Chapter 13
Experimental Contact with Electrons

Abstract Both Zeeman and Thomson conducted experiments towards the end of the nineteenth century that gave evidence for the existence of the particle now known as the electron. Their experiments were responses to specific problems in nineteenth century physics and were able to take advantage of technological advances of the latter half of that century. A variety of experiments gave similar values for the ratio of charge to mass of the particles detected that were three orders of magnitude greater than estimates of that ratio for the hydrogen molecule. Further experiments soon indicated that this was due to the minute mass of the particle rather than an excessively large value for the charge. The robust character of the arguments drawn from the experiments and the extent to which they reinforced each other made it difficult to deny the existence of the electron as a component of atoms. Whilst this achievement signals the end of the story told in this book, it marked the beginning of atomic physics and chemistry rather than their conclusion.

13.1 Introduction

Strong evidence for the existence of micro-particles preceded Perrin's experiments by a decade. It was provided by experiments that involved the detection of the negatively charged particle now known as the electron. The most notable experiments were those conducted by Pieter Zeeman and J. J. Thomson and his students in the closing years of the nineteenth century, although the compatibility of their results with those produced by others, such as Emil Wiechert and Walter Kaufmann was an important dimension of the argument.

There is a reason why experimental access to charged particles such as the electron is more readily achieved than to neutral molecules or atoms. Because of their charge, electrons and ions can be manipulated by accelerating and deflecting them in electric and magnetic fields. Also because of their charge, such particles cause ionisation and act as the locus of condensation, leading to a range of effects that are readily visible. Experiments revealed that electrons and ions have a charge, and also yielded a measure of the ratio of their charge to their mass and, eventually, of their charge and mass individually. There is an irony here. In the long tradition of atomism that we have investigated in this book, an entrenched idea was the notion of brute

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matter constituting the material of atoms, characterised by some property such as impenetrability or, after Newton, mass. From that perspective, electrical phenomena associated with charged bodies experimented on in the laboratory were treated by atomists as phenomena to be explained by reference to atomic mechanisms. This view was modified by Maxwell in the 1860's insofar as he introduced a continuous aether, in addition to, and interacting with, atoms and molecules. But his aether was a mechanical aether, governed by the fundamental laws of mechanics. For the Maxwellians, charge was a discontinuity in a strain in the aether brought about by its interaction with matter. After the experiments of Zeeman and Thomson with which this chapter is concerned, the charge of particles like the electron was treated as a primitive along with their mass. As far as access to experiment is concerned, it is the charge of micro-particles that is tangible and detectable. Mass is less so, and, as a consequence, the mass of uncharged particles is measured indirectly via experiments on the charged ones. Charge, as a primitive property of micro-particles, had not been anticipated by those seeking an account of the ultimate structure of matter. Its introduction converted atomism into an experimental science in ways that had been impossible before and in a way that had not been anticipated by philosophical atomism.

The identification of charged particles at the atomic and sub-atomic level by Zeeman and Thomson was fairly direct. However, there are identifiable reasons why it was not until late in the nineteenth century that this became possible. In part the preconditions involved the development of the necessary electrical, vacuum and spectroscopic technology. In part they involved an identification of the law governing the action of electric and magnetic fields on moving charged particles now known as the Lorentz force law. Embellishments of the program were made possible by discovery of the photoelectric effect, X-rays and radioactivity. There are historical reasons, then, why scientific versions of atomism blossomed in the late nineteenth and early twentieth centuries and not before.

13.2 Historical Background to the Experiments of 1896/7

We saw in the previous chapter that by the concluding decade of the nineteenth century the kinetic theory, although not problem-free, had considerable support. That theory, in conjunction with the experimental determination of quantities such as the diffusion rate of gases, made it possible to estimate absolute parameters of molecules, their mass and size, and also the number of them in a given mass of gas. Distinct from these arguments, evidence for atoms and molecules from a quite different direction emerged in the course of the nineteenth century. They involved the electrical properties of matter including those connected with the transmission of electricity through liquids and gases, the magnetic effects of electric currents, spectroscopy, and, after Hertz's experiments of 1888, the production of electromagnetic waves by fluctuating currents. Alongside the experimental developments were two theoretical approaches to electricity and magnetism. One in vogue on the Continent involved distance forces between elements of positive and negative electric fluids. The other, the Faraday/Maxwell approach, sought to explain electric and magnetic phenomena as the results of the action of a material aether that became identified with the aether assumed in the wave theory of light. These two approaches were eventually reconciled and their mutual strengths combined in the ‘electron’ theories of H. A. Lorentz and Joseph Larmor in the 1890s. I elaborate a little on the background to the experiments of Zeeman and Thomson in the remainder of this section, drawing heavily on the work of others.[1]

After Hans Christian Oersted’s experiments of 1820 the magnetic effects of electric currents became an experimental fact. Ampère gave a theoretical treatment of these effects and of the forces acting between current-carrying conductors. He postulated ‘molecular currents’ as the cause of permanent magnetism.

