ONE HUNDRED YEARS OF ELECTRONS

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The search for the true nature of electricity led to the discovery of the electron and the proof that it is a constituent of all atoms. These achievements gave the scientists the first definite line of attack on the constitution of the atom and on the structure of matter.

In a lecture on 'The Stability of Atoms' given to the Royal Society of Arts in 1924, Ernest Rutherford said:

The trend of physics during the past twenty-five years has been largely influenced by three fundamental discoveries made in the closing years of the nineteenth century. I refer to the discovery of X-rays in 1895, of radioactivity in 1896 and the proof of the independent existence of the negative electron of small mass in 1897.

The first two of these discoveries were revelations of totally unsuspected phenomena, rare events in the progress of science. The third was quite different - it was a watershed in the long quest to understand the nature of electricity. In the present paper we focus on the period of activity concerned with discharge in gases and cathode rays which culminated in the discovery of the electron. Finally and briefly we comment on some of the developments of the concept during the following hundred years.

Already in 1874, at the British Association meeting in Belfast, the Irish physicist George Johnstone Stoney had pointed out that, on the basis of Faraday's law of electricity, an absolute unit of quantity of electricity exists in that amount of it which attends each chemical bond or valency. This talk was later published (Stoney 1881). Stoney subsequently suggested the name *electron* for this small unit quantity of electricity (J.J. 1911/12). Hermann von Helmholtz (1881), independently, drew similar conclusions. In the Faraday lecture delivered before the Chemical Society in 1881 he declared:

If we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid concluding that electricity also, positive as well as negative, is divided into definite elementary portions which behave like atoms of electricity.

The discovery of the cathode rays by Wilhelm Hittorf in 1869 forms the first link in a chain of events that leads not only to the triumphant confirmation of the above hypothesis but also to the brilliant discoveries made in the closing years of the 19th century: that of X-rays by Wilhelm Conrad Röntgen in 1895 and that of radioactivity by Henri Becquerel in 1896.

Cathode rays occurs when electricity is discharged in a rarefied gas. At a given low pressure of the gas, rays are emitted from the negative pole, the cathode. The cathode rays themselves are invisible, but they can be observed by the phosphorescence that they induce at the walls of the glass tube and by the shadows from objects placed in their path. The cathode rays propagate in straight lines, but unlike ordinary light rays they can be deflected by a magnetic field.

The phenomena exhibited by the electric discharge in rarefied gas had long been familiar from studies by Julius Plücker, Wilhelm Hittorf, Eugen Goldstein and other physicists. In a lecture delivered before the British Association at the Sheffield Meeting in 1879, William Crookes first used the expression *radiant matter* or matter in the ultra-gaseous state, to explain the phenomena of phosphorescence, trajectory, shadows, mechanical action, magnetisation and heat associated with the cathode rays (Crookes 1901/02). Crookes considered the ultra-gaseous state a 'fourth state of matter'. In the Bakerian Lecture for 1883, speaking of radiant matter, he considered that the particles flying from the the cathode were of the dimensions of molecules (W.A.T. 1919/20). Following Crookes many British physicists held that the cathode rays were particles. In contrast, the majority of the German physicists maintained that the cathode rays were analogous to electric waves. They were inspired by Heinrich Hertz (1892) who, in 1892, had shown that the cathode rays could pass through thin sheets of metal. At Hertz' suggestion, Philipp Lenard made a kind of discharge tubes equipped with a thin aluminium window, allowing the cathode rays to enter the open air outside the tube.

At the end of 1884, when the English physicist Joseph John (J.J.) Thomson was not quite 28 years old, he succeeded Lord Rayleigh as professor and director of the Cavendish Laboratory in Cambridge. He immediately began experiments on the passage of electricity through gases. He was convinced, he later said, that "whenever a gas conducts electricity, some of its molecules must split up and that it is these particles which carry electricity" (Thomson 1926). Originally, he thought that the molecule was split up into two atoms. It was not until 1897 that he was to realize that the At the beginning of 1897 Thomson made some experiments to clarify the nature of the cathode rays, in particular to test some consequences of the particle theory (Thomson 1897). He first repeated, in a modified form, the experiment of Jean Perrin of Lille, France, to show that the cathode rays carry a negative charge.

