The Conceptual History of the Classical Electron

Submitted by Anna-Eugenia Binnie B.Sc. Dip. Ed.

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Contents

Summary

This work examines the notion of the "Scientific Revolution" as it may be applied to the development of a single concept: that of the electron. It spans a period of approximately 400 years and traces the development of both the theoretical as well as the experimental work which finally led to the concept of the electron.

The concept of the "Scientific Revolution" as developed by Thomas Kuhn will be examined and discussed with respect to whether it may be directly applied to the areas of electricity and electromagnetism. It will become apparent that each significant series of new discoveries in this area was preceded by the development of various devices which allowed these discoveries to be made. Specifically the development of vacuum pumps, vacuum tubes, reliable sources of electricity and the cloud chamber will be discussed in some detail.

The discussion will start with the early documented discoveries and speculations on the nature of static electricity and magnetism. The development of Volta's pile allowed work to commence on the effects of a continuous current of electricity and later into the electromagnetic nature of this current. This will be followed by the work on electrical discharges in evacuated glass tubes which ultimately led to the discovery of the particle nature of cathode rays.

The focus of this thesis will be on the work carried out in the later part of the Nineteenth Century, much of it in the Cavendish Laboratory at Cambridge. A detailed discussion of the work of J.J.Thomson and his students C.T.R.Wilson, J.Townsend, H.A.Wilson and E.Rutherford will be made. The work of the Dutchman, P.Zeeman will also be considered since the discovery of the Zeeman Effect and its subsequent explanation supported the existence of a negatively charged subatomic particle.

The experimental determination of the magnitude of the unit electric charge on the electron will also be discussed from the early work at the Cavendish to R.A.Millikan's successful oil drop experiment and the later X-ray diffraction methods. This section will conclude with a description of T.H.Laby's work in Melbourne around 1940.

This work will conclude with a brief exposition of the theoretical development of the electron theory of matter. Specifically the work of J.C.Maxwell and H.A.Lorentz will be examined against the background of the concepts of the aether and force at a distance. Since this is a history of the classical electron the vast history of the development of quantum ideas is not a part of this story consequently the final chapter will very briefly mention the developments of quantum mechanics and the development of modern atomic theory.

Certificate of Submission

This is to certify that this thesis had not been submitted for a higher degree to any other university or institution.

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Introduction

In the development of Western European history certain periods stand out as being times in which immense changes occurred in human society. These changes were marked by new geographic discoveries, changes in the structure of society, new scientific discoveries, and technological advances and changes in religious attitudes and in the ways in which these religious beliefs were expressed. The Renaissance, the Reformation and the Enlightenment are three such periods. These changes which occurred in Western society appeared revolutionary and indeed the Enlightenment ended with a political revolution; the French Revolution.

By the mid Eighteenth Century a number of significant advances had occurred in all the sciences which were studied at this time: in Astronomy with the Copernican model of the Solar System supported by observations using telescopes, in Chemistry with the discovery of Oxygen and the atomic theory of Dalton, in Mathematics with the development of calculus and mechanics and in Natural Philosophy with the developments of electricity. These sudden and significant changes which started in the Sixteenth Century and continued into in the Eighteenth Century were termed a "Scientific Revolution". This expression had been coined by mathematicians such as J.d'Alembert (1717-83) when he observed that "*Once the foundations of a revolution have been laid down it is almost always the succeeding generation which completes that revolution."*[1] This statement was made in 1759, at which time d'Alembert believed that this "scientific revolution" was still in progress. This two hundred year period is also termed the Enlightenment.

When one observes the developments in scientific thought during the last century or so, certain discoveries and theoretical developments stand out as distinct turning

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1 p 1 Harkins 1985

points at which scientific thought appeared suddenly to change direction and start to develop along different lines. These sudden changes in direction could be called "Scientific Revolutions", a term which has been developed and formalised by Thomas Kuhn (b 1922). According to Kuhn "*scientific revolutions are taken to be those non-cumulative developmental episodes in which an older paradigm is replaced in whole or in part by an incompatible new one"*. [2]

Kuhn uses the term "paradigm" to refer to an achievement which is "*sufficiently unprecedented to attract an enduring group of adherents away from competing modes of scientific activity"* and "*sufficiently open-ended to leave all sorts of problems for the redefined group of practitioners to resolve"*. [3] Thus the concept of a paradigm includes both the theoretical explanation of a phenomenon as well as the methodology of empirical investigations or as Kuhn later states "*a paradigm is an accepted model or pattern"*, it "*is rarely an object of replication"*, and *"is an object for further articulation and specification under new or more stringent conditions"*. [4] Kuhn further defines the phrase "normal science" to mean "*research firmly based upon one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice"*. [5] Hence, Kuhn's "normal science" has both a historical and cultural bias in its definition.

Further normal science consists in the "*actualisation achieved by extending the knowledge of those facts that the paradigm displays as particularly revealing, by increasing the extent of the match between those facts and the paradigm's predictions"*. [6] Scientific research in this case "*is directed to the articulation of those phenomena and theories that the paradigm already supplies"*. [7] Consequently, Kuhn

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[2] p 92 Kuhn 1970
[3] p 10 Kuhn 1970
[4] p 23 Kuhn 1970
[5] p 10 Kuhn 1970
[6] p 24 Kuhn 1970
[7] p 25 Kuhn 1970

believes that normal science aims to perpetuate the paradigm to which earlier discoveries have led. Scientific research, under normal conditions aims to perpetuate the status quo and little more.

Kuhn's definition of scientific revolutions is further expanded to include "*discoveries as revolutionary"*[8] and are "*inaugurated by a growing sense that an existing paradigm has ceased to function adequately in the exploration of an aspect of nature to which that paradigm itself had previously led the way"*.[9] Finally, Kuhn states that "*scientific revolutions need seem revolutionary only to those whose paradigms are affected by them. To outsiders they may seem normal parts of the developmental process"*.[10] One could assume that Kuhn is implying that scientific revolutions are events or discoveries which cause a paradigm shift, be it sudden or gradual. The periods of scientific activity between these scientific revolutions are periods of "normal science" during which scientific activity is concentrated on reinforcing and strengthening the current paradigm or model and observations not in accord with the current paradigm are admitted grudgingly into the corpus of scientific knowledge.

Kuhn further states that in the early developments of scientific inquiry there was a period in which all the facts related to that inquiry were regarded as being equally relevant. Scientific activity in this period was almost random. Once a paradigm had been established, then scientific activity gained a direction and attempted to support that paradigm.[11] Finally when Kuhn discusses a change in paradigm, the new paradigm is such that it "*is not only incompatible but often actually incommensurable with that which has gone before"*.[12] This change from one model to a new one which is incompatible with the old implies that once a paradigm change has occurred then many aspects of that discipline have changed also. These changes could even include the empirical investigative methods.

[8] p 8 Kuhn 1970
[9] p 92 Kuhn 1970
[10] p 72-3 Kuhn 1970
[11] p 15 Kuhn 1970
[12] p 103 Kuhn 1970

Kuhn's essay "*The Structure of Scientific Revolutions"* does not account for the continual gathering of data and its progressive and gradual synthesis into a model which is continually changing. Kuhn suggests that the progress of scientific advances commences with a near random acquisition of data which at some point is synthesised into a model or paradigm. Further activity on this model is then designed to reinforce or enhance it and continues until such a time that sufficient contradictory data has been gathered or phenomena observed to cast doubt on the original paradigm or to contradict the paradigm. At this time a new model or paradigm is developed which accounts for these new data or phenomena and supplants the old paradigm, being "incommensurable" with it. A scientific revolution has occurred.

In popular non-scientific usage, the idea of a scientific revolution implies that various scientific advances, either empirical or theoretical or both, appear suddenly, in a number of places, almost instantaneously. This does not happen by accident. Non-scientific observers often fail to recognise the immense amount of work carried out by forgotten scientists, often over several generations, as they strive to understand the ultimate truth of their discipline.

A science which is based on the gathering of observable and reproducible data, discovering any patterns that may exist, and developing a theoretical model which will account for the immediate observations as well as making some prediction of the phenomena which would occur in other conditions. The strength of any scientific model is based on its ability to explain the known facts as well as to predict correctly future events. This methodology, while accepted today, itself developed as scientists sought techniques for developing their understanding of their world. Even the methods of communicating scientific ideas and experimental observations and the discussion and development of possible models have evolved over time, as has the socio-economic background of those individuals engaged in scientific inquiry. The era of the professional scientist developing models of the world and then attempting to verify these models is relatively recent. Science was once the domain of those men and women with the leisure and economic freedom to indulge in such activities.

When discussing scientific revolutions, one rarely, hears of the technological revolution that, in many cases, occurred just a short time earlier. Even Kuhn, though a historian of science, seldom mentions the developments in technology. In fact, technology or the development of tools which enable the experimenter to measure previously intractable quantities and to produce or refine experimental apparatus, is an essential ingredient in the story of scientific endeavour. Often it is the development of certain tools that allows scientists to engage in the discovery process which ultimately leads to scientific revolutions.

Even the communication of scientific knowledge is dependent, at least to some extent on the technology of the time, though the importance of human contact in which individuals discuss their discoveries and their apparent failures, stimulating each other to try again or to start all over again, should never be overlooked. The explosion of scientific thought and experimentation that occurred during the Enlightenment may well have been depended on the invention of the printing press in the Fifteenth Century. Ideas may be shared among those working in the same field as well as among individuals whose disciplines seem unrelated. Sometimes ideas are passed from one generation of scientists to the next in much the same way as children learn from their parents. Schools or trends in scientific thought may thus develop.

Finally, the individuals involved in scientific endeavour represent different social classes at different times in human history and in different places. While science in Europe was once open to any interested individual with the time, patience, and economic resources to indulge in the pursuit of knowledge, today the scientist tends to be a university trained professional engaged in the discovery process and working for a salary.

The story of the conceptual development of the electron is one which covers a period of five hundred years. It started as the phenomenon of electrical attraction which had been known from antiquity. As the social organisation of science evolved, allowing groups of literate and educated individuals to explore these phenomena further, the development of agreed experimental and scientific standards started to occur. Individuals now communicated their observations, discussed and shared their ideas. In the centuries after Galileo ideas and phenomena were divorced from the supernatural and a belief was developed that the universe could be explained as a mechanism.

Kuhn cites the development of the concepts of electricity in the first half of the eighteenth century and the research which allowed this development as an "*example of the way a science develops before it acquires its first universally received paradigm*". [13] Kuhn, continues to use the development of electrical theory during the eighteenth and nineteenth centuries as examples to his various arguments concerning the nature of paradigms and normal science. [14] Further, Kuhn also uses the introduction and final acceptance of Maxwell's electromagnetic theory of light as an example of a paradigm shift and hence a scientific revolution. [15]

The development of the concept of the electron encompasses both of these two examples that Kuhn cites in support of his theories. When one studies, at some depth the development of the concept of the electron, one sees a gradual development of ideas about electricity. This development is nurtured by the technological developments which allowed the production of static electricity and a flow or current of electricity. This nurturing was further enhanced by discoveries in

[13] p 13 Kuhn 1970
[14] p 10-22 Kuhn 1970
[15] p 107-110 Kuhn 1970

areas quite divorced from electricity; i.e. work on air pressure, the vacuum and vacuum pumps. Consequently, one could question whether Kuhn's account of these developments in electricity and electromagnetic theory of light capture the reality of the development of these concepts of electricity, electromagnetic radiation and the electron. A careful analysis might suggest a gradual development of the concept of the electron with no scientific revolution, no paradigm shift and no random method of research. The detailed history suggests a continuous and cumulative gathering of data from which certain patterns slowly emerge. These patterns form the basis of a theoretical construct which is continually revised and reviewed.

The early electrical experimenters, instead of attempting to reinforce the established model, attempt to discover new phenomena or properties associated with electricity. In this process technological advances are made which provide researchers with new tools to allow them to further probe the mysteries of electricity, thus allowing further additions of data and further modifications to the theoretical constructs. As this process continues the models are constantly revised until the more modern models may have no resemblance or may even appear incompatible with earlier theories. However, this ultimate incompatibility resulted from innumerable minuscule changes in the concept of electricity, not from a "revolution".

Moreover, sudden discoveries, it will be shown, result from advances in research equipment e.g. the development of vacuum pumps or the development of the Geissler tube. These discoveries, in themselves, do not lead to abrupt changes to theoretical models. They give the impression of being revolutionary but in reality are cumulative.

The development of electron theory also required the discoveries in other areas of science such as the experiments on air pressure which led to the concept of a vacuum. A series of devices to produce at least a partial vacuum were developed, the vacuum pumps. This, together with the development of high voltage friction machines, led to the observation of gas discharge glows. These glows formed a new area of study. Consequently the early developments of electron theory required several distinct roots which were themselves developed independently. Later, the development of other roots would be required to develop and synthesis this theory; the developments required would be in the areas of meteorology, light and mathematics.

For a time the advances in the observation of the properties of glow discharges in gases came hand in hand with the development of better vacuum pumps, better designed discharge tubes, and more reliable sources of high voltage power supplies. The properties of these so- called "cathode rays" after 1860, were noted and speculated on by the scientific community. By this stage, instruments had been developed to detect and measure the magnitudes of charges, electric currents and electric potential, thus allowing experimenters to start replicating experiments and later modifying them or developing new techniques. The modern approach to empirical science was now well established.

From Newton onwards, the use of mathematics had been developed not only as a descriptive tool for calculating the magnitudes of interactions, but also as a model of the real world. The theoretical models of Maxwell, and later Lorentz, allowed predictions to be made as to the behaviour of electrons under conditions which at that time had not been observed empirically. The use of mathematics changed in the late Nineteenth Century from being a merely descriptive tool to being a powerful predictor or model. Maxwell's equations were the first spectacular example of this new role for mathematics. The model could then be verified when the technology had developed sufficiently to provide the experimenters with the tools required.

As experimental evidence concerning the properties of cathode rays and finally electrons was accumulated, this knowledge was communicated within the scientific community in a number of ways. The first and most direct was from teacher to student such as occurred in the Cavendish laboratory. As one teacher stimulated his student (there were very few women at this time engaged in scientific research), this student would in turn stimulate his own students. The academic paper presented at meetings, lectures, symposia and discourses was the method most widely used, particularly in the Eighteenth and Nineteenth Centuries. The scientific societies which emerged throughout the seventeenth and eighteenth centuries and continued during the nineteenth centuries also assisted in the dissemination of information not only to the active researcher but also to interested non-scientists. Such societies included the Royal Society and the Philosophical Societies of Cambridge and London, the Berlin Academy of Science, the Russian Academy, the Paris Academy of Science and the Swedish Academy of Science, to name but a few. Many of these societies published pamphlets and papers many of which were later collected and printed as proceedings of meetings at which these discoveries or developments were communicated. The academic publication as a pamphlet or in journal form has been one of the main media for communicating new discoveries since the Seventeenth Century. Letters and other correspondence also played their part.

While Kuhn has defined and formalised the notion of a "scientific revolution" he ignores the contributions made to science from developments in technology. The developments in technology often also require developments in science e.g. the development of the Geissler tube could not have occurred without the development of the vacuum pump which could not have occurred if the concept of air as a substance whose weight gave rise to a pressure and which could be pumped out of a closed volume producing an absence of air or any matter i.e. a vacuum, had not been developed. As will further be shown, cathode ray experiments could not have been conducted without both vacuum tubes and reliable sources of high voltage electricity. The development of a tool or experimental device often led to new discoveries.

Kuhn does not account for the contributions of a variety of sources in the development of a concept. Scientific progress, rather than being a linear progression, will be shown to depend on the development of a variety of branches which merge into the scientific concept at different times and with different effects. For instance the early development of electric theory had its roots in the early ideas on magnetism. Electron theory later required the discoveries in the refractive properties of visible light, the emission and absorption spectra of elements as well as the theoretical developments of electromagnetic radiation i.e. Maxwell's equations.

The story of the electron will be developed largely following a chronological path. Chapter 1 will discuss the early discoveries of electricity and magnetism as well as the early theories which attempted to explain their existence. While it is recognised that both the Ancient Greeks and Chinese were aware of the existence of both electrostatic attraction and magnetic attraction, neither civilisation utilised or explored these phenomena to any extent. It should be acknowledged that the Chinese used lodestones as navigational aids in the form of primitive compasses. The discussion of these early discoveries will start in the Seventeenth Century with William Gilbert's work on magnetism. The parallel observations of electrostatics commenced during this same period when Niccolo Cabeo discovered electrostatic repulsion. The developments in the fields of electricity and magnetism follow similar paths which at times run parallel to each other and at other times cross, revealing the inter-related nature of electricity and magnetism. The work of Michael Faraday was the culmination of early discoveries in the areas of electricity and magnetism.

The discovery and observation of barometric light occurred only after Torricelli had demonstrated his famous vacuum, in 1644. The development of the Torricellian vacuum ultimately led to the development of vacuum pumps. The desire to discover the nature of barometric light also inspired the development of more efficient vacuum pumps and the development of more effective and reliable sources of high voltage electric power. The desire for more highly evacuated glass vessels in which to observe these phenomena culminated in the development of the Geissler tubes. The development and use of electric power for these tubes are discussed in Chapter 2.

By the middle of the Nineteenth Century, systematic experiments were being carried out using Geissler tubes and the discovery of cathode rays was made. Chapter 3 traces the main work carried out in both Europe and Britain on these cathode rays. Some ideas as to the nature of these rays are also presented in the chronological order in which they occurred.

The development of the cloud chamber and the associated technologies used in the exploration of cathode rays and radioactivity will be discussed in Chapter 4. In particular, the development of Wilson's Cloud Chamber will be followed. The beginnings of the cloud chamber are not found in University laboratories, but in observations made of atmospheric phenomena. It was noted that with increased industrialisation urban Britain was subject to apparently more fogs than the relatively pristine environment of rural Scotland. It had been observed that the air in the Scottish highlands could be saturated with water vapour and yet not produce a fog while in the English cities fogs appeared even when the air was not saturated with water vapour. While the cloud chamber was not directly used in any empirical way to determine the nature of either cathode rays or electrons, its development led to the use and development of an expansion apparatus to suddenly cool supersaturated air. This in turn produced clouds of charged droplets which were studied to determine the charge of the fundamental unit of electricity.

The famous work on cathode rays by J.J.Thomson, featured in generations of elementary physics texts, will be discussed in Chapter 5. The work carried out at the Cavendish laboratory by Thomson and his students on the determination of the fundamental unit of electric charge will be discussed in Chapter 6. By this time, it had been accepted that cathode rays were subatomic particles carrying a unit electric charge.

