Chapter 2
The Spark that Broke the Atom

We are once again brought back to Miletus, Greece, in 585 BC, where the respected scientist – philosopher Thales, discovered electricity by rubbing fur against amber and he could even produce a spark. Since this discovery, electricity remained, more or less, a matter of curiosity and an unresearched phenomenon, until the eighteenth century, when discovery of magnetic properties of lodestone (magnetic materials found in nature) by William Gilbert and his subsequent detailed comparison of electricity and magnetism were made. Preliminary experiments such as those by C.F. du Fay on two different forms of electricity (now known to be positive and negative charges) and by Benjamin Franklin on lightning kept electricity as an interesting research field, but perhaps only still a curiosity. However, once Alessandro Volta made a reliable source of electricity by constructing a battery using alternate layers of zinc and copper immersed in an electrolyte, and Michael Faraday invented the electric motor that could replace animal and manual labor in 1821, the field of electricity had made it into the engineering field and the research on electricity and magnetism became a very profitable necessity. Following the demonstration of the connection between electricity and magnetism by Hans Oersted and Andre-Marie Ampere, and analytical descriptions of circuit currents and voltages by George Ohm, the field became a bread-and-butter activity of scientists around the world. From here on and rightly so, scientific research was concerned with the field of electromagnetism for a long time. Even today, majority of inventions and tools resulted from such research.

In the 1830s, Faraday and Ampere showed that time-varying magnetic field induced electricity and time-varying electric field induced magnetic field. This then implied the possibility of a new kind of wave to enable the coexistence of alternating electric and magnetic fields. In 1864, James Clarke Maxwell settled the issue with his discovery of the equations governing electromagnetism. These equations, which are the equivalent of Newton's laws of motion but for electromagnetism, describe the function of most of the electromagnetic devices we use today. As we shall see, even primary descriptions in many topics in this book require an appreciation of Maxwell's equations.

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Faraday's law is encoded in Maxwell's equation as

$$\nabla \times E = -\mathrm{d}B/\mathrm{d}t, \tag{2.1}$$

where t is time, E is the electric field, and B is the magnetic field induction. The left-hand side gives the "curl" operation of electric field. This states that the variation (and therefore the presence) of electric field in space (curl operator – describing variation with respect to spatial directions, perpendicular to the vector quantity) is associated with time variation of a magnetic field (which is perpendicular to the electric field). This is also the law of induction (see, for example, betatrons) which is the basis of transformers, where a changing magnetic field due to changing current in the primary induces voltage in the secondary of the transformer. Ampere's discovery of magnetic field generation by an electric current and/or time-varying electric field is described by the equation

$$\nabla \times B = \mu_0(J + \varepsilon_0 \mathrm{d}E/\mathrm{d}t). \tag{2.2}$$

(μ_0 and ε_0 are the so-called vacuum permeability and permittivity physical constants, respectively.) This complements the previous equation and states that the spatial variation (existence) of magnetic field is associated with time varying of electric field (which is perpendicular to the magnetic field) and any electric currents driven by electric fields. Obviously, the latter forms the principle behind magnets, while the former is most associated with capacitors. Two other equations,

$$\nabla \cdot E = \rho/\varepsilon_0; \nabla \cdot B = 0, \tag{2.3}$$

describe the electric field variation around a charge density and the fact that magnetic field lines are always closed, respectively (The closing of magnetic field lines implies that magnetic charges do not exist. However, existence or nonexistence of magnetic monopoles, equivalent to an isolated positive or negative electric charge, remains uncertain.). Strikingly, combining these equations one gets the wave equation

$$\nabla^2 E = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}, \tag{2.4}$$

where $c = \sqrt{1/\mu_0\varepsilon_0}$ is the speed of the wave. An identical expression for the wave magnetic field is also obtained. In an astounding discovery, when the speed of light was measured, it turned out to be the same as the speed of the electromagnetic wave. Since then, we have known that all light are electromagnetic waves capable of traveling in vacuum. We also know now that electromagnetic waves span all values of frequency feasible within nature – radio frequency waves to gamma rays.

The Electricity Carrier

All the scientists were convinced now that something precipitated to charge something electrically and ran around to carry a current. The varying ability of this carrier to run through material made the difference between good conductors and bad conductors. They even knew that chemical reaction (valence of elements) and electrolytic properties were connected to the nature of charge on atoms of elements, but did not know what this charge carrier might be. Like many physics results, the discoveries had to await technological developments, which, in turn, depended on previous scientific discoveries. While this symbiosis between science and technology is critical even today, it is only vaguely understood by general public and barely acknowledged by technologists.

It has long been known that when glass tubes are evacuated, one could pass electric current through the evacuated space in the form of arcs from a metal cathode to a metal anode. Then in the 1850s, Heinrich Geissler improved the vacuum techniques and showed that one could get glowing discharges between electrodes in an evacuated tube. In 1879, William Crookes obtained a vacuum of better than 10^{-4} mmHg and found that the tube became dark, filled with the so-called Faraday Dark Space. When other experimenters used this tube, they found that at one point, the glass behind the anode was fluorescing and painting the glass with phosphorescent coating made a very clear illuminated spot. It was surmised that a "cathode ray" was being emitted from the negative electrode and had been accelerated by the anode through the dark space. Crookes called it "radiant matter." Some others thought that these charge carriers were a form of electromagnetic radiation (ethereal disturbance), because Hertz found that the rays penetrated gold foil. It was then inconceivable that solid particles could pass through solid metal.