Next, he measured the deflection of the cathode rays under an electrostatic force, the rays travelling between two parallel and electrically charged aluminium plates. Hertz had been unable to detect any deflection in a similar experiment, but Thomson showed that this was due to the conductivity conferred on the rarefied gas by the cathode rays. The deflection could indeed be detected, even in a weak electric field, provided that the vacuum was good enough. Moreover, he found that the deflection was proportional to the potential difference between the plates. Finally he measured the deflection of the cathode rays under a magnetic field. He concluded (Thomson 1897):

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.

To find out whether these particles are molecules, atoms, or matter in a still finer division, Thomson further made a series of measurements of the ratio of the mass, m, of each of these particles to the charge, e, carried by it. He devised two methods for deflecting the cathode rays, one in a magnetic field, the other in an electric field. In both cases he found that the value of m/e is independent of the nature of the gas in the discharge tube, and its value is of the order 1/1000 of the smallest value known at that time, namely the value for the hydrogen ion in electrolysis. Thomson speculated that the smallness of m/e might be due to the smallness of m, or the largeness of e, or to a combination of these two. A support for the smallness of m was delivered by Lenard, who had measured the absorption of the cathode rays by various media. From Lenard's result the mean free path in air at atmospheric pressure could be estimated to be 0.5 cm. This value is far larger than the value for the mean free path of the air molecules themselves, showing that the cathode ray particles must be small compared with ordinary molecules.

From his experiments Thomson concluded that, in the intense electric field near the cathode, the molecules of the gas are split up, not into ordinary atoms but into particles of a primordinal element, which he called *corpuscles*. These corpuscles, which are charged with negative electricity and projected from the cathode by the electric field, constitute the cathode rays. According to Thomson (1897) cathode rays represent 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, &c. - is of one and the same kind; this matter being the substance from which all the chemical elements are built up.

Thomson gave his first public account of his discovery that in cathode rays there are particles far more minute than anything previously recognized at the Friday meeting of the Royal Institution on 30th April 1897.

Commenting on his talk not three weeks later George Francis FitzGerald (1897) suggested that

"We are dealing with free electrons in these cathode rays."

There is a delightful aptness in this identification, for FitzGerald was related to Stoney, being both his nephew and his cousin! Though Thomson was the undisputed discoverer of the electron, there were others in the hunt who came close to the prize. In particular, Perrin (1965) relates in his 1926 Nobel lecture how he had already begun work involving electric and magnetic deflection of cathode rays when Thomson's 1897 paper appeared.

In his 1897 paper, Thomson tended to consider the smallness of m/e as due to a combination of the smallness of m and the largeness of e. In subsequent work (Thomson 1899) he devised a method for direct measurements of e as well as m/e, thus allowing the mass of the particles to be determined. The measurements showed that e is the same in magnitude as the charge carried by the hydrogen ion in the electrolysis of solutions. Thus Thomson had proved that the mass of the carriers of negative electricity is of the order of 1/1000 of that of the hydrogen atom, the smallest mass known at that time. This numerical result was perfectly adequate for the interpretation adopted and, if not at first very accurate, was soon improved by later experiments. By way of contrast, it followed from experiments by Wilhelm Wien on the ratio of the mass to the electric charge for carriers of positive electrification that these masses were comparable with those of ordinary atoms.

The method for measuring the charge of the ion was based on the discovery by Charles Thomson Rees (C.T.R.) Wilson that the ions form nuclei around which water will condense from dust-free air at a certain supersaturation. The problem of finding the number of ions per volume was now reduced to find the number of drops per volume in the cloud. This was done by observing the velocity with which the drops fall under gravity and by deducing the radius of each drop from a formula containing the viscosity of the gas through which the drop falls. Finally, it was necessary to know the velocity with which the ion moves under a known electric force. This parameter was determined by the New Zealand-born English physicist Ernest Rutherford, who had arrived at Cambridge in October 1895 to carry out research at Cavendish Laboratory under Thomson's guidance.