Chapter 7 will explore the determination of electric charge e from the early work of Robert Millikan and his oil drop method. It will be followed by other methods of determining e, in particular the X-ray diffraction method and finally conclude with Laby and Hopper's oil drop method completed in the 1940's in Melbourne.

An important phenomenon associated with subatomic electrons, the Zeeman effect and its discovery will be discussed in Chapter 8. This work was based on Faraday's later work, but the more powerful induction coils and finer diffraction gratings available at the end of the Nineteenth Century enabled this phenomenon to be observed and explored.

Finally, Chapter 9 includes a brief overview of Maxwell's theories on electromagnetic fields and Maxwell's field equations. This overview is developed historically with a brief discussion on the development of the concept of the aether and the manner in which this model had been utilised. Chapter 9 concludes with Lorentz's refinements to Maxwell's field equations and the development of the Lorentz Theory of Electrons.

This study will not include the developments of Relativity, Modern Quantum Mechanics or Wave-particle Duality, all of which constitute aspects of Modern Physics. While the concept of the electron was developed and refined through the emergence of all three aspects of theoretical physics and their subsequent discoveries, this discussion is restricted to the developments of Classical Physics. The work of H.A.Lorentz is the bridge between Classical Physics and Modern Physics and consequently provides an appropriate conclusion to this discussion.

While it is recognised that mathematical models had been used since the time of Newton to describe and predict the behaviour of mechanical entities, from the time of Lorentz the use of the mathematical model developed a greater significance. Until the time of Maxwell and Lorentz, scientists, on the whole, made observations and then attempted to explain their observations either in philosophical terms or by developing a mathematical model which in most circumstances could be described using concrete models. From the early decades of the Twentieth Century, a mathematical model was accepted if it could systematise existing observations. If this model could also predict the behaviour or the existence of some yet unknown phenomena, and if such a behaviour or phenomena is later observed, then this model would be regarded as a reliable and accurate model.

The focus of scientific endeavour was now switched to proving or disproving the validity of existing models. The previous amateurish and enthusiastic approach of investigation for the sake of perhaps discovering something new has slowly been replaced by a far more methodical approach by professional scientists. Kuhn might call this change a paradigm shift. However, this change in approach to scientific research and the use of mathematical models is not completely incompatible with the classical approach, although the two methods are different. One could even suggest that the modern approach evolved or developed from that of Classical Physics in much the same way as a child learns mathematics. Initially, the child learns through the manipulation of concrete objects and later learns to abstract these ideas until the objects are no longer necessary. The objects are then replaced by symbols and processes and new concepts are then developed through the manipulation of these symbols.

1. Early Concepts of Electricity and Magnetism

1.1. Early Investigations into Magnetism

Since the time of the ancient Greeks the phenomena produced by both lodestones and amber were known and documented. Lodestones were known to attract iron, while amber, when rubbed was known to attract light objects. These phenomena although widely studied at this time were largely forgotten and consequently ignored until the Middle Ages. In 1269 Pierre de Maricourt, also known as Peregrinus, mapped the magnetic field of a rounded lodestone. He placed a compass needle on the lodestone and marked the position of this needle on the stone. He found that the paths traced by the needle were circular and passed around the stone. Further, the paths all crossed at two points each located on opposite sides of the stone. This appeared to be very similar to the way in which the meridians pass around the earth crossing at the poles. Consequently Peregrinus suggested that these two points be called the poles of the magnet. Further, he noted that the way in which magnets attracted each other depended solely on the position of these poles. [1]

Almost 400 years later, in 1600, William Gilbert (1544-1603) wrote *"De Magnete"* in which he describes numerous experiments as well as developing a number of theories based on these experiments in both electricity and magnetism. He appears to be the first person to have observed and noted the similarities and differences in the behaviour of magnets and rubbed amber i.e. in magnetism and electricity.

Gilbert was born in Colchester, England in 1544. In 1558 he entered St. John's College Cambridge and then in 1560 he went to Oxford. In 1573 he was elected Fellow of the Royal College of Physicians and was appointed physician to Queen Elizabeth 1. He died in 1603. [2]

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[1] p 33-4 Whittacker 1951
[2] p ix Gilbert 1958

In *"De Magnete"* Gilbert describes an instrument called a *"versorium"* which comprised of a needle set on a sharp point so that it was free to move. When he brought amber which had been rubbed i.e. was charged, the needle moved toward it. He found similar results for a number of other materials which included sealing wax, hard resin and gem stones such as diamond and sapphire.[3] These materials which could be charged by friction, Gilbert called *"electrics"* and are known today as insulators. Gilbert states *"when rubbed electrics were suddenly applied to a versorium, instantly the pointer turns, and the nearer it is to the electric the quicker is the direction"*[4] and *"in addition to the attracting of bodies, electrics hold them for a considerable time. Hence it is probable that amber exhales something peculiar that attracts the bodies themselves, and not the air."*[5] This *"something"* exhaled by amber, Gilbert termed the *"effluvia"*[6] Further, Gilbert states that *"it pleases us to call electric force that force which has its origin in humours."*[7] A humour was thought to be a solidified fluid which was particular to these "electrics" and hence Gilbert believed that it was this aspect of "electrics" which actually produced the electric force.

This electric force could attract other objects and could thus be compared to the attractive nature of magnetism. Gilbert states that *"a lodestone attracts only magnetic bodies; electrics attract everything. A lodestone lifts great weights. ... Electrics attract only light weights."*[8] He also noted that *"a lodestone does repel another lodestone; for the pole of one is repelled by the pole of another ... driving it, it makes it turn round so that they may come together perfectly according to nature."*[9] This describes the behaviour of a magnet being turned by another until two unlike poles come near each other. Electricity did not seem to have a comparable form of

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[3] p 79 Gilbert 1958
[4] p 88 Gilbert 1958
[5] p 89 Gilbert 1958
[6] p 90 Gilbert 1958
[7] p 85 Gilbert 1958
[8] p 86 Gilbert 1958
[9] p 176 Gilbert 1958

behaviour at this time. The repulsive property of electric charges was discovered some 26 years later, in 1629.

As an educated Elizabethan, Gilbert was acquainted with the philosophical ideas of his time. In particular he would have studied Aquinas' interpretations of Aristotle and would have known of the doctrine that all objects are composites of form and matter. Hence he suggested that *"in all bodies everywhere are presented two causes or principles whereby the bodies are produced, to wit, matter (materia) and form (forma). Electrical movements come from the materia, but magnetic from the prima forma; and these two differ widely from each other and become unlike."*[10] Further he states that *"electrical bodies have material, corporeal effluvia."*[11] This effluvium was emitted from the electric when it was rubbed. It was thought to be a sticky elastic material cloud which made direct contact with any object which was attracted by the electric. *"The effluvia spread in all directions: they are specific and peculiar and different from the common air; generated from humour; called forth by calorific motion and rubbing, and attenuation; they are as it were material rods - hold and take up straws, chaff, twigs, till their force is spent or vanishes; and then these small bodies, being set free again are attracted by the earth itself and fall to the ground."*[12] This concept of effluvia was to be developed over the next 150 years to explain the various properties of static electricity, as will be further developed in this chapter.

Gilbert recorded numerous other experiments on magnetism. One included his work on a miniature globe made of magnetite called a terrella. By mapping the magnetic field of this terrella using a lodestone, Gilbert discovered that:-

1) *"the magnetic force is given out in all directions around the body; around the terrella it is given out spherically."*[13]

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[10] p 85 Gilbert 1958
[11] p 106 Gilbert 1958
[12] p 468 Holton & Roller 1965
[13] p 123 Gilbert 1958

2) *"the (magnetic) poles are dominant in virtue of the force of the whole, for all the forces of the hemisphere tend north, and , conversely, all those of the other hemisphere tend south."*[14]

3) *"meridians, too, indicate tracks from pole to pole, passing through fixed points in the equator; along such lines the magnetic force proceeds and gives direction"*[15]

4) *"the supreme attractional power is at the pole, while the weaker and more sluggish power is in the parts nigh the equator"*[16]

5) *"the earth's centre is the centre of the earth's magnetic movements, though magnetic bodies are not borne direct towards the centre in the magnetic movement save when they are attracted by the pole."*[17]

Thus from this work, Gilbert concluded that the earth behaved as a magnetite terrella and it was the earth's magnetic field which could account for the behaviour of lodestones and compass needles. Finally, Gilbert was the first known person to use iron filings in his experiments with lodestones. His discoveries are reproduced regularly in classrooms where children explore the behaviour of magnetic field lines. Some of Gilbert's observations are summarised in his words, *"Steel filings strewed on paper rise on end and present the appearance of stubby steel hairs when a lodestone is brought near above them; when the lodestone is applied beneath, the hairlike crop also rises... Steel filings, when the pole of a lodestone is brought near, coalesce into one body; but when it would come to the lodestone, the body is broken up and rises to the steel in smaller masses that still hold together. But if the lodestone be beneath the paper, the consolidated masses break up as before, and into very many parts, each of which consists of a multitude of grains; and they remain united, like separate bodies; and while the lower most parts of these eagerly follow the pole of the lodestone beneath, so the separate masses stand like solid magnetic bodies."*[18]

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[14] p 117 Gilbert 1958
[15] p 125 Gilbert 1958
[16] p 129 Gilbert 1958
[17] p 150 Gilbert 1958
[18] p 162 Gilbert 1958

1.2. Early Experiments on Electricity

A few years after Gilbert's death, an Italian Jesuit, Niccolo Cabeo (1585-1650) observed that electrical charges could not only attract but were capable of repulsion in much the same way as the phenomenon of magnetism. [19] Cabeo, as many Jesuits of this time, was trained in Theology as well as the Sciences. He was described as a moral theologian and mathematician and taught in both these disciplines. Further, Cabeo in his *"Philosophia Magnetica"* published in 1629, described the paths transcribed by iron filings placed on paper over a magnet as *"lines of force"*. [20] This later concept was adopted by Faraday, independently, in the 1820's with his work on electricity and magnetism.

By the 18th century electricity was regarded as a property such that any "electric" which had been rubbed possessed an "electric virtue". This property of electricity was keenly observed and studied throughout this time laying the foundations of modern electrical theory. In 1720 a Dutch mathematician Wilhelm 's Gravesande (1688-1742) published *"Physica elementa mathematica experimentis confirmata"* in which he suggests that electrical effects are caused by a vibration in the effluvia which he assumed were permanently attached to electrics such as amber. [21]

Stephen Gray, of whom very little is known, discovered in 1729 that when he rubbed a long glass tube with corks attached to the ends, a feather was firstly attracted to the cork and then repelled, in much the same way as would happen to glass. This led Gray to conclude that the attractive virtue had been communicated by some means to the cork because it had been in contact with the glass. [22] Further, Gray found that some of the best communicators of this virtue were metals. [23] As a result of this work, it was no longer possible to accept the phenomenon of electricity as

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[19] p 36 Whittacker 1951
[20] p 171 Whittacker 1951
[21] p 37, 41 Whittacker 1951
[22] p 470 Holton & Roller 1965
[23] p 42 Whittacker 1951

belonging to an object. It was henceforth regarded as a fluid from which all substances were composed or possessed.

Later that year, Gray was able to show that when two identical oaken cubes, one solid the other hollow, were electrified they produced identical effects which was not expected. This phenomenon led Gray to conclude that unlike heat, electric fluid remained on the surface of the object.[24] Finally in 1731, Gray showed that if glass is rubbed in a darkened room, tiny sparks could be seen to pass between a charged glass tube and a finger (earth). Gray concluded that the electric virtue could thus be communicated through these sparks.[25] A colleague of Gray's, Jean Desaguliers (1688-1744), the son of a refugee Huguenot pastor, continued with Gray's work. In 1736, Desaguliers defined non-electrics to be conductors.[26]

Charles Francois Du Fay (1698-1739), the superintendent of gardens to the King of France had read Gray's papers and suggested that the best material for Gray's transmission line should be a non-electric or a conductor and the supports for this line should be made from an electric or an insulator. Du Fay continued with these researches finding that electrified objects could either attract or repel each other. He specifically found that electrified glass rods repelled each other as did electrified amber. However, electrified glass and amber attracted each other.[27]

This led Du Fay to formulate the beginnings of what was to become the two fluid theory of electricity. He suggested that *"there are two distinct electricities very different from each other: one of these I call vitreous electricity; the other, resinous electricity. The first is that of rubbed glass. The second is that of rubbed amber. The characteristic of these two electricities is that a body of say, vitreous electricity repels all such as are of the same electricity; and on the contrary, attracts all those of the*

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[24] p 43 Whittacker 1951
[25] p 469 Holton & Roller 1965
[26] p 42 Whittacker 1951
[27] p 471 Holton & Roller 1965

resinous electricity."[28] Thus Du Fay has defined two types of electricity, a definition which still persists today.

Du Fay's work was continued among other members of the Court of Louis XV. However, it was the Abbe Jean-Antoine Nollet (1700-70) who developed Du Fay's concepts into the two fluid theory of electricity. Nollet published his *"Recherches"* in 1749 suggesting that *"when an electric is excited by friction, part of this fluid escapes from its pores, forming an effluent stream; and this loss is repaired by an affluent stream of the same fluid entering the body from outside. Light bodies in the vicinity being caught in one or the other of these streams, are attracted to or repelled from the excited electric."*[29]

In 1745 Pieter van Musschenbroek (1692-1761) attempted to preserve the electric charges from decaying into the surrounding air. He suspended a glass phial of water from a gun barrel by a wire which continued through the cork and into the water. The gun barrel in turn was suspended by silk threads near an electrified glass globe. When his assistant touched the gun barrel with one hand and the phial with the other, the assistant received a violent shock and the Leyden phial was thus invented. Musschenbroek had found a way of accumulating electricity.[30]

In England, an apothecary called William Watson (1715-87) worked with his Leyden phial and improved it by coating the glass phial both inside and out with tin foil. This new invention was called the Leyden jar. It was used until the late 19th Century when it was further developed into modern capacitors. In his work with these jars Watson experienced a number of shocks leading him in a memoir read to the Royal Society in October 1746 to suggest that *"electrified actions are due to the presence of an `electrical aether', which in the charging or discharging of a Leyden Jar is transferred but not created or destroyed. The excitation of an electric consists not in*

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[28] p 471 Holton & Roller 1965
[29] p 44-5 Whittacker 1951
[30] p 45 Whittacker 1951

the evoking of anything from within the electric itself without compensation, but in the accumulation of a surplus of electrical aether by the electric at the expense of some other body, whose stock is accordingly depleted. All bodies were supposed to possess a certain natural store which could be drawn upon for this purpose"[31]

From his work on Leyden jars, Watson was also able to conclude that "*the electrical effluvia occupy only the surfaces of bodies electrified; as we found, that a very small quantity of matter, distributed under a very large surface, would occasion a greater accumulation of electricity, than a very much more considerable quantity of matter under less."*[32] He was also able to show that "*the electricity also occupies the whole mass of bodies electrified, and passes through their constituent parts."*[33]

At the conclusion of his 1748 paper, Watson indicated some preliminary results of electrical experiments carried out in evacuated glass tubes where he states that *"upon removal of the air, the electricity pervades the vacuum to a considerable distance."*[34] He foreshadows his next paper in which he describes his vacuum tube experiments which will be discussed in the next chapter.

1.3. Early Concepts of the Nature of Electricity

At this time electricity and electrical experiments were widely explored acting as diversions for the emerging middle class of merchants and manufacturers who had both time and money to enjoy these new phenomena in their own homes. So it was not unusual for a certain Dr Spence from Scotland having only recently arrived in the American Colonies to display a number of electrical experiments to an enthralled Boston audience. A member of this audience was Benjamin Franklin (1706-90) a well respected member of this colonial society. It was thus that Franklin was, in 1746, introduced to the subject of electricity. Franklin later stated that these

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[31] p 46 Whittacker 1951
[32] p 116 Watson 1748
[33] p 116 Watson 1748
[34] p 120 Watson 1748

experiments *"were imperfectly performed, as he was not very expert; but being on a subject quite new to me, they equally surprized and pleased me."*[35]

Franklin conducted a number of experiments in which he charged a second object by using a charged glass rod. If both rod and object were insulated, each could produce a shock on a third object. Franklin concluded from this work that electricity was not created by rubbing but was transferred from one object to another by this process. This suggestion was essentially the same as that put forward by Watson. It is now commonly known as the principle of conservation of electric charge.

Building on this concept that all bodies possess some form of electricity and that rubbing or friction merely transfers the electricity from one object to another, Franklin was able to assign a sign of + for a gain in electricity and a - for a loss of electricity. This seems on the surface a logical step to take, since at this time it was not known what the nature of electricity was or what the charge transfer was. Thus in 1747 Franklin proposed that *"any body is positively electrified if it is repelled by a glass rod which has been rubbed with silk, and we will call any body negatively electrified if it is repelled by sealing wax which had been rubbed with cat's fur."*[36] these definitions of *"positive"* and *"negative"* charge still apply today. As will be seen later in this chapter the flow of electric current follows from this definition and travels from the positive to the negative, a convention for current which still applies today, causing some confusion now that it is known that electricity is usually conveyed by the passage of negatively charged particles.

Franklin finally concluded that electricity could be regarded as an *"elastic fluid consisting of particles extremely subtle, since it can permeate common matter, even the densest metals with such ease and freedom as not to receive any perceptible resistance."*[37] Franklin's work was not at first accepted by the European philosophers

[35] p 46 Whittacker 1951
[36] p 11 Millikan 1917
[37] p 48 Whittacker 1951

of this time and it was Watson who included some of Franklin's letters on the subject when he presented his own papers to the Royal Society. One could suppose that this action was one method by which Watson could support his own theories on the subject. However it is Franklin who is regarded as being the author of what is now known as the single fluid theory of electricity.

In 1759 Robert Symmer suggested that Franklin's positive electricity and negative electricity were two separate *"fluids"* which could penetrate and flow through matter. In Symmer's words *"My notion is that the operations of electricity do not depend upon one single positive power, according to the opinion generally received, but upon two distinct positive and active powers, which is contrasting, and, as it were, counteracting each other produce the various phenomena of electricity; and that, when a body is said to be positively electrified it is not simply that it is possessed of a larger share of electric matter than in a natural state, nor when it is said to be negatively charged of a less; but that in the former case, it is possessed of a larger portion of one of those active powers, and in the latter, of a larger portion of the other; while a body in its natural state remains unelectrified, from an equal balance of those two powers within it."*[38] This hypothesis was accepted by Coulomb who will be discussed later in this chapter. From the modern perspective Symmer's views would appear to be correct, since the negative charge on an electron cannot be seen as a deficiency of positive charge, but exists in its own right.