A decade before Oersted detected the magnetic effect of currents, Humphry Davy had demonstrated that chemical compounds can be dissociated by passing an electric current through a solution of them. Faraday subsequently established laws of electrolysis. He observed that the weights of elements released in electrolysis by the passage of a given current for a given time are proportional to the equivalent weights of those elements. Faraday noted that his electrochemical laws combined with the atomic theory of chemical combination suggested that an equal quantity of electricity is connected with each atom, although Faraday himself was reluctant to embrace the atomic theory. Helmholtz (1881) spelt out the link between electrolytic phenomena and a fixed quantity of electricity associated with each atom in less hesitant terms half a century later. The connection between electrical and chemical phenomena had inspired Berzelius to hypothesise that the atoms and groups of them were held together in molecules by electrostatics attractions. We saw, in Chapter 9, how this idea was eventually threatened by the notion of substitution, including the substitution of electropositive by electronegative elements, that became a powerful device in organic chemistry.

Developments in spectroscopy also had links with atomism. The discovery that the emission and absorption spectra of a gas consists of light of definite frequencies characteristic of the gas in question suggested that those frequencies are associated with vibrational modes in atoms and molecules. Just as the characteristic sound frequencies emitted by a vibrating bell are determined by the size and structure of the bell, so the light frequencies emitted by a gas could be attributed to the size and structure of its component atoms and molecules. Clerk Maxwell (1965, Vol. 2, p. 463) gave clear expression to this line of thinking in the 1870s invoking the analogy with bells.

Connections between magnetism and light, such as the rotation of the plane of polarisation of light on transmission through some transparent materials subject to a magnetic field (the Faraday effect) and the rotation of the plane of polarisation of light on reflection from the pole of a magnet (the Kerr effect), were established experimentally. These results, combined with hypotheses about molecular currents as the source of permanent magnetism and atomic or molecular vibrations as the source of spectra, strongly suggested that the periodic variations that were presumed to be the source of light emitted by atoms and molecules were electrical.

Such speculations meshed with the electromagnetic theory of light developed by Maxwell from the mid 1860s. I say more about Maxwell's theory below. Here I note that it predicted that the ratio of the electromagnetic to the electrostatic units of charge be equal to the velocity of light and that the refractive index of non-magnetic materials be proportional to the square root of the constant measuring their electric polarisability, both predictions receiving experimental support. In 1888 Hertz produced electromagnetic radiation from oscillating electric currents, a possibility entailed by Maxwell's theory. As far as atomism is concerned, this reinforced the idea that spectra of gases can be traced to electrical oscillations within their atoms.

Experimental investigation of the conduction of electricity through gases, made possible by the high voltages provided by a stack of voltaic cells or an induction coil, proved to be more complex, and correspondingly less informative, than conduction through solutions. Some order emerged in the form of cathode rays. These were first produced by Julius Plücker in 1859, who took advantage of improved induction coils devised by Heinrich Rühmkorff and the possibility of producing improved vacua using the mercury diffusion pump devised by Johann Geissler, a technician in his own laboratory. Unlike the discharges at higher pressure, cathode rays are not readily visible, their presence being signalled by the fluorescence they cause when incident on a suitable target. Prior to Thomson's experiments, the nature of the rays was unclear. William Crookes and Arthur Schuster were among those who favoured the idea that they are beams of negatively charged particles whilst Eugen Goldstein and Heinrich Hertz favoured the idea that they were some kind of aether disturbance. In 1883 Hertz failed to deflect cathode rays in an electric field, thereby casting doubt on their identification as beams of charged particles.[2] Their deflection by magnetic fields was well established, however. Jean Perrin, in 1895, showed that negative charge accumulates on a collector receiving the rays.

