 (as Goldstein had done earlier) that cathode-ray particles could travel thousands of times farther through gases than could ordinary atoms or molecules. Since cathode-ray particles are much lighter than atoms, the possibility was open that they are the constituents of atoms.

Thomson was also predisposed to explain his observations in terms of fundamental particles by an atomic tradition, extending back to Leucippus, Democritus, and Dalton. In his 1897 paper, Thomson quoted the speculations of the English chemist William Prout (1785–1850), who in 1815 proposed that the few dozen types of atoms that were believed to make up the known chemical elements were composed of one fundamental type of atom, taken by Prout to be the atom of hydrogen. In Thomson's view, Prout was correct, but the fundamental "atom" was not the hydrogen atom but the vastly lighter cathode-ray particle. Would he have reached this conclusion if Prout and others had not made fundamental particles respectable? As we have seen, while Thomson was measuring the mass/charge ratio, a similar experiment was carried out in Berlin by Walter Kaufmann, with results that we now know were actually more accurate than Thomson's. But Kaufmann did not claim to have discovered a fundamental particle. Like Hertz and other physicists in Germany and Austria, Kaufmann was strongly influenced by the scientific philosophy of the Viennese physicist and philosopher Ernst Mach (1836–1916) and his circle, who held that it was unscientific to concern oneself with hypothetical entities like atoms that could not be directly observed. It is hard to avoid the conclusion that Thomson discovered the cathode-ray particle that we now call the electron because, unlike Mach and Kaufmann, he thought that it *was* part of the business of physics to discover fundamental particles.

At first, Thomson did not use any special name for his supposed fundamental particles. Some years earlier, the Anglo-Irish physicist and astronomer George Johnstone Stoney (1826–1911) had proposed that the unit of electricity gained or lost when atoms became electrically charged ions should be called the *electron*.[19] In the decade or so after Thomson's 1897 experiment, the reality of his fundamental particles became widely accepted and physicists everywhere began to call them electrons.

Notes

1. J. J. Thomson, "Cathode Rays," *Proceedings of the Royal Institution* 15 (1897), 419; "Cathode Rays," *Philosophical Magazine* 44 (1897), 295; "Cathode Rays," *Nature* 55 (1897), 453.
2. Plato, *Timaeus,* translated by R. G. Bury (Harvard University Press, 1929), p. 215.
3. Bede, *A History of the English Church and People,* translated by L. Sherley-Price (Penguin Books, 1955), p. 38.
4. W. Gilbert, *De magnete magnetisque corporibus, et de magno magnete telluro* (London, 1600).
5. S. Gray, "A Letter . . . Containing Several Experiments Concerning Electricity," *Philosophical Transactions of the Royal Society* 37 (1731–32), 18.
6. N. Cabeo, *Philosophia magnetica in qua magnetis natura penitus explicatur* (Ferrara, 1629).
7. C. F. Du Fay, letter to the Duke of Richmond and Lenox concerning electricity, December 27, 1733, published in English in *Philosophical Transactions of the Royal Society* (1734).
8. F. U. T. Aepinus, *Testamen theoriae electricitatus et magnetismi* (St. Petersburg, 1759).
9. B. Franklin, *Experiments and Observations on Electricity, made at Philadelphia in America* (London, 1751).
10. See, for example, A. D. Moore, ed., *Electrostatics and its Applications* (Wiley, New York, 1973).
11. Isaac Newton, *Philosophiae Naturalis Principia Mathematica,* translated by Andrew Motte, revised and annotated by F. Cajori (University of California Press, 1966).
12. Joseph Needham, *The Grand Titration: Science and Society in East and West* (Allen & Unwin, London, 1969).
13. *Epistola Petri Peregrini de Maricourt ad Sygerum de Foucaucourt, Militem, De Magnete* ("Letter on the Magnet of Peter the Pilgrim of Maricourt to Sygerus of Foucaucourt, Soldier").
14. H. C. Oersted, *Experimenta circa effectum conflictus electriciti in acum magneticum* (Experiments on the Effects of an Electrical Conflict on the Magnetic Needle), Copenhagen, July 21, 1820. For an English translation, see *Annals of Philosophy* 16 (1820), reprinted in R. Dibner, *Oersted and the Discovery of Electromagnetism* (Blaisdell, New York, 1962).
15. J. J. Thomson, "Cathode Rays," *Philosophical Magazine* 44 (1897), 295.
16. W. H. Brock, "The Man Who Played With Fire" [review of *Benjamin Thompson, Count Rumford,* by Sanborn Brown], *New Scientist,* March 27, 1980.
17. J. J. Thomson, "Cathode Rays," *Philosophical Magazine* 44 (1897), 295.
18. J. J. Thomson, *Recollections and Reflections* (G. Bell and Sons, London, 1936), p. 341.
19. G. J. Stoney, "Of the 'Electron' or Atom of Electricity," *Philosophical Magazine* 38 (1894), 418.