Consequently during the middle of the 18th Century the first of many conflicts between rival theories on electricity occurred i.e. between Nollet's two fluid theory and the Watson-Franklin single fluid theory. Eventually the single fluid theory gained acceptance and in a more modern form can still be regarded as a working hypothesis in some educational areas. The final acceptance of the single fluid theory came through the work done in the first half of the 19th Century on the phenomena discovered in vacuum tubes (see chapter 2). By the end of the 18th Century the

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[38] p 58 Whittacker 1951

concept of the effluvium had virtually been abandoned because of the results obtained by Aepinus (1724-1802) and Wilke (1732-96). They had initially looked at Franklin's idea that glass in a Leyden phial was impenetrable to an electric fluid, they replaced glass by other non-conductors and hence were able to generalise that non-conductors were impenetrable to the electric fluid. Consequently the concept of an electric effluvium surrounding a charged body appeared incompatible with the experimental evidence. [39]

1.4. Quantitative Experiments on Electricity

Joseph Priestley (1733- 1804) who was acquainted with Franklin, discovered in 1766, while verifying an earlier experiment of Franklin's, that an electrified hollow metal vessel had no charge on its inner surface and hence no electric force. This led Priestley to the correct conclusion *"that the attraction of electricity is subject to the same laws with that of gravitation, and is therefore according to the square of the distances."* [40]

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[39] p 51 Whittacker 1951
[40] p 53 Whittacker 1951

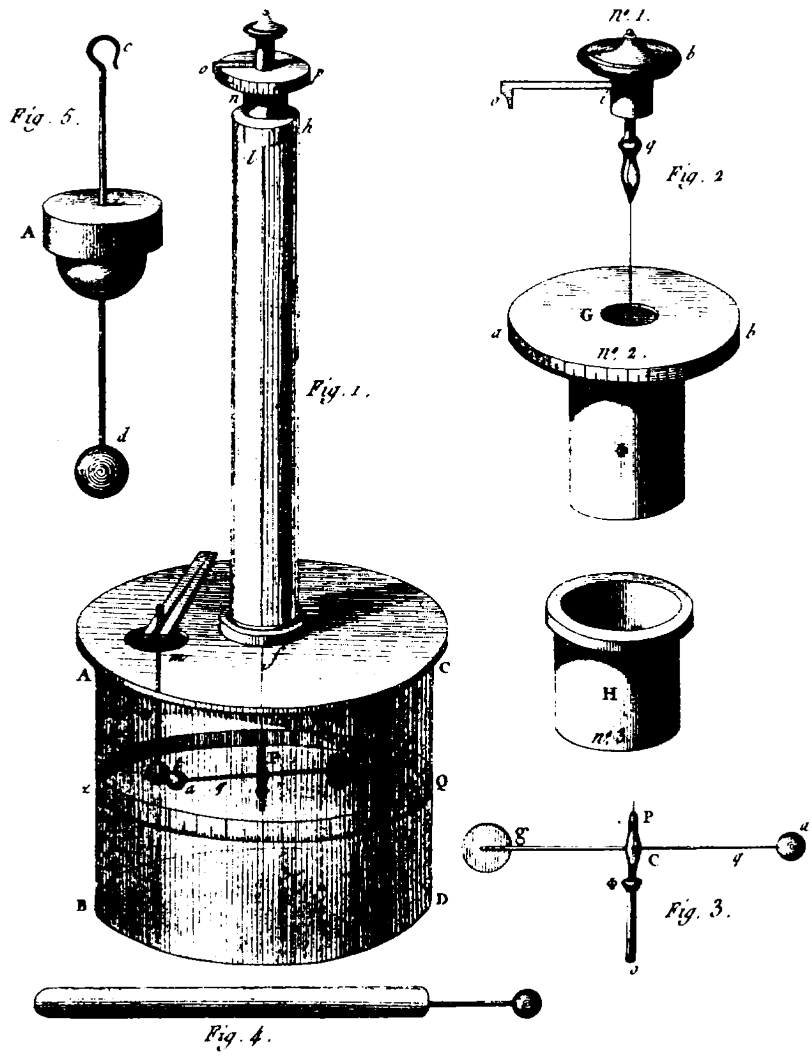

Diagram 1 A (p116 Segre-1984)

This latter statement was experimentally verified by Coulomb (1736-1806) in 1785. By this time it had been demonstrated by Michell (1724-93), and verified by Coulomb in 1777 that the force of magnetic attraction and repulsion also obeyed an inverse square law.[41] In his 1785 experiment Coulomb used his torsion balance to demonstrate that the repulsive force between two small globes charged with the same type of electricity obeyed this inverse square law. (see diagram 1-A) Later Coulomb extended his work to include the attractive force between two globes charged with opposite electricities.[42] Coulomb's discoveries in electricity are summarised in the law which bears his name and states

41 p 56-7 Whittacker 1951
42 p 57 Whittacker 1951

$$F = K\frac{q_1 \cdot q_2}{r^2}$$

$$K = \frac{1}{4\pi\varepsilon_0} \qquad \text{(q in Coulombs)}$$

$$K = 1 \qquad \text{(q in esu as in Coulomb's time)}$$

$$r = \text{distance between centres}$$

$$q_1, q_2 = \text{charges}$$

As previously stated, Coulomb favoured the *"two fluid theory"* in which he stated that *"we can explain all phenomena (electrical) by supposing that there are two electric fluids, the parts of the same fluid repelling each other according to the inverse square of the distance, and attracting the parts of the other fluid according to the same inverse square law"*.[43] According to this theory Coulomb was able to conclude that this fluid which was contained in all matter could be decomposed by use of an electric field into two equal quantities of vitreous and resinous electricity.[44] This is an extraordinary deduction, considering that the electrical decomposition of water and experiments in electrolysis would not be demonstrated for another fifteen years. It was on 30th April 1800, that Nicholson (1753-1815) and Carlisle (1768-1840) produced the electric decomposition of water, thus opening up the new science of electrochemistry.

Although the two popular theories of this time were both described in terms of an electric fluid or fluids, the phenomena described and explored were all based on static electricity. The electric machines of this time were capable only of producing large static charges. Devices which produced a flowing current had not yet been invented. Electric currents were discovered almost by accident by Galvani (1737-98), an anatomist. In 1780, Galvani was studying the susceptibility of nerves to irritation. His subjects were frogs which he had dissected and exposed a nerve in the leg. Galvani, like other natural philosophers of his day experimented in other areas of science, including electricity. So on a particular day he had charged his

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43 p 58 Whittacker 1951
44 p 58 Whittacker 1951

electric machine, exposed the nerve in the frog's leg and when it was touched with a scalpel a spark was drawn from the machine and the frog's leg convulsed.[45]

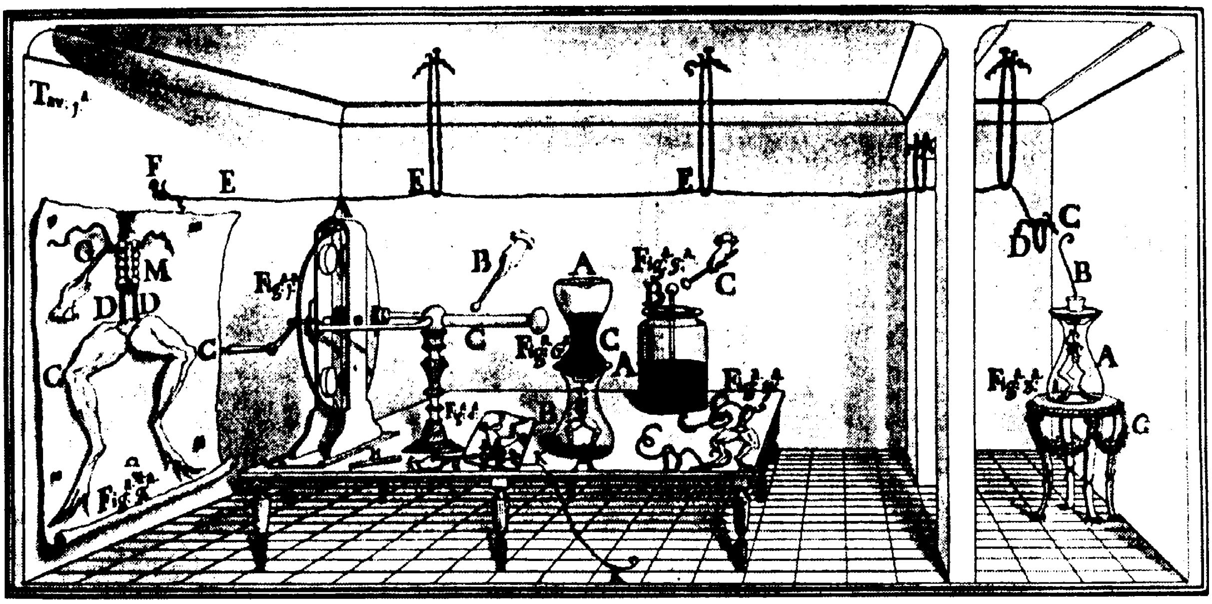

Diagram 1 B(Segre-1984)

Galvani experimented using other sources of electricity, including atmospheric electricity which resulted during thunderstorms. As a result of this work Galvani concluded *"that the limbs of the frogs were convulsed whenever a connection was made between the nerves and muscles by a metallic arc, generally formed of more than one kind of metal"*.[46] He proposed the hypothesis *"that the convulsions were caused by the transport of a peculiar fluid from the nerves to the muscles, the arc acting as a conductor"*.[47] Galvani published his results thus causing some discussion as to the nature of the phenomenon which he had discovered. Although others suggested that this fluid was somewhat different, suggesting animal electricity, Galvani himself considered it to be the same as the ordinary electric fluid, and even regarded the entire phenomenon as similar to the discharge of a Leyden Jar. (see diagram 1-B)

[45] p 67 Whittacker 1951
[46] p 69 Whittacker 1951
[47] p 69 Whittacker 1951

1.5. Volta

Alessandro Volta (1745-1827) the Professor of Natural Philosophy at the University of Padua, suggested in 1792 that the contractions observed in the frog's legs were caused by the connection of two different metals through a moist body, *"the metals used in the experiments, being applied to the moist bodies of animals, can by themselves, and of their proper virtue, excite and dislodge the electric fluid from its state of rest, so that the organs of the animal act only passively."*[48] Volta continued his work suggesting that *"in a perfect circle of conductors, a circulation of this fluid (i.e. electricity) ceases only when the circle is broken and is renewed when the circle is again rendered complete."*[49] We of course now know that an electric current cannot flow if there is a break in the circuit i.e. a break between the conductors. Volta was now on the verge of the next great development, the production of a source of a continuous electric current.

Volta experimented with different types of conductors (both wet and dry) and found that an electric current flowed when the conductors were arranged alternately as wet, dry, wet, dry etc. When this circle was broken, current ceased to flow. By 1800 he found that if a long chain of different conductors was used instead of only two, the convulsions of the frog were no more violent.[50] However, he found that if any number of couples, each consisting of a zinc disc and a copper disc in contact, were separated from the next by a disk of moistened pasteboard (i.e. copper, zinc, pasteboard, copper, zinc, pasteboard etc.) the effect of the pile was greatly magnified. Further, he discovered that when the highest and lowest discs were simultaneously touched, a distinct shock was felt. This could be repeated again and again, the pile thus appearing to have an infinite recuperative ability. (See diagram 1-C which also shows a number of Volta's inventions and experiments.)

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[48] p 69 Whittacker 1951
[49] p 70 Whittacker 1951
[50] p 71 Whittacker 1951

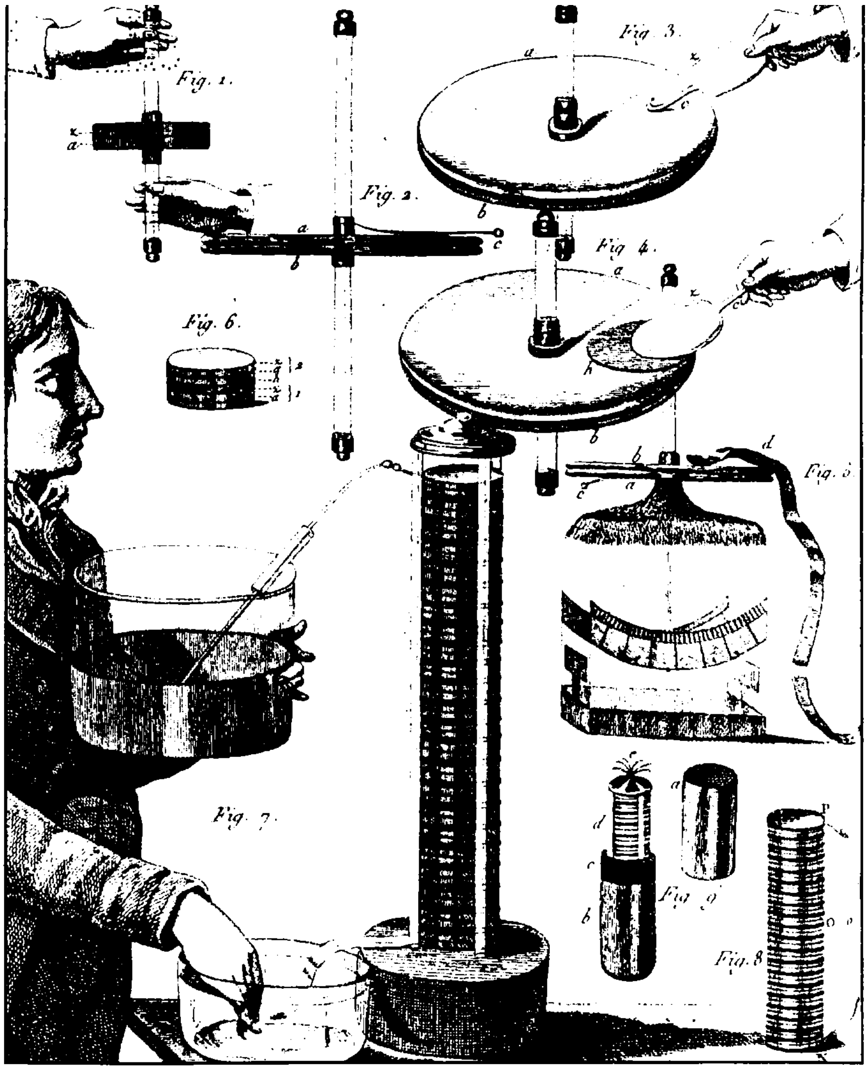

Diagram 1 C (p123 Segre-1984)

When Volta performed the following experiment with the copper and zinc discs, he found that the zinc was positively electrified, while the copper was negatively electrified. He took a disc of copper and one of zinc and held each by an insulating handle and applied them to each other for an instant. After the discs had separated, they were brought into contact with a delicate electroscope, which showed that the discs were electrified. An electroscope is a device made of a conducting arm with a movable conducting leaf attached to the main arm all of which is enclosed in an evacuated case. It was and still is used to indicate the presence of an electric charge.

Volta continuing his work on the pile, found that the more coupled pairs, the greater the potential difference between the ends of the pile.[51] Further, he found that when the moisture was acidified the pile worked more efficiently, this greater efficiency being attributed to the superior conducting ability of acids.[52] Volta thus produced for the first time a reliable source of electric current. This pile later developed into the voltaic battery which provided the power source for later experiments in cathode ray discharges. A feature of laboratories for the next 100 years was large arrays of copper-zinc voltaic piles, often containing hundreds, or even thousands, of cells.

As well as his work on the pile, Volta developed a number of electrostatic machines based on his invention of the electrophorus. The Electrophorus consists of two discs each with an insulating handle which can be screwed to the back of the plate. (see the top part of diagram 1-C) One disc is made from resin or ebonite in front and supported by a metal back, in the centre of this disc is a metal pin which just touches the ebonite and is connected to the metallic back. The surface of this disc is electrified by stroking it with a flannel or cat's fur. The other disc is made wholly from metal.

This second disc is brought near the ebony disc using the insulating handle. When it comes within a certain distance of the metal pin, a spark passes, and if the discs are now separated, the metal disc is found to be positively charged and the ebony/metal disc is negatively charged. (see diagram 1-D).

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[51] p 72 Whittacker 1951
[52] p 73 Whittacker 1951

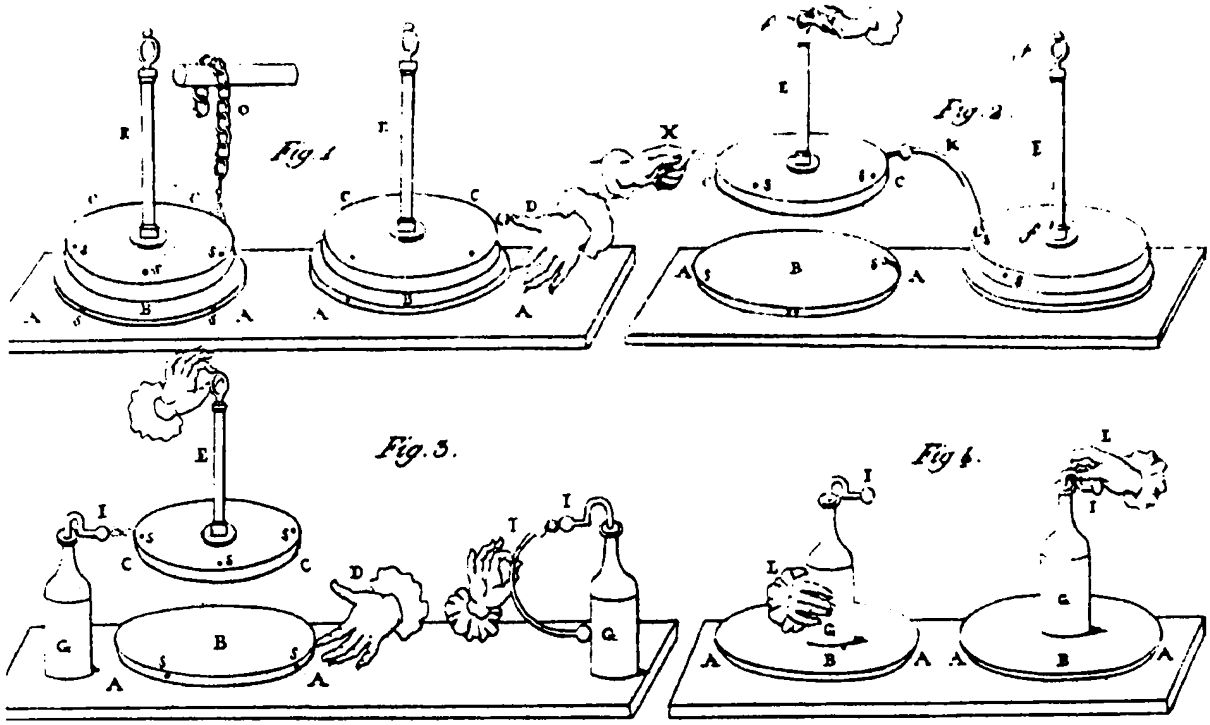

Diagram 1 D (p68 Hankins-1985)

In using this instrument one of the discs is kept connected to one conductor while the other is applied alternatively to the first disc and then the other conductor. By this process, the two conductors will become charged with equal quantities but opposite charges of electricity. [53] His desire to measure quantitatively electrical magnitudes led him to the development of the electrometer which allowed potential differences to be measured in a reproducible way. [54]

An electrometer is an instrument which measures electric charge, in some cases it produced an absolute value which allowed the experimenter to compare the values of two or more charges. In other cases the instrument was calibrated to some quantity which it measured producing a value for the charge. Usually, the electrometer measures the force acting between charges and this force is calibrated to give some measure of charge. The simplest or earliest electrometer was Coulomb's torsion balance (mentioned earlier in this chapter). The quadrant electrometer was developed in the late 19th Century and proved an extremely useful device in experiments on the determination of electric charge (see chapter 5).