As mentioned in the opening paragraph of this section, there were two approaches to the theoretical problem of unifying and perhaps explaining electrical and magnetic phenomena, the Continental theories that attributed them to distance forces between electrical fluids and Maxwells theory that sought to explain them by an aether and its interactions with matter. Prior to the discovery of electromagnetic radiation it was the former that had the strongest links with atomism. As well as Ampère's assumption that permanent magnetism is caused by electric fluids circulating within molecules there was the assumption that electric polarisation is due to the displacement of the fluids within molecules. By the 1870's, Wilhelm Weber, one of the most sophisticated articulators of the fluid theory, was suggesting that the electric fluids were composed of electrical particles with mass and that an atom is composed of a highly massive negative particle at its core with lighter positive particles in orbit around it. In that decade, too, Lorentz developed accounts of reflection, refraction and dispersion of light on the assumption that molecules of matter contain charge particles that execute harmonic oscillations in response to an incident light wave. We have already mentioned the incorporation of an atom of electricity associated with molecules into accounts of electrolysis. These examples show the strongest aspect of the fluid theories of electricity. They could readily be adapted to explanations of the electrical, magnetic and optical properties of materials by invoking some appropriate microstructure. However, the fields involved in electromagnetic radiation, an undeniable reality following the experiments of Hertz and which were a natural consequence of the rival theory developed by Maxwell, were alien to the Continental approach based on distance forces between current elements.

From the mid-1860s Maxwell constructed an electromagnetic theory built on Faraday's notion of lines of force and attempted to construe electric and magnetic fields as strains and vortices in an aether that he was able to identify with the medium presumed to be the seat of light waves. On this view, electric charge was the result of an interaction between the aether and matter. It was a discontinuity in a strain in the aether (the 'displacement') at the boundary between a conducting and insulating body. Maxwell's aether theory construed light as an electromagnetic wave and it received some support when the two predictions mentioned above were confirmed experimentally. The theory received a boost in 1888 when Hertz produced the radio waves predicted by it.

Maxwell construed electric charge as a discontinuity in that state of the aether that he referred to as its displacement, **D**. Electric current was equal to the rate of change of this displacement, d**D**/dt. It was this conception that made it possible for Maxwell to accommodate the idea of currents in space empty of matter (but not of aether) and to construct a theory able to predict radio waves. Displacement currents gave rise to magnetic fields, whilst changing magnetic fields gave rise to electric currents. As a consequence, changing electric and magnetic fields leapfrog each other through space, giving rise to each other and so constituting electromagnetic waves. Maxwell's theory thus readily accommodated the phenomenon that posed most problems for competitor theories based on action at a distance. However, Maxwell's theory was at a disadvantage insofar as it offered little guidance to the construction of accounts of the electrical, magnetic and optical properties of matter. For Maxwell, those properties were a result of some interaction between matter and the ether but he did not attempt to specify what that interaction might amount to. Maxwell was an atomist insofar as he accepted the kinetic theory, a theory that he did much to develop as we have seen. However, his electromagnetism involved the interaction of atoms and molecules with a continuous aether. This theme is explored in detail by Buchwald (1985).

There was a fundamental difficulty in Maxwell's theory. It involved an adequate interpretation of conduction currents, that is, of the passage of electricity through conductors. If electric currents are changing displacements of the aether, how is the current through a wire to be construed? On Maxwell's picture a conductor interacts with the aether in such a way that displacement cannot be sustained. A current through a wire consists of a constantly collapsing displacement.[3] A symptom of the problem of reconciling the notion of electric charge as a discontinuity in displacement and the idea that a current through a wire involves the transfer of electricity through it is the muddle Maxwell got into over the sign of the charge on the plates of a charged capacitor. After Faraday, a natural view is that the insulating material separating the plates of a capacitor becomes polarised, with negative electricity attracted towards the positive plate and positive charge attracted towards the negative plate. Maxwell himself frequently described the situation in this way. But this way of thinking suggests two adjacent charges opposite in sign, the charge on the conducting plates of the capacitor and the adjacent charges resulting from the polarisation of the insulator. Maxwell's identification of charge with a discontinuity in the polarisation of the aether does not leave room for this distinction between the two charges. As a consequence, he was tempted to regard the charge on the plate attached to the positive terminal of a battery as positive when considering the flow of current through the connecting wire and as negative when considering the polarisation of the aether. The resulting indecision becomes apparent in Maxwell's own writing, at one place in the form of a formal inconsistency.[4]

As Buchwald (1985, pp. 30–31) has shown, by the time he wrote his *Treatise* in 1873, Maxwell has contrived a conception of aether displacement that got around the difficulty associated with the sign of the charge on the plate of a capacitor. But other deep problems remained. As Maxwell observed on more than one occasion, a crucial feature of his theory is that all currents, including the transitory ones involved in the charging of a capacitor, flow in closed circuits. Conduction currents charging a capacitor are closed by displacement currents that involve changing displacements in the region between the plates. In Maxwell's view (1954, Vol. 1, p. 69), not only do the two currents form a closed circuit but also they are of the same kind.

> [W]hatever electricity may be, and whatever we may understand by the movement of electricity, the phenomenon which we have called electric displacement is a movement of electricity in the same sense as the transference of a definite quantity of electricity through a wire is a movement of electricity, the only difference being that in the dielectric there is a force which we have called electric elasticity which acts against the electric displacement, and forces the electricity back when the electromotive force is removed; whereas in the conducting wire the electric elasticity is continually giving way, so that a current of true conduction is set up –.