Fig. 2.1 J.J. Thomson's Cathode Ray Tube with deflecting electrodes and Helmholtz coils. Image No. 10324719 © Science Museum/Science & Society Picture Library

Others such as Shuster thought this was a charged atom (after all, in those days, the atom was indeed the atom, the indivisible).

The First Fundamental Particle in the First Philosophy: The Electron

Crookes did believe that the rays were negatively charged, because they were attracted by the anode. But Hertz found that these rays were not deflected by electrically charged plates, as they should have been if these were charged particles. The fascinating experiments with the marvelous discharges went on with ever improving techniques. In 1897, with these advances, Joseph John Thomson at the Cavendish laboratory in Cambridge not only finally proved that the rays were made of particles, but he also managed to determine their mass.

When J.J. Thomson repeated Hertz's experiment at a very low pressure, the rays were indeed deflected by charged plates. It turned out that in Hertz's experiment, the tube pressure was not low enough and the remaining ionized gas shielded out the electric field from the plates. At this time, the physics of electromagnetic phenomena and charge motion were well established and therefore, Thomson could make measurements and calculate the properties of the current (charge) carrier from those measurements. In his defining experiment, Thomson measured the ratio of the particle charge to its mass.

Thomson determined the charge-to-mass ratio by applying an electric field (perpendicular to the direction of cathode ray particle moving with velocity v) to bend the path of the particles, and compensated the deflection by applying a magnetic field and brought the ray back to the direction it was traveling before encountering the electric field (see Figs. 2.1 and 2.2). This used the fact that force in a magnetic field depends on the charge and the velocity with which the particle travels (The magnetic field direction has to be perpendicular to the direction of the ray as well as the deflection). Then, for a given force, the acceleration (and the velocity gained in the transverse direction after traveling certain distance in the field) depends on the mass.

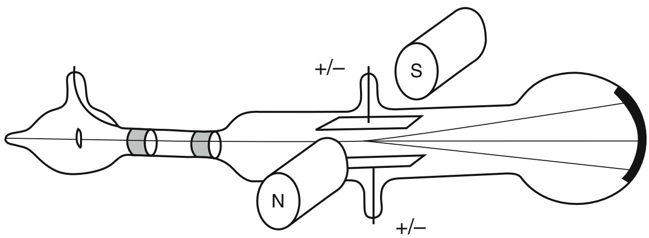

Fig. 2.2 A schematic of arrangement used by J.J. Thomson to measure electron charge-to-mass ratio

A particle with a charge $-e$ experiences a force $-eE$ in an electric field E. If a magnetic field B is applied in a direction such as to compensate the bending, then the force is eE (direction compensating). When the deflections cancel,

$$eE = -evB, \quad \text{so that} \quad v = -E/B. \tag{2.5}$$

Now, the radius of deflection of a charge was even then known to be equal to $mv/(qB)$, where q, m, and v are the charge, mass, and velocity of the ray particle and B is the magnetic field. Therefore, the deflection when only magnetic field is applied is proportional to the ratio of mass to charge. This results in the relationship which gives the ratio of particle charge to mass as

$$e/m = (\theta E/LB^2) \tag{2.6}$$

Thomson also measured the deflection angle θ of the ray when only magnetic field was present (by the arrangement described above, this is also the deflection caused by the electric field only). Each of the quantities on the right-hand side of (2.6) (where L is the length of the magnetic field region) was measured by Thomson. When he calculated it, he found the ratio of charge to mass to be very high, 2,000 times that of the hydrogen ion (positively charged hydrogen). This meant that the cathode ray particle was very light, 2,000 times lighter than that of the hydrogen ion, or it had a charge 2,000 times larger than hydrogen. From (2.5), he also determined the speed of the cathode ray particle to be about 100,000 km/s, a third of the speed of light! From the estimates of energy absorbed, he suspected that the cathode ray particle was much lighter than hydrogen. Philipp Lenard conclusively showed that cathode rays were lighter rather than being highly charged, by studying their passage through various gases (later, Robert Milliken would measure the charge of the electron to high accuracy to confirm this). Thomson concluded that the particle, whatever it was, appeared to "form a part of all kinds of matter under the most diverse conditions; it seems natural therefore to regard it as one of the bricks of which atoms are built up." He called these particles "electrons," as befitted the carrier of electricity. Thomson also invented the new method of "detecting" and measuring particles using electric and magnetic fields, which is used even today in mass spectrometers for selecting particles with specific velocities. The Cathode Ray Tube pioneered by Crookes and others forms the basis for television tubes.

When Thomson announced the discovery of electron on April 30, 1897 to an audience, they thought he was pulling their legs. This startling conclusion laid the atomic basis of matter as the indivisible building block to rest. The electron would become the first and enduring fundamental particle, and Thomson became the celebrated pioneering discoverer of a fundamental particle. To this day, there is no evidence that the electron has any underlying structure. Electron behavior influences every moment of this universe and our own lives.

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