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[53] p 319 Whittacker 1951
[54] chapter 4 Segre 1984

1.6. Experiments on Electric Currents and Electromagnetism

The situation now changes to one in which most experimentation is now taking place using continuous electric current, rather than static electricity. This production of a continuous current allowed new branches of science to be developed e.g. electrochemistry and electromagnetism. The first studies in electromagnetism i.e. the interaction between electric and magnetic fields and the production of magnetic fields by electric currents were made in 1820 by Hans Christian Oersted (1777-1851), a Danish Professor of Natural Philosophy.

Oersted's equipment consisted of a Galvanic apparatus i.e. an electrochemical battery, of 20 copper troughs (length 12", height 12", breadth 2.5"), in which are two plates of copper "so bent that they could carry a copper rod, which supports the zinc plate in the water of the next trough. The water of the troughs contained 1/60 th of its weight of sulphuric acid and an equal quantity of nitric acid. The portion of each zinc plate sunk in the water is a square whose side is about 10" in length." [55] This apparatus was *"strong enough"*[56] to heat a metallic wire to red heat.

The opposite ends of this galvanic battery were joined by a metallic wire, the straight part of which was placed horizontally above a pivoted magnetic needle. When the current flowed the needle was deflected. When this was repeated with the current carrying wire below the needle the deflection occurred in the opposite direction.

From these experiments Oersted found :-

(a) the declination of the deflection of the needle varies with both the power of the battery and the distance between the current carrying wire and the needle

(b) the effect is unaltered if the wire and needle are separated by glass, wood, water or metals

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[55] p 379 Maxwell 1954

[56] p 379 Maxwell 1954

(c) the effects do not occur when the needle is made from glass or brass

(d) the effect appears to form circles around the wire. [57]

Oersted concluded that the effect which takes place in the conductor and in the surrounding space, which he named *"conflict of electricity"*, *"acts only on the magnetic particles of matter. All non-magnetic bodies appear penetrable by the electric conflict, while magnetic bodies, or rather their magnetic particles, resist the passage of this conflict."* [58] According to Mary Hesse this was the first apparent experimental proof that *"forces at a distance"* may be other than direct attractions or repulsions. [59]

By October 1820 two French Scientists, Jean-Baptiste Biot (1774-1862) and Felix Savart (1791-1841) had repeated and extended Oersted's original work which had been described at a meeting of the French Academy in September 1820. As a result of their work Biot and Savart could state that if one *"draws from the pole a perpendicular to the wire; the force on the pole is a right angle to this line and to the wire, and its intensity is proportional to the reciprocal of the distance."* [60] Stated mathematically, the Biot-Savart Law states that *"the magnetic force due to an element ds of a circuit in which a current I is flowing, at some point whose vector distance from ds is r, then we have*

$$\bar{B} = \frac{I d\bar{s} \times \bar{r}}{\bar{r}^2}$$ " [61]

This equation may be written for a whole circuit as

$$B = \frac{-\mu_0}{4\pi} \oint \frac{I\,ds}{r^2}$$

In September 1820, Andre-Marie Ampere (1775-1836) showed that two parallel wires carrying currents, were attracted to each other if the currents flowed in the same direction and repelled each other if the currents flowed in opposite directions.

57	p 380	Maxwell 1954
58	p 82	Whittacker 1951
59	p 216	Sambursky 1974
60	p 82	Whittacker 1951
61	p 83	Whittacker 1951

As a result of his work in this area during the following three years, Ampere began to formulate the view that all physical phenomena could be explained in terms of equal and oppositely directed forces acting between pairs of particles.[62] Further, Ampere suggested that the forces between wires carrying electric currents were caused by *"the reaction of the elastic fluid which extends throughout all space, whose vibrations produce the phenomena of light and which is put in motion by electric currents."*[63] This was a remarkable insight particularly since it predates Maxwell's work on electromagnetism and Hertz's discovery of electromagnetic waves by more than 60 years.

Ampere's experiments led him to discover that circuits carrying electric currents exert forces on each other and that these forces can be exerted on the currents by magnets. Subsequently, he suggested that electricity and magnetism obey the following laws:-

(a) the effect of a current is reversed when the direction of a current is reversed
(b) the effect of a current flowing in a circuit twisted into small sinuosities is the same as if the circuit were smoothed out
(c) the force exerted by a closed circuit on an element of another circuit is at right angles to the latter
(d) the force between the elements of two circuits is unaffected when all linear dimensions are increased proportionately, the current strengths remaining unaltered.[64]

These four laws led Ampere to formulate a relationship between the force produced by the current elements flowing through the wires as

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[62] p 84 Whittacker 1951
[63] p 84 Whittacker 1951
[64] p 85 Whittacker 1951

$$F = C\frac{\bar{I}_1 \times \bar{I}_2}{r}$$

where I_1 ,I_2 are the currents carried by the wires respectively

r is the distance between the wires

C is the constant dependent on the units employed

From this relationship between force and current, one could define the current in the wires in terms of the force acting between them. In modern units the constant $C = \mu_0 / 2\pi$. This formula of course is dependent on the distance between the wires which is measured at right angles from one wire to the other. Thus, there is an inherent assumption that the force is directed along the line joining both elements. If this restriction is removed, the force could be assumed to be acting along a closed current loop. If one now assumes that the force per unit length of a current carrying wire in a magnetic field is

$$\bar{F} = \bar{I} \times \bar{B}$$

where I is the current in the wire

B is the magnetic field obtained using the Biot-Savart Law

The modern notation of Ampere's Law becomes apparent i.e.

$$\oint B \cdot dl = C \times I_{\text{through the loop}}$$

where C is $\mu_0 = \frac{1}{\varepsilon_0 c^2} = 4\pi \times 10^{-7}$ in s.i. units

and μ_0 is the permittivity of air

ε_0 is the permeability of air

c is the velocity of light in a vacuum

Ampere continued with his work on the magnetic effects of current carrying circuits which ultimately led him to believe that the magnetic effects observed resulted from electric currents and hence that the electric current was the fundamental entity.

In 1826 Georg Ohm (1787-1854) produced a theory of voltaic circuits in which the driving power, or the electric potential difference between the terminals of the pile were accounted for. Ohm had for some time studied the behaviour of voltaic cells having already discovered that if the resistance in a circuit was high then the current drawn by the circuit was proportional to the number of cells placed in series. However, if the load resistance was small then the current was independent of the number of cells used. This observation led to the formulation of one of the basic laws of Physics, Ohm's Law written in modern notation as

$$V = I \cdot R$$

where V is the potential across the load[65]
I is the current in the load
R is the resistance of the load

Ohm's work had not arisen in isolation; some 20 years before in 1801, Humphrey Davy (1778-1829) had made a number of investigations on the voltaic pile showing that no current flows in a pile if the water between them is pure.[66] One needed some form of ion e.g. H^+ as in sulphuric acid to enable current to flow. Further, Davy studied the conductivity of various metals and wires of various cross-sections, finding that the conductivity of a wire is inversely proportional to its length but directly proportional to its cross-sectional area. Thus by Ohm's time the problem being investigated was the way in which the current flow was not only dependent on the conductivity of the wires but also on the driving force of the voltaic cell or battery of cells.[67]

1.7. Faraday

In 1812 Davy was approached by a young bookbinder's apprentice who had attended many of Davy's public lectures. This apprentice was Michael Faraday (1791-1867) who was seeking employment in a scientific laboratory. While uneducated in mathematics, Faraday through his experimental researches in electricity and magnetism laid the foundation of a number of modern sciences

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65 p 90 Whittacker 1951
66 p 74 Whittacker 1951
67 p 90 Whittacker 1951

including electrochemistry and electromagnetism. His work in this area started in 1821 when Faraday read about the work and discoveries of Oersted.[68]

By the time Faraday had been employed by Davy, he had already experimented both with voltaic piles and the decomposition of various compounds. Consequently, by 1831 Faraday started to investigate the property of electromagnetism. In doing so, he developed or more correctly rediscovered a method of mapping magnetic field lines which had been used almost two centuries before by Niccolo Cabeo (see the earlier part of this chapter). While examining the magnetic force using iron filings, Faraday discovered that the magnetic force describes itself in the form of lines which form closed loops around the magnet. He described these lines as *"lines of magnetic force"*, a concept which later developed into field theory.[69]

As a result of his work on induction Faraday concluded that a current is induced in a circuit either when the strength of the current in an adjacent wire is changed, or when a magnet is moved in the vicinity of the wire, or when the wire itself is moved in the presence of another current or magnetic field. Further, in 1832 he found that the currents produced by the same process of induction in a variety of wires was proportional to the conductivity of the wires thus indicating that an e.m.f. produced in the wire was independent of the material of the wire. Thus he was able to conclude that the process of induction was dependent on the relative motion of the wire and the magnetic field lines in its vicinity. The induced e.m.f. is proportional to the number of field lines intersected by the wire per second.[70] This latter effect is now known as Faraday's Law which in modern terminology is stated as

$$\text{e.m.f.} = {}^{-d\Phi}\!/_{dt}$$

where Φ is the magnetic flux which is the product of the magnetic field strength B and the area through which the conductor intercepts

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68 p 170 Whittacker 1951
69 p 171 Whittacker 1951
70 p 172-3 Whittacker 1951

The following year, Faraday was also able to show that all the electrical phenomena known at that time, physiological, magnetic, luminous, chemical, mechanical and heat could be obtained by using electricity from either static sources i.e. friction machines or continuous sources i.e. voltaic batteries. He was able to demonstrate that the two types of electricity were identical.

As a result of further work in electromagnetism, Faraday suggested *"that in the ordinary condition of a body, the molecules consist of atoms which are bound to each other by the forces of chemical affinity, these forces being really electrical in their nature; and the same forces are exerted, though to a less degree, between atoms which belong to different molecules, thus producing the phenomena of cohesion. When an electric field is set up, a change takes place in the distribution of these forces; some are strengthened and some are weakened, the effect being symmetrical about the direction of the applied electric force"*. [71] Faraday thus introduced the concept of lines of electric force, which he defined as *"a curve whose tangent at every point has the same direction as the electric intensity"*. [72]

In explaining the conduction of electric currents, Faraday suggested that *"an action of contiguous particles, dependent on the forces developed in electrical excitement; these forces bring the particles into a state of tension or polarity; and being in this state the contiguous particles have the power or capability of communicating these forces, one to the other, by which they are lowered and discharge occurs"*. [73] By 1838 Faraday had concluded that *"it appears to me possible and even probable, that magnetic action may be communicated at a distance by the action of intervening particles, in a manner having a relation to the way in which the inductive forces of*

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[71] p 186 Whittacker 1951
[72] p 186 Whittacker 1951
[73] p 189 Whittacker 1951

static electricity are transferred to a distance".[74] Hence he suggested even further that there was a close connection between electric and magnetic forces.

After an absence of four years due to ill health, Faraday returned to the laboratory in 1845 working now on the possible connection between light and magnetism. It is from this work that Faraday developed what could be regarded as an early theory of electromagnetism. He believed that an atom could be regarded as a field of force surrounding a central point. An atom could have no definite size but would be completely penetrable. Further he believed that light and heat were transverse vibrations along these force lines. Hence Faraday eliminated the aether, replacing it with lines of force. Finally he states in 1851 *"it is not at all likely if there be an aether, it should have other uses than simply the conveyance of radiations."*[75]

Faraday, like many of his contemporaries, did not restrict his work to a narrow band of inquiry. While he was working on electricity and magnetism, he was simultaneously experimenting on electric currents passing through solutions. He commenced this work in 1833 and quickly discovered that many of these solutions decomposed as a result of this passage of electricity. As was previously stated, Faraday was essentially uneducated in literature and the Classics, consequently when he discovered various phenomena concerning the decomposition of these solutions, he enlisted the aid of W. Whewell (1794-1866) who suggested the terminology which is now used. Thus solutions which are decomposed directly by current are called electrolytes, the point at which this occurs is called the electrode. The high potential electrode is the anode while the low potential electrode is the cathode. Anions are attracted to the anode, while cations are attracted to the cathode.[76]

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74 p 189 Whittacker 1951
75 p 194 Whittacker 1951
76 p 179 Whittacker 1951

He found that the rate at which an electrolyte is decomposed depends solely on the intensity of the electric current passing through it and not on the size of the electrodes or concentration of the solution. Further he found that for a given amount of current passing through a solution the amount of a univalent element e.g. hydrogen or silver, deposited on the electrode is exactly proportional to its atomic weight. While for the same current the amount of a divalent element deposited at the electrode would be half its atomic weight, i.e. half the amount.[77] This quantitative law suggested to Faraday to indicate that *"the atoms of matter are in some way endowed or associated with electrical powers, to which they owe their most striking quantities and among them their mutual chemical affinity"*.[78] These observations lead to the concept of Faraday's constant,

$$F = N_A \cdot e$$

where N_A is Avogadro's number
e is the unit electric charge

W. Weber (1804-1891) in 1871 developed his own theory of electromagnetism on a basis which was almost identical to Franklin's much earlier theory of electricity. Weber explained that all electrical phenomena exhibited by conductors was based on the assumption that atoms have within them two constituent types of electricity, one of which in more mobile that the other. Weber believed that the positive charge was more mobile than the much heavier negative charge. He writes *"Let e be the positive electrical particle. Let the negative be exactly equal and opposite and therefore denoted by -e. But let a ponderable atom be attracted to the latter so that its mass is thereby so greatly increased as to make the mass of the positive particle vanishingly small in comparison. The particle -e may be then be thought of as at rest and the particle +e as in motion about -e"*.[79]

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77 p 27 Hesse 1961
78 p 179 Whittacker 1951
79 p 20 Hesse 1961

1.8. The Electron, an Atom of Electricity.

These ideas of Weber may be regarded as the very beginnings of electron theory since the latter theories of Lorentz were based on similar assumptions, but the relative positions of positive and negative charges within the atom are now reversed.[80]

Alex Williamson (1824-1904), who like Faraday was experimenting with electric currents passing through liquids, had by 1850 concluded that in liquids which are now known to be ionic in nature, decompositions and recombinations of the molecules are continually taking place throughout the whole mass of the liquid, quite independently of the application of an external force.[81]

This view of Williamson's was further clarified and developed by R. Clausius (1822-1888) who, in 1857, stated that *"electromotive force emanating from the electrodes, does not affect the dissociation of the electrolyte into ions, since a degree of dissociation already exists. The applied electric force, therefore causes a general drift of all the ions of one kind towards the anode and of all the ions of the other kind towards the cathode. Thus the opposite motion of the two kinds of ions constitutes the galvanic current in the liquid"*.[82]

As a result of this work in the area of electrolysis, the concept of an atom of electricity was slowly beginning to evolve, however, it was not until 1873 that Maxwell (1831-1879) stated *"that we simply assert the fact of the constant value of the molecular charge, and that we call this constant molecular charge, for convenience of description, one atom of electricity"*.[83]

This atom of electricity was regarded by G.J.Stoney (1826-1911) as one of the three fundamental physical units of nature; the others being the *"coefficient of universal*

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[80] p 20 Hesse 1961
[81] p 335 Whittacker 1951
[82] p 335 Whittacker 1951
[83] Fournier 1918

gravitation" and the *"maximum velocity of light"*.[84] In his paper *"On the Physical Units of Nature"* of August 1874, given to a meeting of the British Association at Belfast, Stoney states *"And, finally, Nature presents us, in the phenomenon of electrolysis, with a single definite quantity of electricity which is independent of the particular bodies acted on. ...i.e. For each chemical bond which is ruptured within an electrolyte a certain quantity of electricity traverses the electrolyte which is the same in all cases. This definite quantity of electricity I shall call E. If we make this our unit quantity of electricity, we shall probably have made a very important step in our study of molecular phenomena"*.[85]

Stoney used the term ELECTRON to describe this atom of electricity in a paper he presented to the Royal Dublin Society in February 1881. Stoney had been conducting experiments on electrolysis in which he had observed that "*for each chemical bond which is ruptured within an electrolyte a certain quantity of electricity traverses the electrolyte which is the same in all cases."*[86] It was this unit quantity of electricity which caught his interest. He had previously, in 1868, calculated that the number of molecules present in a cubic millimetre of gas at standard temperature and pressure to be of the order of 10^{18}. He then calculated, using the Faraday constant, that the quantity of electricity required was 10^{-20} of an ampere which at that time was an electromagnetic unit quantity of electricity. In the 1894 discussion of this earlier paper, Stoney calculated this quantity of electricity to be 3×10^{-11}esu. In this 1894 article, Stoney also mentions that Prof Richarz obtained a similar value for the unit charge on the electron of 12.9×10^{-11}esu. Stoney fails to mention how this value was obtained. As is known today both these values are in considerable error to the 4.804×10^{-10}esu. which is commonly accepted today.[87]

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[84] Fournier 1918
[85] p 419 Stoney 1894
[86] p 419 Stoney 1894
[87] p 419-20 Stoney 1894

Finally in this 1894 paper, Stoney notes that the previous year Prof Ebert had also noticed *"that the motions going on within each molecule or chemical atom cause these electrons to be waved about in the luminiferous aether, and that in this constrained motion of the electrons the distinctive spectrum of each kind of gas seems to originate: since lines in the spectrum will be furnished by each term of the Fourier's series which represents the special motion of each electron."*[88] This explanation of line spectra comes three years before J.J.Thomson's paper *"Cathode Rays"*, four years before the *"plum pudding"* model of the atom and some 20 years before Bohr's 1913 paper in which he describes his *"electron shell"* model of the atom. The insight that both Stoney and Ebert exhibited at a time when Dalton's indivisible atom theory was the accepted atomic theory, was truly remarkable. Both men appear tantalisingly close to the concepts embodied in Rutherford's and later Bohr's model of the atom, without quite reaching it.