Maxwell had some picture of how changes in the elastic distortions of the aether could give rise to vortices corresponding to magnetic fields. But this picture could not apply to currents in conductors because conducting materials are presumed to negate the elasticity of the aether in some way.

In Maxwell's theory, displacement currents are readily intelligible and conduction currents are problematic. In the continental fluid theories the reverse is the case. Conduction currents involve the flow of electric fluids through conductors but displacement currents are mysterious. In the 1890's both H. A. Lorentz and Joseph Larmor came to appreciate these problems and, by slightly different routes, responded to them by separating charged bodies and the field. In their transformation of Maxwell's theory, arrangements and motions of charged bodies, which Larmor called electrons and Lorentz called ions, were the source of electromagnetic fields whilst it was those fields that exerted forces on bodies via their charge, with effects determined by their mass. The resulting theory was able to accommodate Maxwellian fields and hence account for electromagnetic radiation, the latter being an experimental fact following Hertz's experiments of 1888. It was also able to construe conduction currents and the polarisation of insulators as the flow and displacement of electrons (or ions) respectively.

One other theoretical issue needs to be mentioned. By the time Zeeman and Thomson embarked on their experiments there was general agreement on the formula for the force on a charged body moving in an electromagnetic field (now known as the Lorentz force). The force figured centrally in the theories of Lorentz and Larmor that had freed charged bodies of the field in the sense that they were no longer viewed as discontinuities in the field. The formula for the force had already been derived in the Maxwellian framework in the 1880's, through work by Heaviside, Fitzgerald and Thomson himself.[5] The force on a charge, q, moving with velocity, **v**, in a magnetic field, **H**, is q.**v**x**H**, a force that is perpendicular to **v** and **H** and proportional to each of their magnitudes. The theoretical interpretation of the force by the Maxwellians differed from that required by the theories of Lorentz and Larmor. But the important point for the present purpose is that, in 1997, Zeeman and Thomson could avail himself of an agreed-upon formula for the forces exerted by electric and magnetic fields on a moving charged body.

As the discussion of this section illustrates, nineteenth century treatments of electricity, magnetism and optics involved a range of hypotheses that attributed an atomic or molecular structure to matter. But there is a key difference between such hypotheses and those involved in philosophical theses about the ultimate structure of matter of the kind that we have discussed in detail earlier in this book. Unlike the latter, the nineteenth-century hypotheses of the physicists were not general theories of the structure of matter but specific hypotheses designed to explain specific phenomena identified in the course of experimental programmes. Ampère's proposal of molecular currents, for instance, was put forward to explain permanent magnetism taking advantage of Oersted's discovery of the magnetic effect of electric currents, not as a general matter theory. On the other hand, there was an analogy between the atomic speculations of the nineteenth-century scientists and atomic matter theories defended by natural philosophers. Both were accommodated to, rather than confirmed by the available evidence. If Amperè's molecular currents existed they could explain permanent magnetism. But did they exist? Was Ampère's explanation of permanent magnetism the right one? What was required was some detailed specification of the details concerning the molecular currents and independent evidence for them that would make it difficult to deny their existence. Similar claims could be made of the atomic hypotheses of the nineteenth-century generally. We saw in the previous chapter how Perrin was able to strongly counter objections of this kind to the kinetic theory. In the remainder of this chapter we see how Zeeman, Thomson and others were able to do likewise in the domain of electricity.

13.3 Discovery of the Zeeman Effect

Zeeman began experimental research on the interrelation between magnetism and optics in Lorentz's laboratory at the University of Leiden in 1890.[6] His focus was the interaction between magnetic and optical phenomena. His early attempts to detect the effect of a magnetic field on the sodium spectrum were not successful. He did eventually succeed to observe an effect in 1896 by taking advantage of improved spectroscopic techniques. Zeeman investigated the spectrum of the sodium in common salt situated in the flame of a Bunsen burner between the poles of an electromagnet. What he observed was that the two D-lines of the sodium spectrum, that appeared as sharply defined lines in the absence of a magnetic field, became broadened when the field was switched on. He took a range of measures to ensure that the observed broadening was indeed due a change in frequency of the emitted light rather than to some other cause such as a change in density or temperature of the sodium in the flame, which was observed to change shape under the influence of the magnetic field.[7]