Thomson concluded that the negative charge carrier, its mass and charge being invariable, must represent a fundamental conception in electricity, or indeed in matter in any state. He proposed to regard the atom as containing a large number of smaller bodies, which he called corpuscles. With regard to their size he estimated what would come to be known as the 'classical electron radius' to be of the order of 10^{-13} cm. In the normal atom, the assembly of corpuscles forms a system which is electical neutral. Detached corpuscles behave like negative ions, each carrying a constant negative charge and having a very small mass.

The atom left behind behaves like a positive ion with a mass much larger than the negative ion. In short, the corpuscles are the vehicles by which electricity is carried from one atom to another. Thomson was convinced that there are more corpuscles in the atom than the one or two that could be torn off by processes known at that time. A strong support for this hypothesis was afforded by the Zeeman effect, which accordingly affects a large number of lines in the spectrum from a given atom.

Through Thomson's discovery of the electron, numerous strange effects observed in the past got their natural explanation. In a paper read before the Royal Society on 6th February 1902, Sir William Crookes (1901/02) summarized:

Nearly twenty-five years ago I was led by experiments in highly rarefied tubes to assume the existence of matter in an *ultra-gaseous* state. /.../ What I then called "Radiant Matter" now passes as "Electrons", a term coined by Dr. Johnstone Stoney, to represent the separate units of electricity, which is as atomic as matter. What was puzzling and unexplained on the "Radiant Matter" theory is now precise and luminous on the "Electron Theory". /.../ The electrons are the same as the "satellites" of Lord Kelvin and the "corpuscles" of J.J. Thomson.

J.J. Thomson received the Nobel Prize in physics in 1906 in recognition of the great merits of his theoretical and experimental investigations on the conductivity of electricity by gases, and he was knighted in 1908. At his seventieth birthday, 18th December 1926, he received numerous messages of congratulation from abroad. Niels Bohr, professor of the Institute of Theoretical Physics in Copenhagen wrote (Bohr 1926):

Guided by his wonderful imagination and leaning on the new discoveries of the cathode rays, Röntgen rays and radioactivity, he opened up an unknown land to science. Indeed, it is difficult for scientists of the younger generation, who are working on the new land to which Thomson has opened the gates, fully to realize the magnitude of the task with which the pioneers were confronted.

The growth in the understanding of the nature of electricity was a triumph of human curiosity, competition and cooperation. In the electron we recognize the very first of the many fundamental particles that have been proposed during this last hundred years, and it has survived where others have perished.

Advances continue, and the electron of today is not the simple entity it was: it has acquired angular momentum; it has been drawn into the quantum world where its behaviour is brilliantly captured, first by the Schrödinger and Dirac equations and later by quantum electrodynamics; it has been joined by a positive counterpart, the positron. Beams of electrons possess wavelike properties, and electron diffraction joins X-ray diffraction as a powerful probe of the structure of matter. Through the Pauli exclusion principle we understand the Periodic Table and make sense of atomic and molecular spectra, and the characteristic X-radiation. The same principle drove the development of Fermi-Dirac statistics to the puzzling shortfall in the thermal capacity of metals.

The early years of the century brought the discovery of superconductivity in metals, more recently that of high-T_c superconductivity in certain cuprates. In the closing years we find that technology has reached such a pitch of delicacy that 'artificial atoms' can be constructed: nanometer-sized metal or semiconductor systems with a few electrons designed to function as transistors or other devices.

Thus Thomson's discovery of the electron not only produced the explanation of a number of puzzling observations in the past but also opened up new fields of science. Of these the richest is surely that of the electronic structure of matter, a field of unceasing development, which has given us, amongst many other things, the electronic chip, the computer, and, ultimately, an unprecedented power of global intercommunication.

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