It was within this background of exploration into the unknown lands of electricity and magnetism that led to the development of electron theory in the pre-relativity era. Although experimentation in the areas of electricity, magnetism and electrochemistry did not stop with Stoney's definition of the electron, the next major developments came through the area of low pressure gas discharge experiments.

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88 p 420 Stoney 1894

2. Vacuum Pumps and Barometric Light

2.1. Torricellian Vacuum

The development of the modern vacuum pump and the discovery of cathode rays and their properties both had their origins in a single phenomenon first observed in the seventeenth century. Electrical discharges in gases at low pressure were first observed shortly after Evangilista Torricelli (1608-1647) produced an evacuated space above a column of mercury. At the time, Torricelli was studying the properties of air pressure and the apparatus he used later developed into the modern barometer. As more work was done on air pressure, more efficient vacuum pumps were developed. These in turn were used to evacuate glass vessels in which an almost endless variety of experiments were conducted. By the early eighteenth century the first efficient vacuum pumps were being produced and with the development of friction machines, more reliable sources of high voltage electricity were also available. Thus the study of the phenomenon of barometric light led to the study of cathode rays and their properties.

Torricelli, a student of Galileo, communicated to Michel Ricci a description of some experiments he had conducted in 1644. In these experiments Torricelli discovered that when he filled glass tubes, of similar diameters, with mercury, then inverted these tubes in a dish of mercury, the levels of mercury in the tubes were the same regardless of the size and shape of the upper end of the tubes. Torricelli concluded that the space in the tube above the mercury was empty space or a vacuum. [1] In 1667 the Accademia Cimento published in its "*Saggi del Naturali Esperienze"* a series of experiments carried out in a Torricellian vacuum. The results of these experiments included the observation that magnetic force was the same in a vacuum as in air, that the smoke produced by heating bitumen with sunlight focused through the glass wall fell and that when a sheep's bladder, which had been squeezed so as

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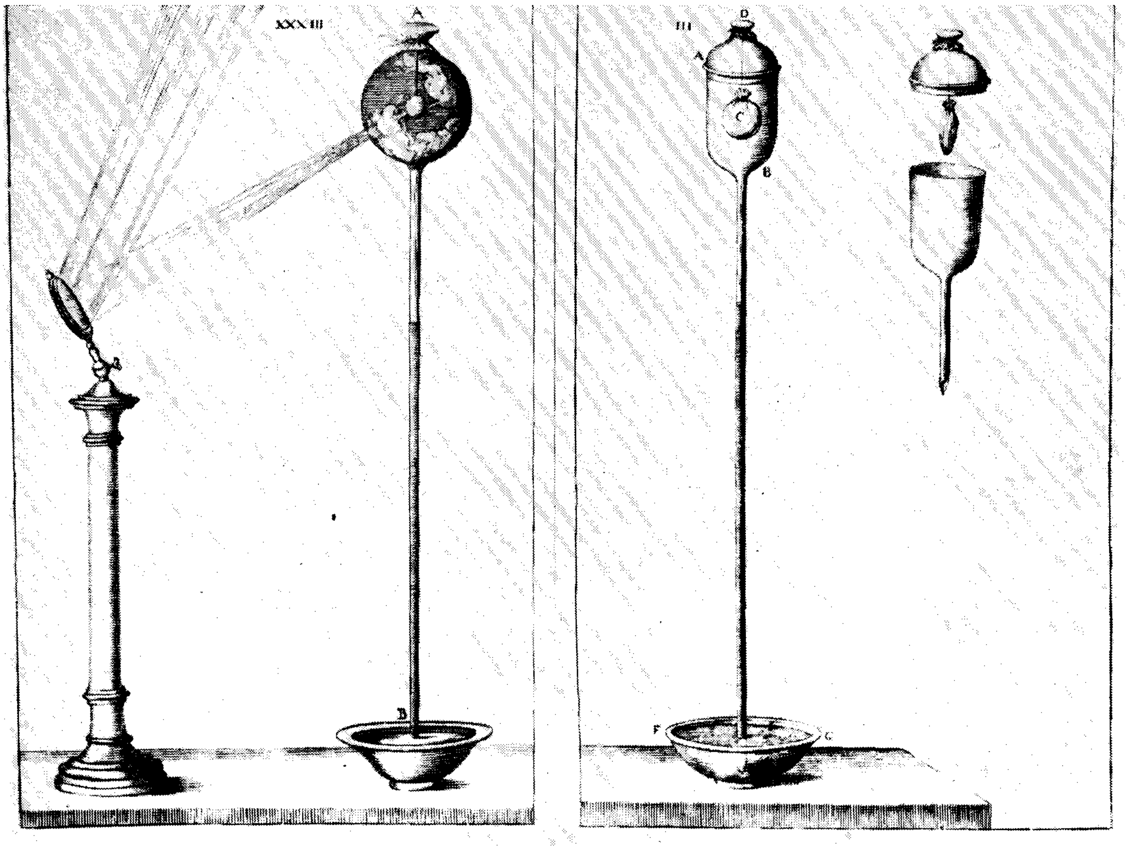
1 p 29 Da C Andrade 1957

to contain only a small amount of air, was placed in the evacuated region, it expanded.[2] (See diagram 2-A). It was not long after this that the first reports of barometric light was made. Barometric light was the term used to describe the occasional flashing or glowing that had been observed in the evacuated region above the mercury in a barometer.[3] It is now quite obvious that this barometric light also required a source of high electric potential which could be produced by friction. How this could occur in the laboratories at this time is open to speculation since friction machines would not be developed for another forty years.



(a) (b)

Diagram 2 A - Experiments carried out by the Accademia del Cimento with the Torricellian vacuum.
(a) shows smoke falling in vacuo; (b) a lamb's bladder, containing a little air, swelling in vacuo. (p28 Da C.Andrade-1957)

2.2. Early Development of Vacuum Pumps

At about the same time as Torricelli was working on his barometers, Otto von Guericke (1602-1686) developed the first vacuum pump. One can define a vacuum pump to be a machine which allows air to be progressively removed from a closed

2 p 29 Da C Andrade 1957
3 p 28 Da C Andrade 1957

vessel. The first description of von Guericke's pump was made by a German Jesuit, Kaspar Schott (1608-1666) in his book "*Mechanica Hydrolico-Pneumatica"* which was published in 1657. This pump was used to demonstrate the force exerted on an evacuated sphere by atmospheric air pressure, it is now known as the Magdeburg experiment which was actually carried out in 1657. In this experiment, two teams of horses were attached to the two halves of an evacuated sphere, to the astonishment of all present, the sphere could not be separated by the teams of horses.

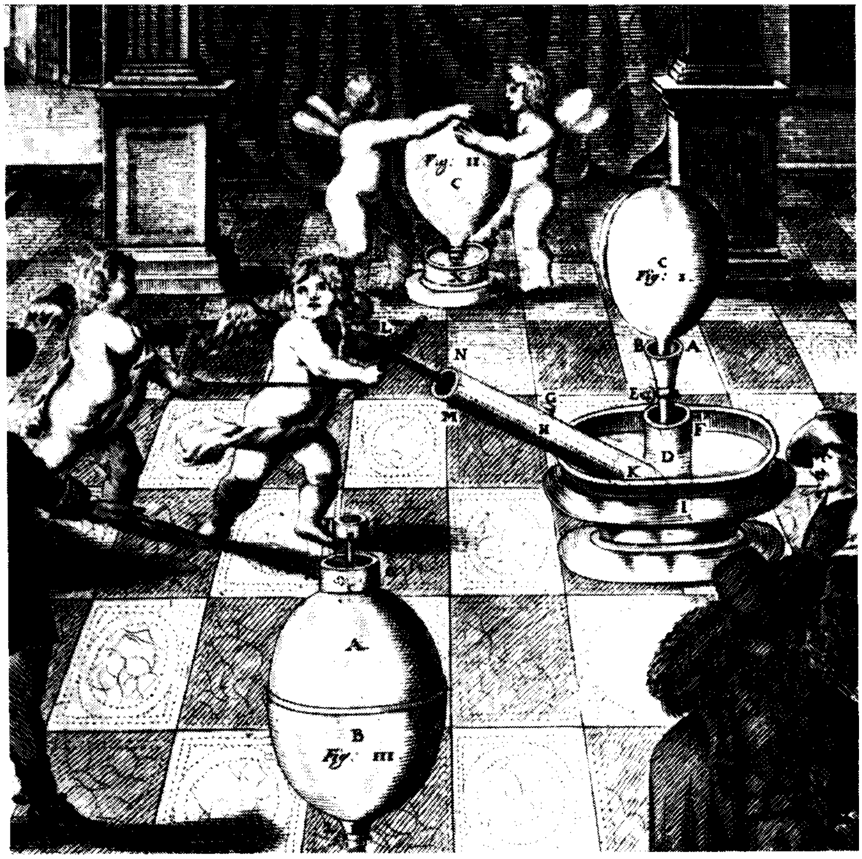


Diagram 2 B - The first representation of a vacuum pump, from the description of Guericke's early work in Schott's Mechanica Hydrolico-Pneumatica. (p30 Da C.Andrade-1957)

Schott described von Guericke's pump as consisting of a cylindrical tube with two valves. (See diagram 2-B). The first valve is located at H halfway along the tube, G is an opening on this tube. The second valve, I, was located at the lower end of the tube. This lower valve opens to D which provides access to the vessel being evacuated, C. When the piston is moved in (i.e. pushed down to D), valve I closes, while, when the piston is drawn out , valve I opens, allowing air from C to be drawn into the cylinder. The valve H opens at G when the internal air pressure increases i.e. the piston moves out and closes when the internal air pressure is reduced. This process could take several hours to evacuate the vessel C, depending on its capacity. Finally, tap E could be used to shut off the evacuated vessel which could then be removed. Water was used to make all the joints air-tight. [4]

Von Guericke described his own work in "*Experimenta Nova Magdeburgica de Vacuo Spatio*" which was published in 1672. (See diagram 2-C). A vertical cylinder gh is supported on a tripod. A wooden piston moved inside the cylinder. Its operation was similar to that described by Schott. [5]

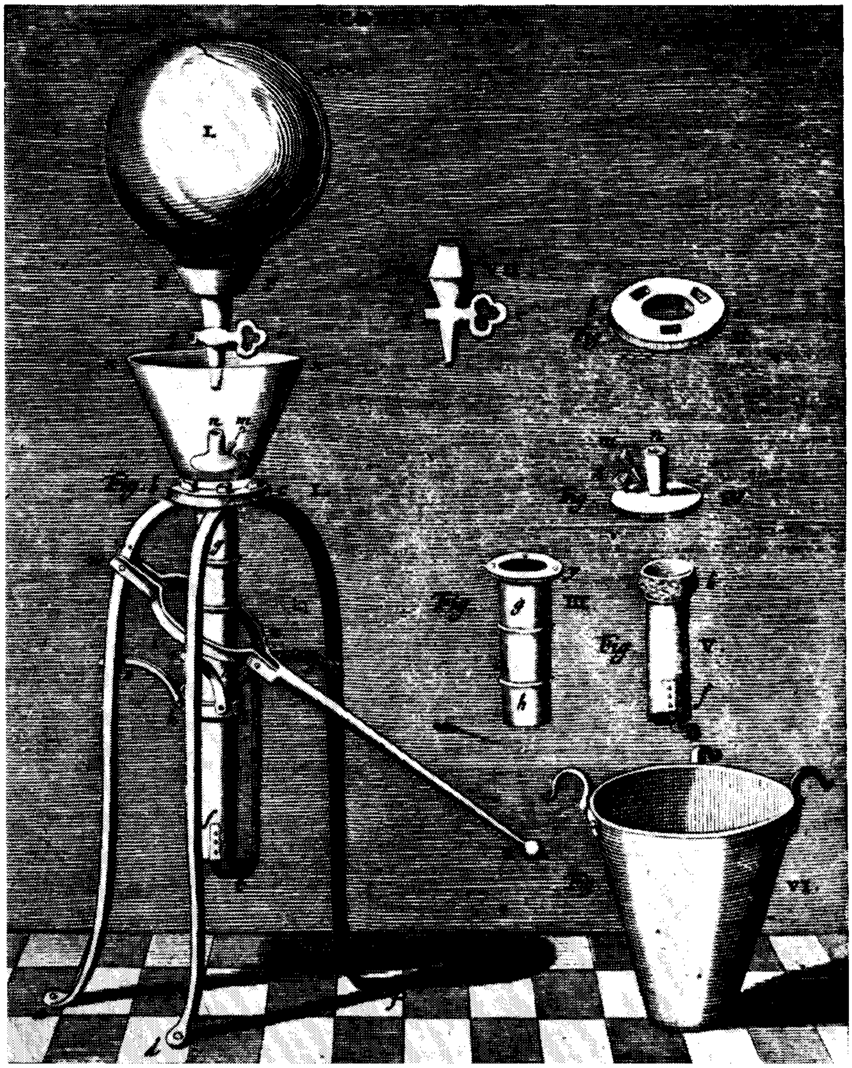


Diagram 2 C - Guericke's pump as figured in de Vacuo Spatio.
(p30 Da C.Andrade-1957)

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4 p 30 Da C Andrade 1957
5 p 31 Da C Andrade 1957

Robert Boyle (1627-1691) first became interested in air pumps after reading Schott's book. By 1660, Boyle had a pump built by Robert Hooke (1635-1702) who at this time was his assistant and instrument maker and had published his "*New Experiments Physio-mechanical Touching the Spring of Air*". (See diagram 2-D). This pump worked in a similar way to von Guericke's pump. However, Hooke used oil or an emulsion of oil and water to produce an air tight seal, hence avoiding the need for the water reservoir which von Guericke had used. Boyle also developed a combination of peg and tap valves so that he may achieve even lower air pressures. In 1669 Boyle replaced the receiver vessel with a bell jar which could be cemented using bees' wax to a flat plate which could then be removed for experiments.[6] The sketches of von Guericke's pump and that of Boyle appear similar. Since von Guericke published his book several years after Boyle had published his, it is quite possible that von Guericke was influenced by Boyle's clearer diagrams.

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[6] p 31-2 Da C Andrade 1957

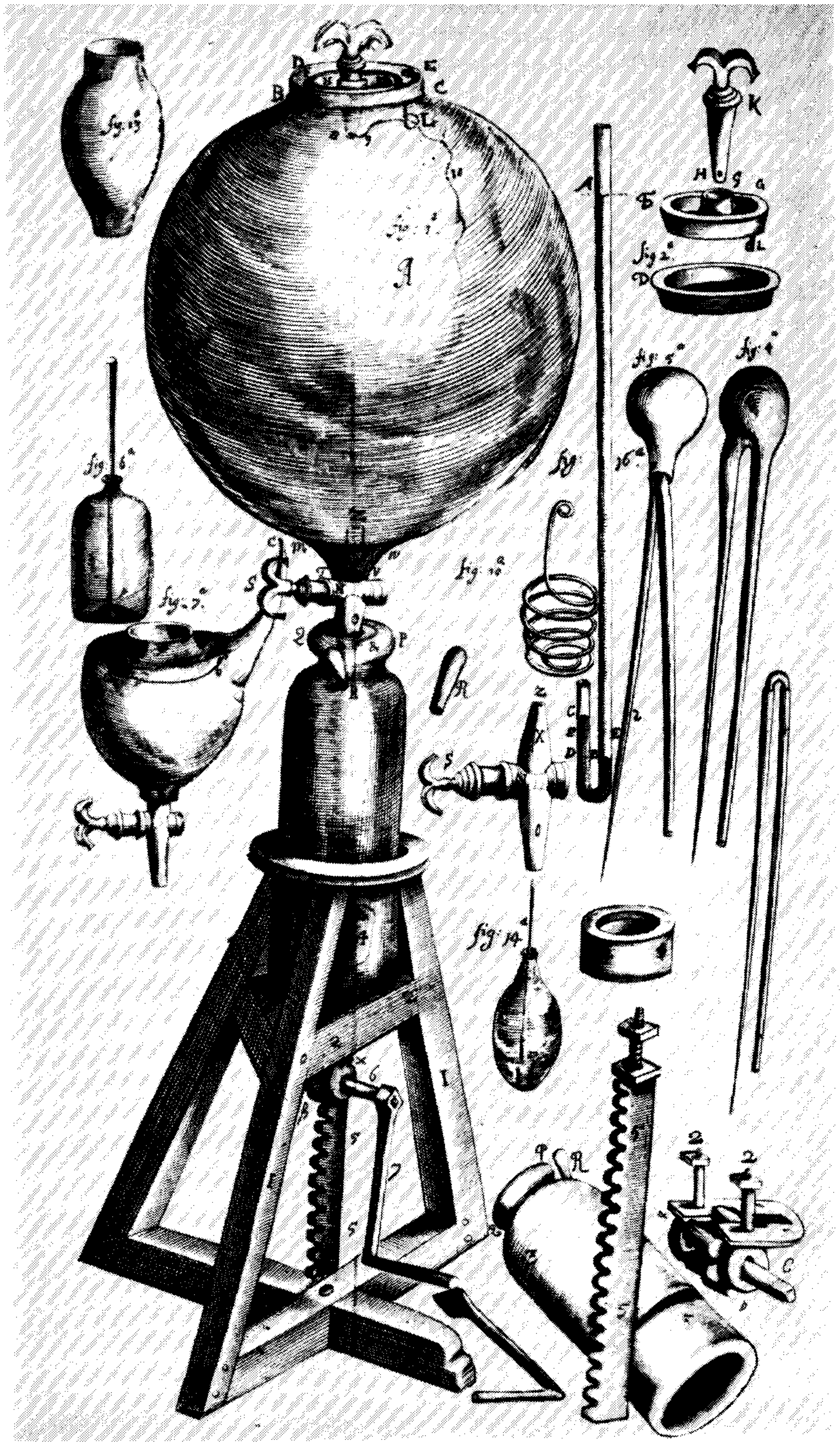

Diagram 2 D - Boyle's first pump, made by Robert Hooke. (p31 Da C.Andrade-1957)