Subsequent elaborations of the experiments were inspired by Lorentz's theoretical analysis of the broadening effect. After Hertz's production of radio waves it was natural to attribute the emission spectra to radiation caused by the oscillations of charged particles. Lorentz was able to spell out the effect a magnetic field would have on such vibrations by taking into effect the force, $e.\mathbf{H}x\mathbf{v}$ experienced by a particle with charge, e, moving with velocity, $\mathbf{v}$, in a magnetic filed, $\mathbf{H}$. The effect of the field depends on the direction of motion of the charged particle relative to it. Lorentz resolved the oscillations of a particle into three components, one linear oscillation parallel to the field and two oscillations circulating in opposite directions around field lines in planes perpendicular to them. The Lorentz force is zero in the first case and acts in a way that increases or decreases the frequency of oscillation in the case of the two circular oscillations. It was these changes in frequency that were held responsible for the broadening of the spectral lines that Zeeman had observed.

There were detailed consequences of Lorenz's theoretical analysis that posed an experimental challenge to Zeeman. On the assumption that the source of the radiation constituting the sodium D-lines is vibrating charged particles, Lorentz's analysis implies that when the spectrum is viewed in a direction perpendicular to the field a triplet of lines should be observed, corresponding to the three components of the vibration, one along the field and two around it in opposite directions. The light of the central line should be plane polarised and the light in the other two lines circularly polarised in opposite directions. Finally, the theoretical analysis yields a quantitative value for the line splitting. The Lorentz force, $m.\ d^2x/dt^2$, is equal to the x-component of $\mathbf{e}.v.\mathbf{H}$. The magnitude of the acceleration of the charged particle by the field is thus e/m.v.H. It depends on the ratio e/m, as well as the speed of the particle and the magnitude of the field. An acceleration of this magnitude yields a fractional change in period of vibration, T, equal to $e/m.HT/4\pi$. Since the frequency of the light and the strength of the magnetic field are known, measurement of the frequency (or period) difference between the two edges of the sodium line broadened by the magnetic field yields a value for e/m.

By the end of 1897 Zeeman had confirmed and taken advantage of these consequences of Lorentz's theoretical analysis. He improved the resolving power of his spectroscope by employing a Rowland diffraction grating and was eventually able to resolve the triplets of lines (rather than the mere broadening of a single line) using cadmium instead of sodium as a source. Lorentz's predictions about the polarisation of the light corresponding to the various lines making up the triplets were confirmed. Finally, a value for e/m for the oscillating particles was obtained.

The theoretical analysis of Zeeman's experiment rested on the assumption that the sources of light in the sodium and cadmium spectra that he observed were the vibrations of massive, charged particles subject to the Lorentz force. The fact that the spectral lines were split into a doublet when viewed in the direction of the magnetic field and into a triplet when viewed perpendicular to it were in accord with that assumption as was the experimentally-confirmed facts concerning the polarisation of the light associated with the components of the triplets. There was strong experimental support for the assumption that vibrating charged particles were the source of the spectra of sodium and cadmium.

The results of the e/m measurements were a surprise. Lorentz referred to the charged particles of his electron theory as 'ions'. While the details of the theory require only particles with charge and mass it is clear that Lorentz thought of his ions as the ions of electrolysis, that is, charged atoms or molecules. This explains why Lorentz responded to Zeeman's estimate of e/m by declaring '[t]hat looks really bad; it does not agree at all with what is to be expected'.[8] If one assumes the source of the light in atomic spectra are the movements of charged atoms corresponding to those presumed to be transported through electrolytes then 'what is to be expected' is a value for e/m derived from the mass of atoms and the value of the charge they carry, both of which can be derived using estimates of Avogadro's number readily available in 1897. The values measured by Zeeman were three orders of magnitude smaller than that! The implication, soon drawn by Zeeman and Lorentz, was that the charged particles whose vibrations are responsible for emission spectra are to be distinguished from charged atoms and molecules (ions) and are rather components of them. Zeeman was able to conclude from the direction of polarisation of the light associated with the split spectral lines that the vibrating particles were negatively charged. By the end of the century Lorentz was referring to the particles in his theory as electrons rather than ions.

13.4 Thomson's Experiments on Cathode Rays

J. J. Thomson was a follower of Maxwell. In his theoretical work he had construed charge as the opposite ends of Faraday 'tubes of force' where the tubes corresponded to vortices in the aether. This conception was the key model exploited by Thomson in his *Notes on recent researches in electricity and magnetism* that, in 1893, he presented as a sequel to Maxwell's *Treatise*. This conception repeated Maxwell's notion of charge as a discontinuity in the aether and so was not destined to remove the difficulties inherent in that conception. Thomson's experiments on cathode rays that complimented Zeeman's in leading to the introduction of the electron were not motivated by the theories of Lorentz and Larmor but the results, once available, were, like those of Zeeman, readily interpreted by and gave support to, those theories.

Opponents of the view that cathode rays were beams of charged particles countered Perrin's demonstration that interception of the rays resulted in an accumulation of charge. They argued that showing the rays to be *accompanied* by the transfer of charge did not demonstrate that they were *constituted* by a flow of charge. Thomson responded to this, in 1897, by demonstrating that when the rays were deflected by a magnetic field the flow of charge follows the deflection.[9]

The amount of deflection of a moving charged body in a magnetic field depends on the velocity, the greater the velocity the greater the deflection. The amount of deflection also depends on the ratio of the charge to the mass of the deflected body, the greater the charge the greater the deflecting force and the greater the mass the less deflection that force results in. Measuring the deflection in a magnetic field thus enabled a relationship to be deduced between two unknowns, the velocity, v, of the cathode ray particles and their charge to mass ratio, e/m.[10] One further relationship was required to enable v or e/m to be measured. Thomson provided two ways of providing the needed relationship.

In the first method Thomson built on Perrin's experiment involving the accumulation of charge. He measured both the charge accumulated and the heat generated by capturing cathode rays for a small length of time. The heat generated is equal to the kinetic energy, W, lost by the particles. If there are N of them then that energy is $1/2Nmv^2$. Thomson measured this quantity by having the rays strike a thermocouple of known mass, so that the heat gained by it, calculated from the temperature rise, gave the energy lost by the incident particles. The charge, Q, carried by the N particles is N.e, where e is the charge on a single particle. Thomson measured Q using an electrometer. Substituting Q/e for N in the expression for W yields a value for the relationship between v and e/m. The combination of this with the relationship between e/m and v deduced from the magnetic deflection experiment yielded values for e/m and for v.

Thomson provided a second way of measuring these quantities. Here he succeeded, where Hertz had failed, to deflect the cathode rays with an electric as well as a magnetic field. Thomson was able to produce lower pressures than those achievable by Hertz by taking advantage of technological advances made by manufacturers of electric light bulbs. He realised that gas is released into vacuum tubes from the solid surfaces in them, an effect that can only be countered by prolonged heating and pumping. As Thomson came to appreciate, ionisation of gas molecules remaining in the tube generates charges that swamp the effects of the electric field on cathode rays. Thomson supported this position by demonstrating that gases not adequately evacuated become conducting. In any event, Thomson showed that at sufficiently low gas pressures cathode rays are deflected by an electric field and also showed that when the pressure rose to be of the same order as Hertz was able to accomplish the deflection disappeared.

Thomson arranged for simultaneous deflections of the rays by both electric and magnetic fields. Values for these two fields that resulted in the two effects cancelling each other out leaving no net deflection enabled both v and e/m to be calculated. Various values resulting from the two separate methods differed amongst themselves and from each other by a factor of up to 3. But they were of the same order of magnitude as those obtained by Zeeman and by other researchers at the time, namely Emil Wiechart and Walter Kaufmann. As Thomson realised, they implied that the particles constituting cathode rays either have a charge that is very large compared to those they can be attributed to ions involved in electrolysis on the basis of values of Avogadro's number estimated by assuming the kinetic theory or a very small mass compared with that of atoms and molecules estimated on a similar assumption, or some combination of the two.

The conjecture that had emerged by the end of Thomson's experimental researches of the late 1890s was that the cathode particles are all alike, and are components of atoms orders of magnitude lighter than the atoms themselves.[11] Thomson had demonstrated that his values for e/m were independent of the nature of the gas in the discharge tube and of the material of the cathode from which the particles were emitted. The implication was that identical cathode particles are components of all atoms. Here Thomson's reasoning meshed with that of Zeeman. By the end of the century a range of experiments on cathode rays and other phenomena associated with what we now call the electron served to add support to the clams that what soon became known as electrons have a measurable mass and charge, are components of all atoms, and that electrolysis and conduction of electricity through gases at high pressure involve the transfer of ions, these being atoms with a dearth or excess of one or more electrons. Zeeman's experiments, in particular, supported the further conjecture that spectra are to be attributed to oscillations of electrons within atoms