The Frenchman, Denis Papin (1647-1712) was employed by Huygens in 1674. At this time, Huygens asked Papin to build him a pump similar to the type described by Boyle. Papin's contribution to pump design was the development of the two way tap in which one channel was an ordinary bore hole to communicate with the evacuating vessel and the other a groove which allowed access to atmospheric air. This two way tap was a perfect fit hence making it unnecessary to use a water sealant.[7]

In 1675 Papin was working in England as an assistant to Robert Boyle. Papin brought with him a two cylinder pump which Boyle described in 1682 in his "*A Continuation of New Experiments Physico-mechanical"* (See diagram 2-E). The pistons in each cylinder were coupled together by a cord which passed over a wheel which allowed the pressure of the atmosphere on one piston to withdraw the other piston. This arrangement made evacuation of a vessel much easier and more efficient than the single piston design.[8]

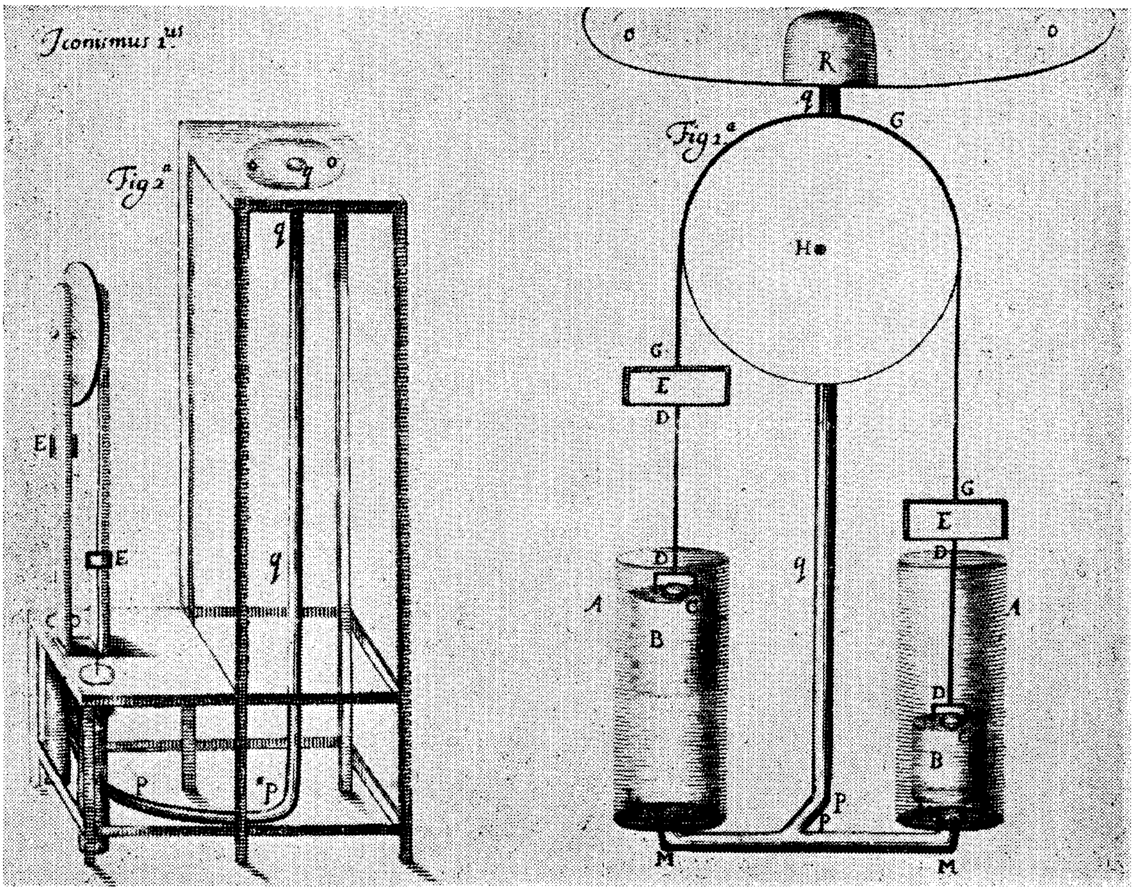

Diagram 2 E - The two-cylinder pump described by Boyle in "A Continuation of New Experiments Physico-mechanical" (p34 Da C.Andrade-1957)

The next major developments both in pumps and in the investigation of barometric light were made by an Englishman, F.Hauksbee (1666-1713).In 1705 Hauksbee began his research on the luminosity of phosphorus. As part of his investigation he

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7 p 34 Da C Andrade 1957

8 p 35 Da C Andrade 1957 and p 43 Da C Andrade 1959

studied the phenomenon of barometric light. He soon discovered that a barometer was not necessary to produce these flashes which could also be produced when mercury was dribbled over a glass surface in a partial vacuum. He further discovered that these flashes became brighter as the air was pumped out and then started to dim as the air pressure dropped further. When he replaced mercury with other materials rubbed together in a partial vacuum, the flashes still occurred. Finally he observed that this purple glow was still produced when an evacuated glass vessel was rubbed with wool, thus producing a static electric charge on the glass. [9]

In his article of 1705 Hauksbee describes this glow as *"a purple light ensued .... and continued so during attrition.* (i.e. while the vessel was being evacuated) *Upon letting in a little air, both the light and its colour did diminish: and as the air at several times was suffered to re-enter the receiver, so the light became manifestly more pale and less vivid"*. [10] Hauksbee next discovered that if an evacuated globe was placed on an axle and spun, it glowed brightly when he placed his hands against it. Further he discovered that a glowing spinning globe would cause a nearby evacuated globe to glow as well. He concluded that the electrical *"effluvium"* carried by the spinning globe must be rubbing against the nearby globe, but all attempts to prove this idea failed. [11] (See diagram 2-F).

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9 p 58 Harkins 1985
10 p 2170 Hauksbee 1705
11 p 58 Harkins 1985

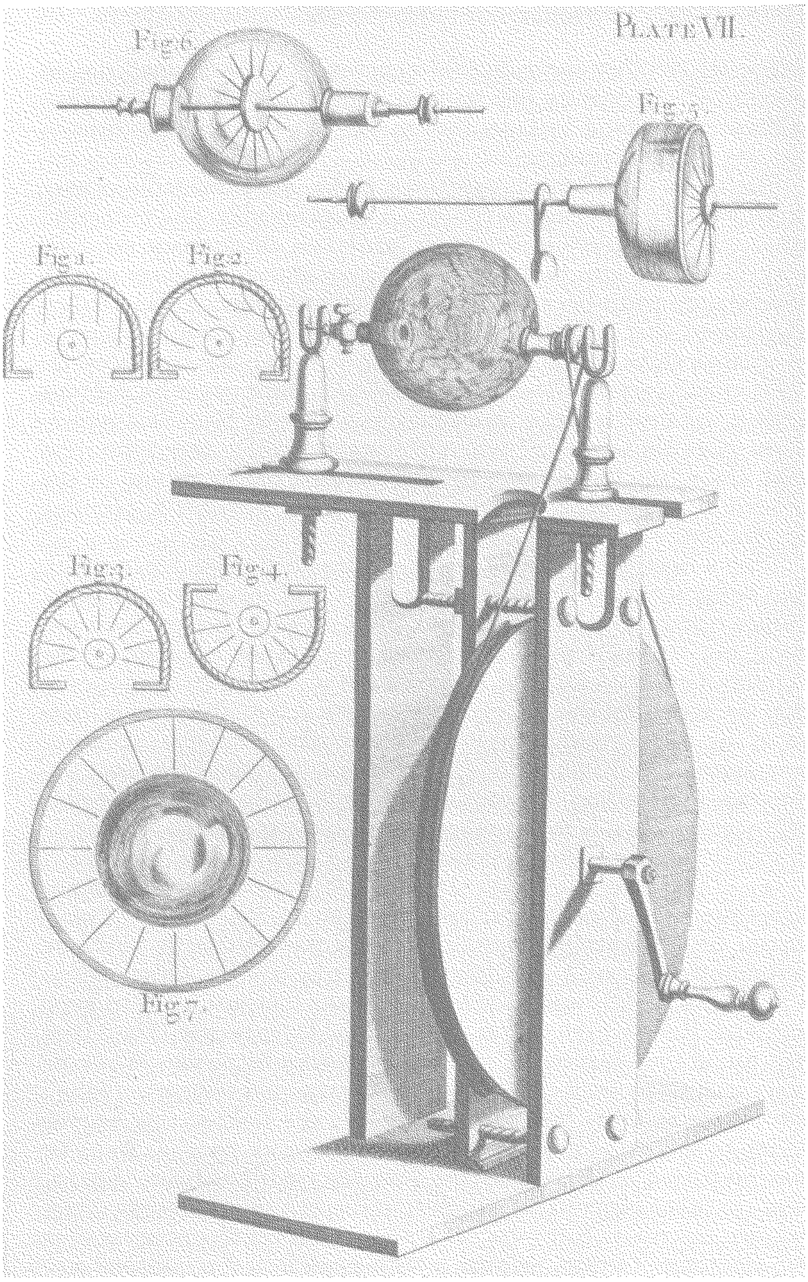

Diagram 2 F (p60 Harkins-1985)

Hauksbee's success in these investigations was not unrelated to his development of a greatly improved vacuum pump. In 1709 he produced a two cylinder pump. The two pistons were worked by rack and pinion, and they were arranged so that as one went up the other was going down. The valves were made of bladder and the evacuated bell jar was arranged directly above a mercury column manometer. It was estimated that this pump in Hauksbee's words *"gave a vacuum within about one inch of mercury of perfect"*. [12] It should be noted that an electric discharge in an

[12] p 45 Da C Andrade 1959

evacuated vessel may occur when the pressure is approximately 5mm of mercury or less. (See diagram 2-G).

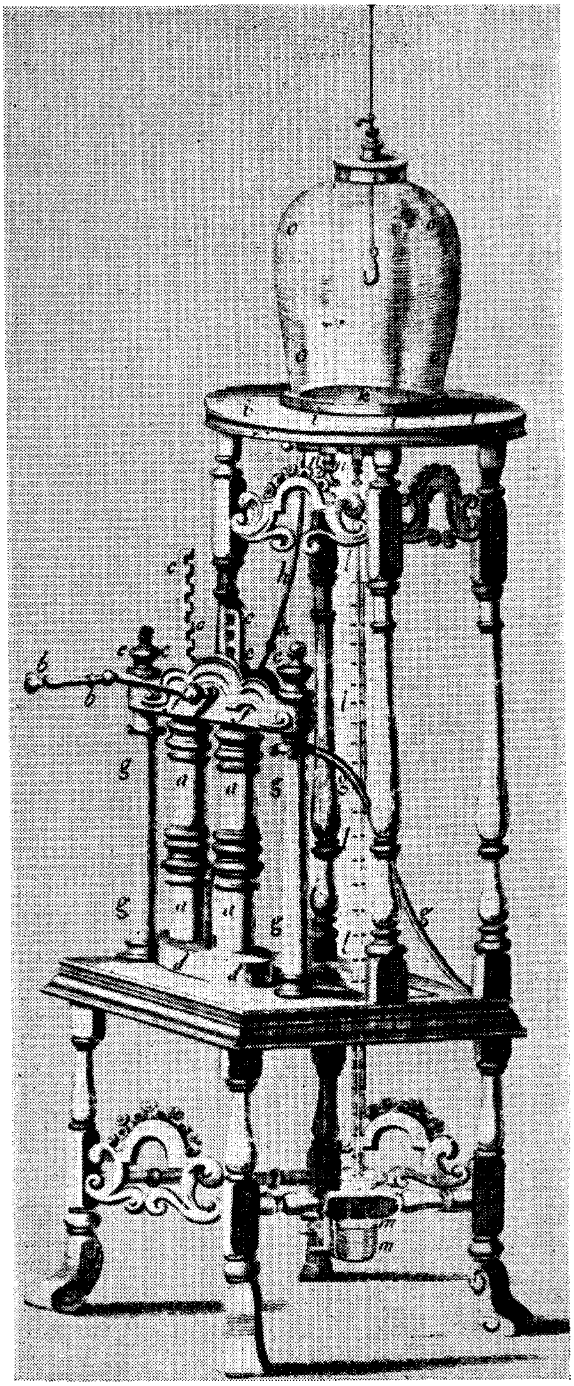

Diagram 2 G- Francis Hauksbee's pump. (p35 Da C.Andrade-1957)

Thus in his investigations Hauksbee described, and verified the conditions required to produce an electric discharge in an evacuated vessel i.e. a strong electric field and a gas contained under low pressure. Hauksbee's version of the vacuum pump changed little until the latter half of the nineteenth century.

2.3. Barometric Light

The first investigations of the continuous discharge through a rarefied gas seem to have been made independently by G. H. Grumment (1719-1776) in 1744 and in 1752 by the English apothecary, G. Watson who had also made contributions in the early theories of electricity (see chapter 1). [13] Watson initially used a pump of Boyle's design but constructed by Smeaton which obtained *"air rarefied to a thousand times its natural state; whereas commonly we seldom arrive at above one hundred and fifty"*[14] Watson used an electrical machine (no description is given in his account) to send a current through an exhausted glass tube which was three feet long and three inches in diameter. *"A ring of brass, exactly fitting this tube, was cemented to both its extremities, into each of which was screwed a hollow brass cap, nearly of a hemispherical figure. Into the top of one of these caps was adapted a brass box of oiled leathers, through which was admitted a slender brass rod of a length sufficient to reach within eight inches in length. Thus the extremity of one of these brass rods might at pleasure, without letting in the air, be made to touch the other. A small brass circular plate was made to screw into each of these extremities."*[15] This vacuum tube appears to have the same basic design that Thomson and later researchers used in their work. Watson, even at this stage, was aware of the basic requirements for this discharge i.e. that of a good vacuum, *"the inside of the glass made use of should be perfectly dry"* and *"the more complete the vacuum was, the more considerable were the effects"*.[16]

Watson described the phenomenon of electricity passing through a rarefied gas as *"a most delightful spectacle, a bright silver hue. These resembled very much the most lively coruscations of the aurora borealis. At other times, when the tube has been exhausted in the most perfect manner, the electricity has been seen to pass between the brass plates in one continuous stream throughout its whole length."*[17]

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[13] p 349 Whittacker 1951
[14] p 364 Watson 1752
[15] p 365 Watson 1752
[16] p 363-4 Watson 1752
[17] p 367 Watson 1752

Watson's desire to improve on these experiments stimulated the search to provide a better vacuum. Most of Watson's problems in this area were overcome when Lord Charles Cavendish presented Watson with a new apparatus. *"This apparatus consisted of a cylindrical glass tube of about three tenths of an inch in diameter, and of seven feet and half in length, bent somewhat like a parabola in such a manner that thirty inches of each of its extremities were nearly straight, and parallel to each other, from which an arc sprung which was likewise of thirty inches. This tube was carefully fill'd with mercury; and each of its extremities being put into a basin of mercury; so much of the mercury ran out, until, as in common barometrical tubes, it was in equilibrium with the atmosphere. Each of the basins containing the mercury was of wood, and was supported by a cylindrical glass of about four inches in diameter, and six inches in length; and these glasses were fastened to the bottom of a square wooden frame, so contrived, as that to its top was suspended by a silk lines the tube filled with mercury before mentioned; so that the whole of the apparatus without inconvenience might be moved together. The Torricellian vacuum then occupied a space of about thirty inches."*[18] (See diagram 2-H).

[18] p 370-1 Watson 1752

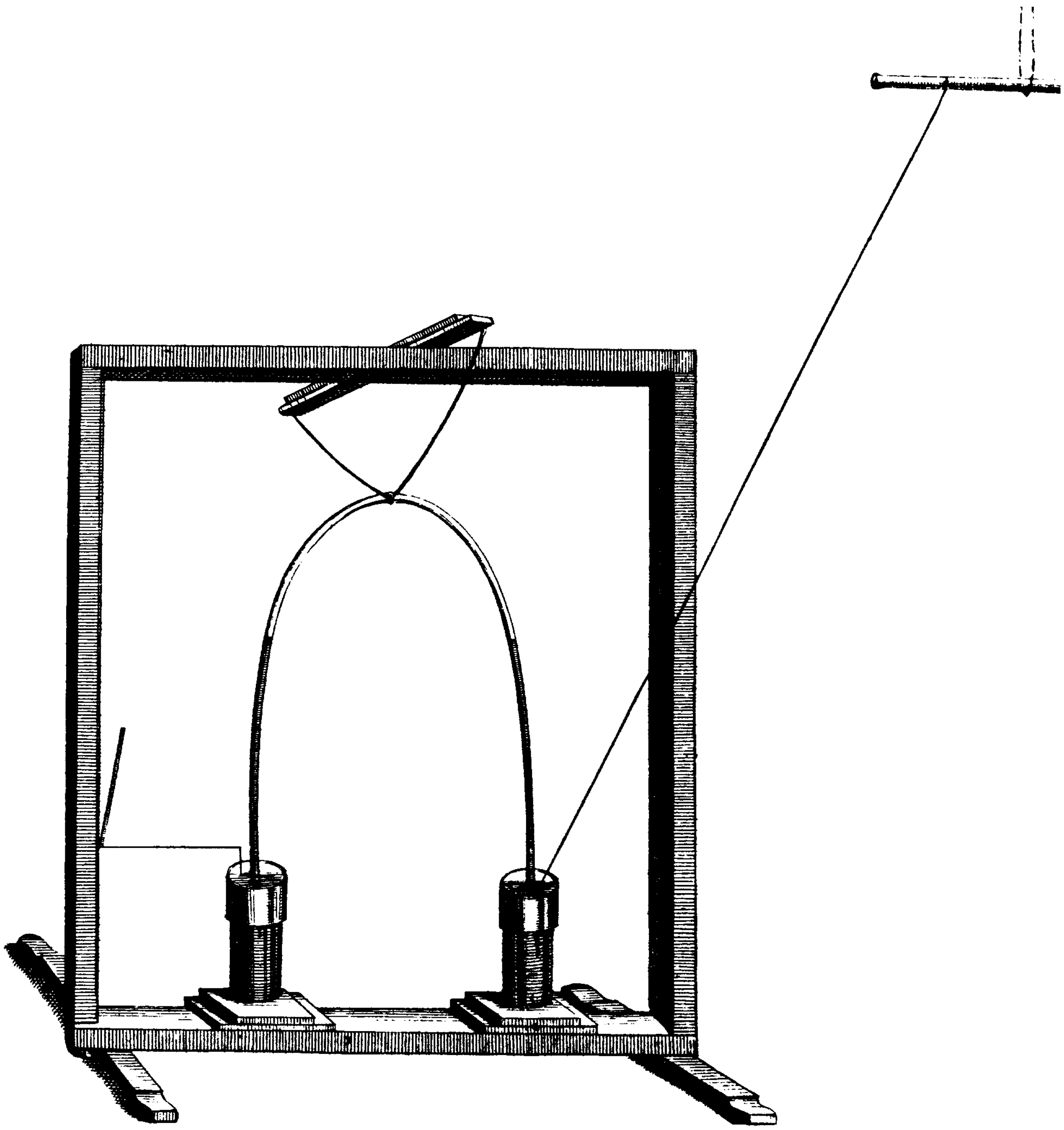

Diagram 2 H (p37 Watson-1735)

From his observations, Watson was unable to make a single conclusion as to the nature of the phenomenon he had observed. He concluded his article with *"By what denomination shall we call this extraordinary power? From its effects in these operations shall we call it electricity? From its being a principle neither being generated nor destroyed; from its being everywhere and always present, and in readiness to show itself and its effects though latent and unobserved, rendered visible; from its penetrating the densest and hardest bodies, and its uniting itself to them and from its immense velocity, shall we call it elementary fire? Or shall we, from its containing the substance of light and fire, and from the extreme smallness of its* *parts, as passing through most bodies we are acquainted with denominate it, with Homberg and the chemists, the chemical sulphureous principle, which, according to the doctrines of these gentlemen, is universally disseminated? ... certain it is, that the power we are now treating about is, besides others, possessed of the properties before mentioned, and cannot but be of very great, moment in the system of the universe."*[19]

Later Watson concluded that the glow was electrical in nature and *"is seen ... pushing itself through the vacuum by its own elasticity, in order to maintain the equilibrium in the machine".*[20] This concept follows from a combination of Watson's one fluid theory of electricity and with the then prevalent idea of electrical atmospheres.