Thomson himself added to the experimental support for such claims. In 1898, drawing on experimental work carried out in his laboratory at Cambridge by C. T. R. Wilson and Ernest Rutherford, Thomson (1898) devised experiments to measure the charge on ions generated in gases by the passage of X-rays. Rutherford had conducted experiments to measure the velocity of ions in conducting gases. Wilson had introduced a method, destined to have a significant future, for estimating the charge on particles. He had found that charge particles act as loci for the condensation of water droplets. By inducing condensation by rapid expansion and assuming that one water droplet was formed on each charged particle Wilson could estimate the number of charged ions by dividing the weight of water collected by the weight of each drop. He determined the later by using Stokes' law to deduce the size of a drop from its rate of fall, the method that Perrin was later to adopt in his experiments on Brownian motion that we discussed in the previous chapter. Using Rutherford's measurements of the velocity of ions and Wilson's measure of their number, Thomson estimated e/m for the ions caused by X-rays and compared the results with the value calculated for the value of the charge on the hydrogen ions presumed to carry current through electrolytes using estimates of Avogadro's number. They were of the same order of magnitude. A year later, Thomson (1899) measured e/m for particles emitted in the photoelectric effect and from incandescent filaments, achieving measurements consistent with his measurements of e/m for cathode rays. He also used the methods of his 1998 paper to measure the charge on the particles emitted in the photoelectric effect, with results of the same order of magnitude as estimates of the charge on the hydrogen ion. This latter result gave a direct indication that the large value for e/m for the particles was indeed due to a small mass rather than a large charge compared with the hydrogen ion.

Within a few years experiments by a range of experimenters in a variety of contexts gave converging evidence to support a range of claims concerning the ubiquity of electrons as small components of atoms, as the source of spectra in atoms, as comprising cathode rays and as responsible for the charge on ions through their presence or absence. Electrolysis and conduction in gases could be readily understood by appeal to ions. Already in 1898 Wilhelm Wien had employed magnetic and electric deflection to measure e/m for positive ions and this technique was to be fashioned into the mass spectrograph, so that, by 1913, Thomson's assistant, F. W. Aston, was able to distinguish the mass of isotopes. Experimental accuracy also increased to the extent that, by 1913, R. A. Millikan employed an adaptation of Wilson's techniques for measuring charge to measure the charge on the electron to four significant figures. By that time the electron was a central assumption in the Bohr theory of the atom, which met with success in a way that Thomson's own plumb-pudding model of the atom did not.

13.5 The Significance of Experiments on Charged Particles

In the introduction to this chapter I described the theoretical background to the experiments that were to vindicate atomic theory by identifying charged ions and the electron. In particular I described the theories of Lorentz and Larmor that set charged bodies free of the fields that they give rise and react to. The experimental results of Zeeman and Thomson found a ready interpretation in that theory, which has become known as the Lorentz electron theory. However, whilst experiments on electrons and ions did vindicate the Lorentz theory, formulated independently by Lorentz and Larmor, it is misleading to view the situation exclusively in that way. Theory needed to be adapted to the results of experiment in a way that was forced by the experiments and not anticipated by theory.[12]

There were two aspects of the experimental findings made by Thomson, Zeeman and others that were not anticipated. One was the large value for e/m, eventually attributable to the small value of m, for the particles now called 'electrons'. The other was the asymmetry between the role of positive and negative charges. Whilst there are positive and negative ions there appeared to be no positively charged analogue of the electron. It is significant that before 1906 Thomson did not use the word 'electron' to describe the sub-atomic particles that his experiments showed cathode rays to be. He used the word 'corpuscle'. G. Johnstone Stoney had coined the word 'electron' to describe the unit of charge, both positive and negative, presumed to accompany ions in electrolysis. Larmor had used it to describe the positive and negative vortices he considered to make up atoms in his theories of the 1890s. Lorentz adopted the term only after 1899, before that using the term 'ion' to refer to the charged particles in his theory. In the main I have tried to avoid using the term in my discussion of the history in this chapter. It was only after the experiments of Thomson and others that the referent for 'electron' in the form of a negatively charged and massive body of sub-atomic size was identified. In particular, Lorentz's 'electron theory' as developed by both Lorentz and Larmor was symmetric with respect to positive and negative charge and involved no necessary assumptions about the size of the charged particles that they assumed caused and responded to the electric and magnetic fields. However, it is clear that both authors thought of their elementary charges as corresponding to the ‘ions’ assumed in atomistic explanations of electrolysis. This explains their subsequent surprise at the values for e/m implied by experiment. The small mass of the electron and the asymmetries with respect to charge due to the part played by the electron in cathode rays, its contribution to the charge of ions by its presence or absence and its role as the source of spectra, were indeed experimental discoveries.

The nature of electricity and its connection with matter were seen as fundamental issues in the latter decades of the nineteenth century as we have seen. Thomson himself was inclined to the Maxwellian view that charge was some discontinuity in a state of the aether and adopted the Faraday tube as a device for expressing this. The experiments we have described put an end to the debate, but in an unanticipated way. Electromagnetic phenomena became explicable in terms of the motions of particles such as the electron with charge and mass generating and interacting via the electromagnetic field. Electrons give rise to radiation when they accelerate, constitute a conduction current when they flow through metals, and figure in electrolysis and discharges through gases either through the formation of ions or as cathode rays. The charge on the electron became a primitive along with its mass. This need not be interpreted as disallowing the question of what charge might be. Rather, the point is that a major programme had opened up and many explanations became possible in a way that did not require an answer to the question. The inability to explain the charge on the electron became a move analogous to Newton’s inability to explain gravity.

Although it has not been the focus of my attention, a similar fate befell fields and their relationship with the aether. The fields in Lorenz’s electron theory had been presumed to be states of a stationary aether. Increasingly, questions about the state of that aether became irrelevant, or, in the light of the Michelson-Morley and other experiments, problematic, whilst the Special Theory of Relativity was to reinforce the move to treat the electromagnetic fields as primitives. Electromagnetic waves were understood as the propagation of fields not as the propagation of states of an aether. Displacement currents in space are fluctuating electric fields that do not involve the displacement of anything. Successes of the wave theory of light in the nineteenth century notwithstanding, experiment gave no endorsement to the assumption of an aether. The same kind of experimental practice that led eventually to the confirmation of the existence of atoms and electrons led to the banishment of the aether.

The early twentieth century left many questions about atoms and electrons to be answered. Some of the answers took very unexpected forms. Wave-particle duality and the strange property of half-integral spin that it proved necessary to ascribe to the electron provide ready examples of that. The discovery of the electron was a beginning rather than the end of the story. But the experiments of Zeeman and Thomson, together with those of Perrin, mark the end of *our* story. There is no sensible reason to doubt that here we find experimental contact being made with atoms and their components. Microparticles became a part of experimental science in a way they had not been before.

The status of electrons after Thomson is no more problematic than the existence of air had been for Boyle, or, for that matter, the Ancient Greeks. Air cannot be directly seen, but its presence can be detected in a range of independent and mutually supporting ways. Air can be felt to resist compression in a syringe and can be felt in the form of a wind when forced out of the syringe. Boyle could not see air, but, by the time he had finished experimenting on it there was no doubt that there is such a thing as air, that it has a pressure, and that that pressure is responsible for the height of the mercury in a barometer. Thomson could not see electrons, but he could manipulate them in controlled and mutually reinforcing ways. By the time he had finished, and compared his findings with those of others, the existence of electrons with a specified charge and mass was as firmly established as Boyle's air pressure. What is more, the methods used to establish the two sets of results were entirely on a par. Scientific versions of atomism were the legacy of experimental science that had its serious beginnings in the seventeenth century and not of philosophical matter theories dating back to the Ancient Greeks.

Notes

1. Some key sources are Darrigol (2000), Buchwald (1985), Hunt (1991) and Arabatzis (2006).
2. For an analysis of Hertz's experiment see Hon (1987).
3. The best attempt to make consistent sense of Maxwell's view of conduction is that of Buchwald (1985, pp. 30–31) but he himself stresses the fundamental difficulties posed by this conception in Maxwell's theory as a whole. Buchwald (1985, pp. 65–70) analyses the deep difficulties the conduction current posed for Maxwell and his followers.
4. I identify the formal inconsistency in Chalmers (1973a). Siegel (1991, pp. 145–152, 180–181) has elaborated on this theme. He has identified direct evidence of Maxwell's indecision in unpublished drafts of Maxwell's 'Dynamical theory of the electromagnetic field'. The fact that there are two charges, opposite in sign, one on the conducting plate of a condenser and one on the adjacent insulator can be demonstrated experimentally by rotating either the plate or the insulator and measuring the magnetic field generated. An experiment of this kind was performed by Pender (1901). For further discussion and references see Chalmers (1973b, pp. 479–480).
5. See Hunt (1991), pp. 187–188, 236–237.
6. My account of the history of Zeeman's experiments draws heavily on Arabatzis (1992) and Arabatzis (2006).
7. These moves were analogous to those made by Perrin a decade later to establish that the motions of Brownian particles did indeed have their source in motions of the liquid in which they were suspended, as was described in the previous chapter.
8. As cited by Arabatzis (2006, p. 82).
9. Thomson, (1897). My account of Thomson's experiments draws heavily on Smith (2001c).
10. Thomson in fact gave values for m/e rather than e/m. I talk in terms of the former in line with what has become the norm.
11. A slight threat to the assumption was a small spreading of the beam resulting in a spatial extension of the fluorescent spot caused by the impact of the rays on the glass tube. The difficulty was removed within a year or two when R. J. Strutt identified the cause of the spreading as fluctuations in the voltage generated by the induction coil used by Thomson to generate the rays. See Smith (2001c, p. 42.)
12. Arabatzis (2006, p. 83) stresses this point in connection with Zeeman's experiment.