Nollet (1700-1770) who was also performing electrical experiments in rarefied air at the same time as Watson had a contradictory explanation. He felt that *"the particles of the effluent stream collide with those of the effluent stream which is moving in the opposite direction; and being thus violently shaken are excited to the point of emitting light".*[21] This interpretation is in close agreement with our modern understanding of what actually occurs in a discharge tube. It is also remarkable that Nollet had the additional insight to suggest that these excited particles could produce enough energy in their collisions to produce light. Although a great deal of work was done in the study of this phenomenon, virtually no new discoveries were made until almost the middle of the nineteenth century.

In 1838 Faraday was passing a current from an electrical machine between two brass rods in a rarefied air. He noticed that the resulting purple haze or stream of light stopped short before it arrived at the negative rod. The negative pole, which was itself covered in a glow, was separated from the purple column by a narrow dark

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19 p 375 Watson 1752
20 p 349 Whittacker 1951
21 p 349 Whittacker 1951

space which has subsequently become known as Faraday's dark space.[22] Faraday, in this 1838 paper, commented that "*the results connected with the different conditions of positive and negative discharge will have a greater influence on the philosophy of electrical science than we at present imagine."*[23] This comment indicates Faraday's near prophetic vision of the ultimate impact of his discoveries.

Another twenty years were to pass before the next advances were made. The single most important technological development was the invention of the mercury air pump by Johann Heinrich Wilhelm Geissler (1815-1879) in 1855. Geissler was a mechanic and glass blower, it was in both these capacities that Geissler made major contributions to vacuum tube technology. As well as devising the mercury pump Geissler also developed the Geissler vacuum tube.[24] Geissler's pump was based on an earlier pump described by Swedenborg (1688-1772) 130 years earlier in 1722. Swedenborg's pump consisted of a small table with three long legs on which stood the glass bell-jar which was to be exhausted. The bell-jar was connected from below to an iron vessel. This vessel was then connected to an iron tube which was joined by a flexible leather tube to another iron tube. By placing the moveable tube upright or laying it down, the mercury which filled both tubes would rise and fall, thus emptying the iron vessel. The use of appropriate valves in the iron vessel allowed the bell-jar to be exhausted.[25]

Geissler's pump described in 1858 had the following improvements over Swedenborg's pump: the pump was made entirely from glass except from the rubber tube which was used as a substitute for the leather joint.[26] The pump consisted of a glass bulb which was connected by a flexible tube to an open reservoir of mercury. The bulb had at its top a two-way tap which could connect it to either the outside air or to the vessel to be evacuated. When the tap was turned to the outside air the

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22	p 349	Whittacker 1951
23	p 79	Pais 1986
24	p 67-8	Pais 1986
25	p 130	Poggendorff 1865
26	p 131	Poggendorff 1865

vessel was cut off, the reservoir of mercury was raised until all the air had been expelled from the bulb which was filled with mercury. The tap was then turned to connect the bulb with the vessel, and the reservoir lowered. This process was repeated as often as necessary to achieve the pressure required.[27] (See diagram 2-J).

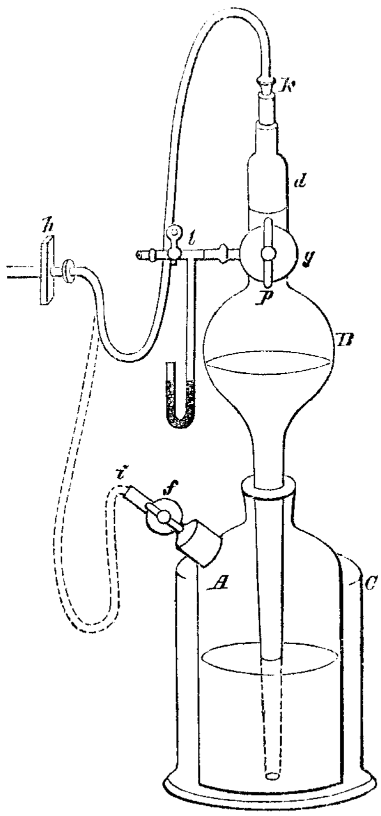

Diagram 2 J (p132 Poggendorff-1865)

Geissler's other invention, the vacuum tube, was based on the earlier work of Faraday and is essentially the same process by which modern vacuum tubes are produced. In 1838 Faraday described an experimental arrangement to study electrical discharges. It consisted of a glass tube containing a fixed electrode inside the tube and a second electrode in the form of a metal pin protruding through the cork which was used to seal the tube. Geissler developed a glass tube which was evacuated and sealed with glass. The electrodes were made to enter the tube during the sealing process. Thus a stable vacuum had been produced which now eliminated the need to evacuate the vessel for each experiment.[28] Geissler's tube

[27] p 131 Poggendorff 1865 and p 45-6 Da C Andrade 1959
[28] p 68 Pais 1986

was first used by Plucker in 1857 and the following year by Faraday for his own experiments. The pressures in these tubes were typically 0.1 mm of mercury.[29] While Geissler's tubes and other vacuum tubes produced in a similar manner would be used during the next 150 years for experiments on electrical discharges, the pressures inside these tubes would be greatly reduced by further improvements in vacuum pumps.

In 1862 Töpler made a number of improvements on Geissler's design. He retained the mercury reservoir and the flexible tubes, but substituted an arrangement of tubes for the tap. This method automatically opened the glass bulb to the outside air and the vessel to be evacuated to the Torricellian vacuum, as the mercury level was in the appropriate position. (see diagram 2-K) It was pumps of this general type that were used in early cathode ray experiments.

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[29] p 68 Pais 1986

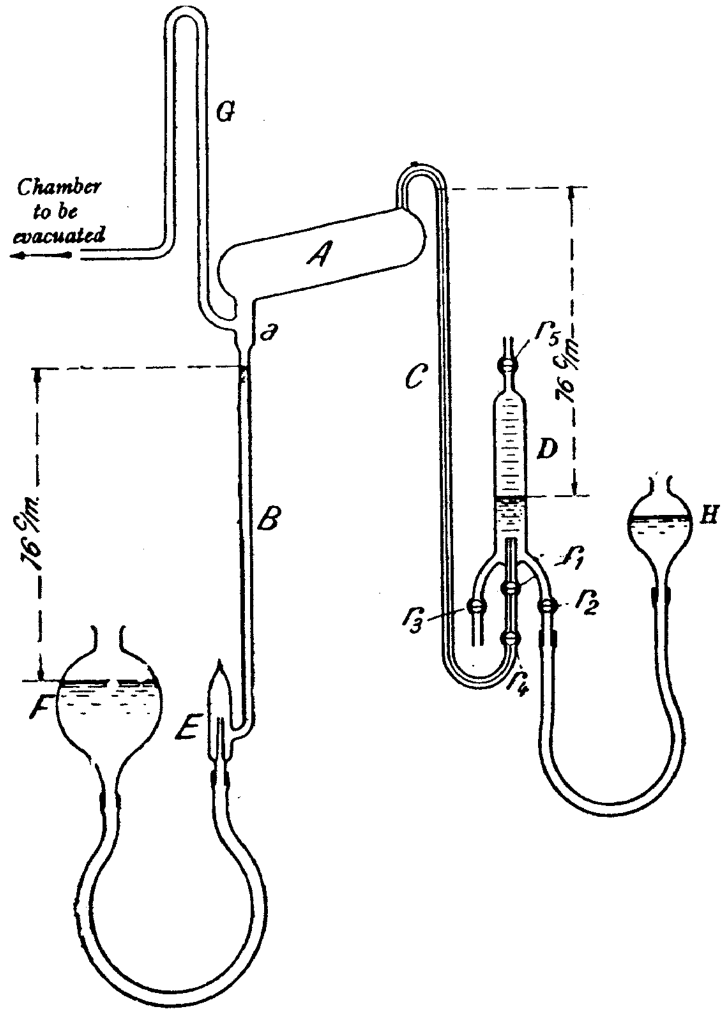

Diagram 2 K - Improved form of Töpler pump. (p45 Da C.Andrade-1959)

Another type of pump which was also used in electric discharge experiments was the Sprengel mercury pump, invented in 1873. In this pump the air is carried away by a succession of falling mercury pellets between which it was trapped. William Crookes (1832-1919) used a pump of this type for his work on vacuum physics. He claimed to have achieved pressures as low as 3×10^{-3} mm of mercury by using phosphorus pentoxide to absorb water vapour, precipitated sulphur to stop mercury vapour, and reduced copper to stop the sulphur vapour entering this evacuated space.[30]

The early cylinder pumps, such as were used by Hauksbee were also improved during the second half of the nineteenth century. In 1892 Fleuss developed what he called the Geryk pump. A new feature of this pump was that the dead space which is left when the piston is pushed to the end of the cylinder was now filled with oil. Thus

[30] p 46 Da C Andrade 1959

these pumps were sometimes referred to as oil pumps. The oil used was required to have a low vapour pressure and it was claimed that pressures as low as 2×10^{-4} mm of mercury were obtained.[31]

2.4. Advances in the Generation of Electricity

The other major advance that allowed the study of electric discharges in vacuum tubes to proceed was the production of a reliable source of high voltage electric current, which could produce a high electric field in these discharge tubes. The frictional machines of the eighteenth century gave way to the electrochemical battery and the magneto-electrical machine. The electrochemical battery was a refinement of Volta's pile and seemed to be used extensively by researchers in electric discharge experiments. The magneto-electrical machine produced an alternating current and is based on Faraday's discoveries and work in electromagnetic induction.

Electrochemical batteries were made up from hundreds and even thousands of individual cell which were connected in series, thus producing a large electric potential across its terminals. The most popular cells used at this time were the Plante cells, the Daniell cells and the Leclanché cells. The Plante cell developed into the modern lead-acid battery commonly used in cars. A battery of Plante cells, described by Hertz, was made up of about 1000 cells. Each cell consists of a test tube 125mm high and 14-15mm diameter. The tube is 2/3 filled with sulphuric acid diluted with 9 times its volume of water. Adjacent tubes are connected by a single bent lead electrode. These electrodes were 10mm wide and 1mm thick. The top of the electrode was varnished with asphalt varnish. Each group consisted of 5 such test tubes connected with these electrodes. Copper wires were soldered onto the two outside electrodes of each group and these were connected to two glass mercury cups which formed the poles of the group.[32] Ten groups of 5 cells were cemented onto boards (i.e. 50 cells in all) and 5 of these boards were put in a box

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[31] p 45 Da C Andrade 1959
[32] p 225 Hertz 1896

with dimensions of $840mm \times 120mm \times 170mm$ high (i.e. each box contained 250 cells). The 100 glass cups which formed the corresponding poles lay in a row in front of the box. Hertz used four such boxes as a source of power in his experiments. This battery took an hour to charge. The potential difference between the poles was equal to about 1800 Daniell cells. The battery lasted about 6 hours and could supply enough current to continuously light a Geissler tube for 2-3 hours.[33]

A Daniell cell consisted of a copper pot which acted as the positive terminal. This copper pot contained a solution of copper sulphate solution. A second porous earthenware pot was placed in this solution. This second pot contained a mercury amalgamated zinc rod placed in a solution of sulphuric acid. The zinc rod was amalgamated with mercury to prevent its dissolution in the acid when the cell was not in use. The porous pot allowed electrolytic contact between the two solutions without actually allowing the two solutions to mix. The e.m.f. of a Daniell cell was fairly constant at about 1.1 volts and provided a small current.[34] (See diagram 2-L).

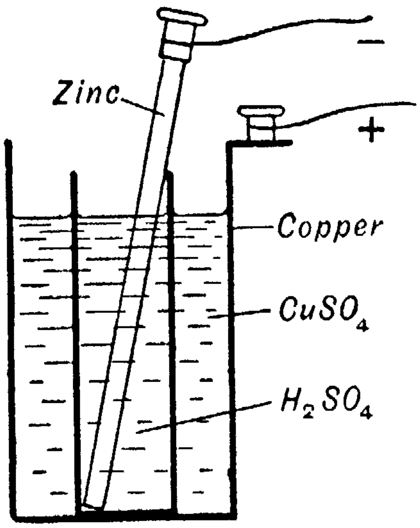

Diagram 2 L-A Daniell Cell (p911 Duncan and Starling-1947)

A Leclanché cell consisted of a glass jar containing a saturated solution of ammonium chloride. In this jar was immersed an zinc rod (the negative terminal) and a porous pot containing a carbon rod around which was packed manganese dioxide. The carbon rod acted as the positive terminal. The ammonium chloride solution

33 p 225 Hertz 1896
34 p 911 Duncan & Starling 1947

diffuses into the porous pot through the manganese dioxide to the carbon rod. When a current passes through the cell, the zinc is dissolved and reacts with the chlorine liberating ammonium ions which react forming ammonia and hydrogen. The hydrogen reacts with the manganese dioxide liberating water. This reaction provides the cell with an e.m.f. of about 1.5 volts.[35] (See diagram 2-M). This developed into the modern dry cell or battery .

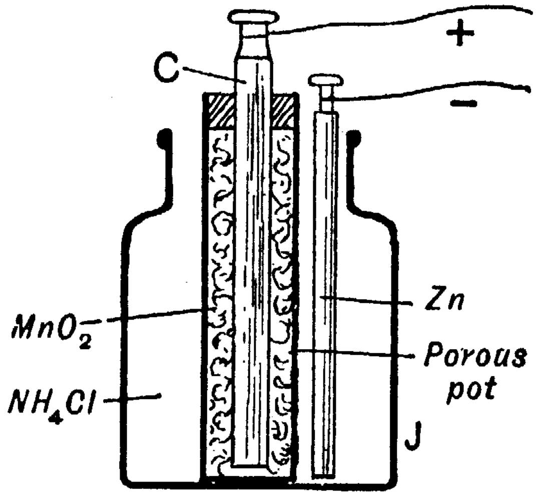

Diagram 2 M-A Leclanché Cell. (p912 Duncan and Starling-1947)

The most popular magneto-electrical machine was the Ruhmkorff coil which was developed in the 1850's. This consisted of a cylindrical iron core around which was wound around a primary coil of insulated wire. The secondary coil consisted of about 300000 windings per meter on the cylinder. As with any induction coil, a small e.m.f. applied to the primary coil resulted in a large e.m.f. on the secondary, Ruhmkorff's coil could produce an output voltage of the order of 1000's of volts. These coils could be powered by the traditional friction machines or the then modern electrochemical batteries.[36]

The first researchers in the area of electric discharge in vacuum tube, Plucker (1801-1868), Hittorf (1824-1914), Goldstein (1850-1930) and Crookes (1832-1919), favoured the induction coil or magneto-electrical machine, while Hertz (1857-1894)

35 p 912 Duncan & Starling 1947
36 p 69 Pais 1986

used both electrochemical cell and induction coils. In his later experiments Hittorf also favoured electrochemical cells.[37]

Thus by the end of the 1850's, scientists had at their disposal vacuum pumps that produced gas pressures of about 10^{-3} mm of mercury, reliable sources of electric power which could produce e.m.f.'s in the kilovolt ranges and vacuum tubes had been developed that once evacuated could have their electrodes sealed in their glass walls. The stage was now set for what appeared to be a revolution in discoveries of the properties of the glow obtained in gas discharge tubes.

[37] p 244 Hertz 1896

3. Cathode Rays

3.1. Early Investigations

Julian Plucker (1801-68), Professor of Natural Philosophy at the University of Bonn, was repeating and extending some of Faraday's experiments on magnetism during the late 1840's and early 1850's. Shortly after Geissler developed his vacuum tube, Plucker obtained one and commenced studying the discharge effects in it. With his background interests in magnetism it was only natural for him to choose to observe the effects of magnetic fields on the cathode glow. In the period 1857 to 1859, Plucker published a number of papers describing his work on the behaviour of cathode glow. [1]

Plucker observed that the presence of a magnetic field produced a deflection in the position of the glow near the cathode. When the cathode was reduced to a single point and in the presence of a magnetic field, the glow now formed a concentrated line along a line of magnetic force (i.e. perpendicular to the field). He also observed that during the discharge a phosphorescence occurred on the walls of the discharge tube near the cathode and the position of this phosphorescence changed when a magnetic field in its vicinity changed. [2] Plucker observed that as the gas pressure in the vacuum tube was decreased the region of glow increased. [3] As a consequence of this work, Plucker was regarded by some, notably J.J.Thomson, as the first person to observe and record cathode ray discharges. [4]

W. Hittorf (1824-1914), one of Plucker's students, found in 1869 that if an object was placed in front of a pointed cathode, a well defined shadow was formed on the wall of the tube. He found that the shape of the shadow was determined only by the

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[1] p 79 Pais 1986
[2] p 350 Whittacker 1951
[3] p 79 Pais 1986
[4] p 621 Thomson, J.J. 1906

shape of the object and not by its composition. He used objects made from conductors and insulators, as well as opaque and translucent materials. The results were the same. He thus concluded that this phosphorescence was the result of rays being emitted from the cathode and travelling in straight lines until they struck the walls of the tube. Hittorf called these rays *"Glimmstrahlen"* or glow rays. [5]

Hittorf's conclusion that the cause of the glow was the result of rays led to the beginnings of the dispute between German and English Physicists as to the exact nature of these discharges: were they particles or were they rays of light. This dispute was to last for almost fifty years, with each side attempting to prove the validity of their own view and at times using exactly the same evidence to support their case. It is of interest to digress here and comment that a similar dispute had occurred concerning the nature of light. Newton and his colleagues thought that light was particulate in nature while Huygens suggested that light was a wave and behaved in a similar manner to a water waves in a pond.

Eugen Goldstein (1850-1930) continued and elaborated Hittorf's work on these "glimmstrahlen". In 1876 Goldstein had discovered that the well defined shadows cast by these rays were independent of the shape of the cathode. The object producing the shadow was, however required to be near the cathode. [6] Goldstein also found that these rays were emitted in a direction normal to the surface of the cathode, concluding that *"the rays which produce the phosphorescence of the glass must be emitted almost normally, and not like light, in all directions, for if the negative surface had been luminous, it would hardly throw a visible shadow of a small body placed near it"*. [7]

Finally, Goldstein found that if the vacuum tube contained two cathodes which were connected together, the rays emanating from each cathode were deflected away

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5 p 137 Thomson, J.J. 1906, p 621 Thomson, J.J. 1908, p 351 Whittacker 1951
6 p 351 Whittacker 1951
7 p 138 Thomson, J.J. 1908

from each other.[8] Despite the evidence that these emanations were deflected by magnetic fields, as well as by each other, and appear to be emitted in a manner very different to that of light, Goldstein continued to hold the belief that this phenomenon could be regarded as rays or waves in the aether and even went to the extent that he regarded the gas as being unnecessary for their propagation.[9] Goldstein introduced the term "Kathodenstrahlen" or "cathode rays" to describe this phosphorescence. The term "cathode rays" soon became widely accepted in both Britain and Europe. The term further reinforced the view that this glow was a disturbance in the aether.

In Britain at this time a proposal was put forward that these rays were in fact particulate in nature. The first such hypothesis of this particulate nature of cathode rays came from Cromwell Varley (1828-1883) who suggested in 1871 that the rays were composed of "*attenuated particles of matter, projected from the negative pole by electricity".*[10] Varley believed that it was because of their negative charge that these particles could be deflected by a magnetic field.

Sir William Crookes (1832-1919) developed his own vacuum tubes some of which had a lower gas pressure than those of Geissler. By 1879, he had developed a number of tubes which he used to investigate the properties of cathode rays. One of these tubes contained a Maltese Cross which cast a distinct sharp shadow on the glass wall. Another tube contained a "paddle wheel" in which a number of vanes were mounted on an axle which was able to move freely along two glass rails. (See diagram 3-A). When the discharge passed through the tube the rays strike the upper vanes causing the wheel to move from the cathode to the anode.[11] This experiment indicated that these rays transmit momentum and hence were probably mechanical or particulate in nature. Thus, Crookes also favoured the particulate nature of these rays, since he "*regarded these rays as consisting of electrified particles, projected at*

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[8] p 138 Thomson, J.J. 1908
[9] p 138 Thomson, J.J. 1908
[10] p 351 Whittacker 1951
[11] p 146 Thomson, J.J. 1908

right angles to the cathode with great velocity, causing phosphorescence and heat by their impact with the walls of the tube". [12]

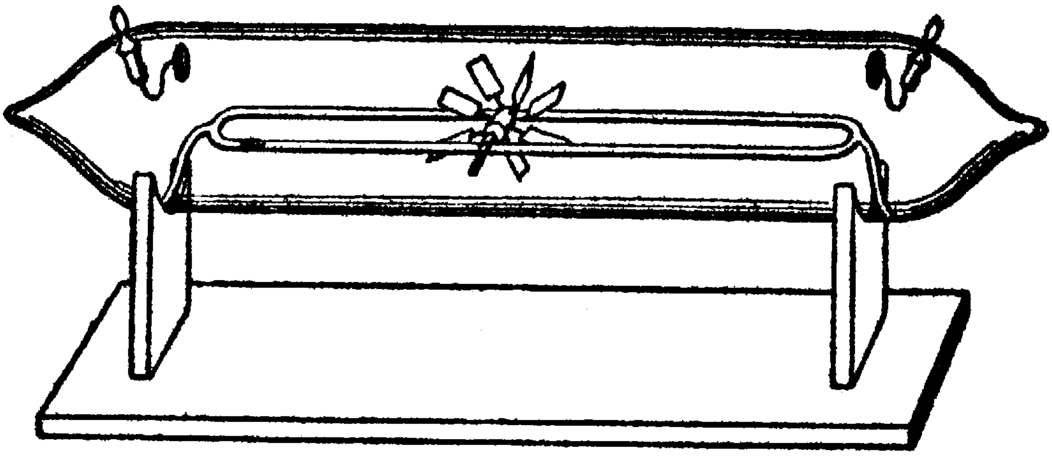

Diagram 3 A Crookes Tube (p146 J.J.Thomson-1908)

As a consequence of Crookes' ability to obtain a better exhaustion of his vacuum tubes, he was able to study the dark region found between the cathode glow and the first band of glow, now known as Crookes' dark space. In a vacuum tube which has a gas pressure of about 10mm of mercury pressure, a glow first appears on the cathode which then proceeds to fill the tube. As gas pressures are reduced a dark space begins to appear near the cathode, the glow on the cathode remains while the glow in the rest of the tube remains unchanged. This dark space is referred to as Faraday's dark space. When the vacuum pressure drops to about 0.1 mm of mercury, a number of things occur, firstly a second dark space appears in the vicinity of the cathode which appears to glow. Immediately after this dark space, called the Crookes' dark space, there appears a region referred to as the negative glow, followed by the Faraday dark space. Finally the remaining region of glow becomes striated until the glowing anode is reached. (See diagram 3-B). As the pressure is reduced further to about 0.01 mm of mercury the dark spaces increase in size until the glow finally disappears. [13] Crookes correctly explained the dark space as a region where there were fewer collisions between the cathode rays and the gas molecules, and the glow as the region where there were many collisions. He

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[12] p 622 Thomson, J.J. 1906

[13] p 1029 Duncan & Starling 1947

attributed the phosphorescence on the glass walls of the tube to the impact of these cathode ray particles on the glass. [14]

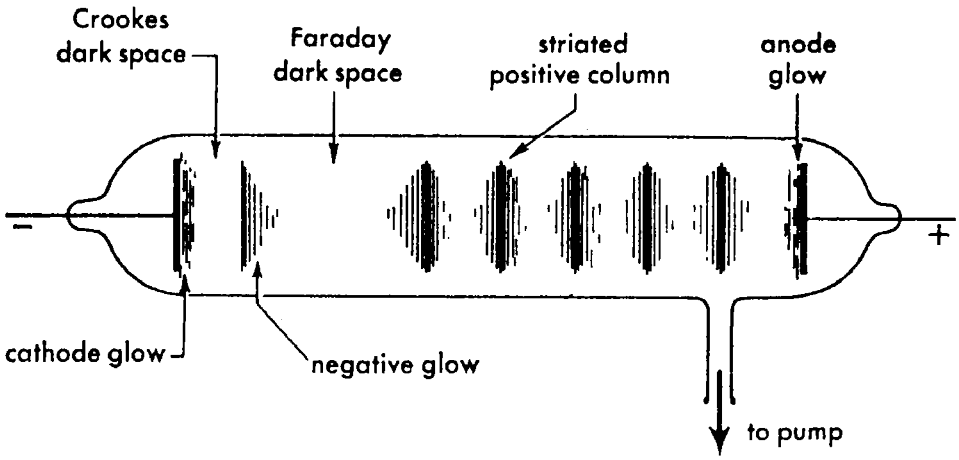

Diagram 3 B

In the years 1880-1900 an explosion of information concerning the properties of cathode rays occurred. It was found that cathode rays heat the body on which they fall, that by concentrating the rays using a spherical shell as the cathode, the heat produced could fuse small pieces of glass, char the surface of a diamond and make platinum become incandescent. [15] Finally it was found that the impact of cathode rays on a body could emit cathode rays and produce Röntgen rays. [16] This phenomenon was discovered by Wilhelm Röntgen (1845-1923) in November 1895. Röntgen had become interested in the experimental results obtained on cathode rays by Heinrich Hertz and Philipp Lenard whose work will be discussed later in this chapter.

Röntgen was repeating an experiment devised by Lenard in which cathode rays are allowed to pass through the end of the vacuum tube. Röntgen now varied this experiment by encasing the vacuum tube with a piece of thin black cardboard and observed that in a darkened room, a screen covered with barium platinocyanide glowed brightly during the discharge. When the screen was moved further away the glow could still be observed. Röntgen moved the screen a distance of two meters

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[14] p 351 Whittacker 1951
[15] p 627 Thomson, J.J. 1906
[16] p 628 Thomson, J.J. 1906

still observing the glow which appeared to be emanating from the discharge tube and not from the apparatus which included a Ruhmkorff induction coil. Röntgen published his results the following month. In this first paper on X-rays, Röntgen first mentions X-ray photography "*I have photographs ... of the shadows of the bones of the hand; ... of a set of weights enclosed in a small box; of a compass in which the needle is entirely enclosed by metal.*"[17]

In 1897 Birkeland found that when he used an induction coil as his power source, the cathode rays produced a phosphorescence which was not only deflected by a magnetic field, but was broken into a number of distinct bands or striations, of glow and dark space. This phenomenon was referred to as the magnetic spectrum. J.J.Thomson also observed a similar deflection and striation effect when an electric field was applied to the cathode rays. This phenomenon was not observed when the power supply used to produce the cathode rays came from a battery of storage cells. It was believed that the striations were caused by the charged particles composing the cathode rays travelling at varying velocities when emitted from the cathode due to the periodic nature of the e.m.f. produced by the induction coil. [18]

3.2. Arthur Schuster

Arthur Schuster (1851-1934) was born into a German Jewish family which for business reasons moved to Manchester. Arthur was educated in Frankfurt and later in Geneva, joining his family in Manchester in 1870. In 1871 he enrolled as a day student at Owens College where in 1873 he was employed as an unpaid demonstrator. In 1875 he joined Maxwell as a researcher at the Cavendish Laboratory where he remained for five years. In 1881 he was appointed professor of Applied Mathematics at Owens College, ahead of J.J.Thomson who had also applied. In 1887 Schuster was appointed to the Chair of Physics at Manchester, a position which he held until 1907.

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[17] p 38 Pais 1986
[18] p 633 Thomson, J.J. 1906

During the 1880's, Arthur Schuster started experimenting with discharge tubes, a research interest which would remain with him for the next thirty years. In 1884, Schuster presented his ideas on the nature of glow in discharge tubes in the Bakerian Lecture which he presented to the Royal Society. He believed that the electrical conduction in gases was due to the diffusion of ions, similar to that which takes place in electrolytes during electrolysis. He commenced with the assumption that " *In a gas, passage of electricity from one molecule to the other is always accompanied by the interchange of the atoms composing the molecule."*[19] Schuster then speculated whether it was possible for a rapidly moving gas molecule to carry with it "*any part of the electricity'* found on an electrified surface and whether it could then pass this electricity on to another molecule. Finally, he assumed that if this did occur then " *we are led at once to the supposition that the discharge in gasses is accompanied by the breaking up of the molecules."*[20] Finally, he states that the purpose of his paper was to prove that " *the molecules are, in all probability, broken up at the negative pole."* (i.e. the cathode)[21]

Schuster conducted a series of experiments, some of which were repetitions of his previous discoveries, in which he observed the differences in the discharge glows of different gases, different gas pressures inside the tubes and different electrodes as well as the behaviour of the discharge in the presence of a magnetic field. He observed the spectra of the gases during the electrical discharge and found the presence of "*two or generally even three distinct spectra in the tube"* which he assumed was the result of "*the formation of a distinct molecule."*[22]

From these experiments, Schuster concluded the following:-
"*once a current is set up in the gas it requires a much smaller electromotive force to keep it going.*[23] This phenomenon is more clearly observed in modern fluorescent

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[19] p 318 Schuster 1884
[20] p 318 Schuster 1884
[21] p 318 Schuster 1884
[22] p 322 Schuster 1884
[23] p 328 Schuster 1884

lights which require a starter switch to establish the discharge which produces the light and once established draws little power.

"*the decomposition of molecules at the negative electrode is essential to the formation of the glow discharge.*" [24] Schuster at this time was of the belief that the negative particles were actually ions. He believed that "*the molecules are decomposed partly by chemical and partly by electrical forces, and the electronegative part will be able to follow the forces acting on it, and acquire a considerable velocity within a small distance. This velocity will gradually be reduced by impacts, and the temperature thereby raised: hence the luminosity of the glow. The dark space must, therefore be considered as the region through which the greater number of atoms can freely pass.*" [25] This conclusion had already been formulated by Crookes.

Finally in this paper Schuster states *"The most conclusive proof of our theory would be the demonstration of the fact that each particle of matter carries with it the same amount of electricity. We shall not, of course, be able to prove this for each single particle, but I propose to show how we can decide the point experimentally as far as the average amount is concerned.*" [26] Schuster's method suggested the use of both the concepts and practice of electrolysis theory. Further, Schuster suggests that a beam of the glow be placed in some uniform force field such as a magnetic field in such a way that the "*lines of force cut the rays of the glow at right angles.*" [27] This would result in the rays curling into a circle. Schuster then suggests that measuring the radii of these circles could also be possible. He states that the force exerted on the current is proportional to the product of the velocity of the particle i.e. the ion and the amount of electricity it carries

i.e. $F \propto ev$

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[24] p 329 Schuster 1884
[25] p 330 Schuster 1884
[26] p 331 Schuster 1884
[27] p 331 Schuster 1884

It is now known that $F = Bev$ where B is the magnetic field strength measured in Tesla. Now if the particle moves in a circle then $F = mv^2 / r$ where r is the radius of the circle.

Thus Schuster concluded that $r \propto v/e$.[28] Further he had actually performed some preliminary experiments to verify that such an experiment could be made.

Schuster assumed that if the current in the discharge is increased, then either the number of charged (i.e. ionised) particles increases, or the velocity of the particle is increased or the amount of electricity increases or some combination of these alternatives. He found, however, that an increasing current produced a larger radius of curvature indicating an increase in the velocity of the particles. He now looked at the relationship between the potential drop in the region of the glow, V, the velocity gained due to this potential and the radius of curvature of the particle due to the applied perpendicular force. Thus using the conservation of energy where the gain in kinetic energy is equivalent to the loss in potential energy he could state

$$\frac{1}{2}mv^2 = Ve$$

i.e. $v^2 \propto Ve$ thus $v \propto \sqrt{Ve}$ and hence $r \propto \sqrt{V/e}$.[29]

Schuster concluded "*here, then, we have a definite experimental problem before us which I hope to decide one way or another as soon as I have the necessary experimental means at my disposal.*"[30] For some unknown reason, Schuster did not at this time attempt to perform the experiments which he suggested. Writing in 1908, Schuster makes the comment " *I realised at an early stage that in order to demonstrate the correctness of the theory of ionic charges it was necessary to find a*

28 p 332 Schuster 1884
29 p 332 Schuster 1884
30 p 332 Schuster 1884

proof that the charge is a definite quantity, and that a crucial experiment could be devised by observing the magnetic deflection of cathode rays."[31]

In his 1887 paper Schuster attempted to show "*that a gas can be converted into a conductor by an independent discharge which is made to pass through it.*"[32] From this series of experiments he concluded that "*the conductivity was found to exist some distance away from the primary discharge. The experiments were explained by the breaking up of the neutral molecules in the primary discharge, the charged atoms acting as we would now say as ions capable of independent diffusion and therefore converting the whole mass of gas into a conductor of electricity."*[33]

Schuster was now asked to present the 1890 Bakerian Lecture. In this, his second Bakerian Lecture, Schuster says that he had desired to show that "*gases may be converted into conductors by ionisation and that the charge of the ion is a fixed quantity*"[34] This concept had previously been widely accepted in the area of electrolysis, so much so that Stoney had actually defined this fixed quantity as the electron (see chapter 1). Schuster quoted the following statement made by Helmholtz in his Faraday Lecture: "*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.*"[35]

Writing in 1908 Schuster mentions that he received a great deal of support during the 1880's from Helmholtz who *"frequently enquired after the progress of my experiments. I consistently received helpful encouragement from him, as I did from no one else, more especially in the prosecution of the investigation of the magnetic deflection of cathode rays, which he quite realised would yield the key of the*

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[31] p 62 Schuster 1911
[32] p 62 Schuster 1911
[33] p 62-3 Schuster 1911
[34] p 64 Schuster 1911
[35] p 526 Schuster 1890

position."[36] Helmholtz was at this time actively involved in this area of research, his contributions and those of his successors, Hertz and Lenard will be discussed later in this chapter. It is a pity that Schuster felt at the time that he received more support from someone who held an opposing view as to the nature of these cathode discharges than from his contemporaries whose views he supported.

Returning to Schuster's second Bakerian Lecture, Schuster felt that the results he presented were of a preliminary nature, requiring far more extensive work. The value of this paper lies in two areas. Firstly, Schuster summarises all the then available knowledge on the conduction of electricity in gases and secondly, he developed the theoretical basis for the determination of the ratio e/m. Schuster's argument on how to obtain the quantitative value of the relationship e/m, comes directly from his second Bakerian lecture in which he states *"According to one theory, particles are projected from the cathode. The observed effect of the magnet on them is exactly what it should be under the circumstances. The path of the particles can be traced by means of the luminosity produced by the molecular impacts. If the trajectory is originally straight, it bends under the influence of a magnet. The curvature of the rays depends on two unknown quantities, the velocity of the particles and the quantity of electricity they carry.*[37]

By equating the two forces, magnetic and centripetal, acting on the particles Schuster obtained

$$\frac{mv^2}{r} = Bve$$

where v is the velocity of the particle
m is the mass of the particle
B is the magnetic field strength.

This produces the relationship $e/m = v/Br$.

[36] p 65 Schuster 1911
[37] p 545 Schuster 1890

Now Schuster compared the energy gained by the particle as it started from rest at the cathode and moved with a velocity v to the anode. The potential drop between the cathode and the anode was V volts, hence $\frac{1}{2}mv^2 = Ve$. By combining these equations and eliminating v, Schuster obtained $e/m = \frac{2V}{B^2r^2}$, in which all the quantities could be measured.

This relationship is one of two that J.J.Thomson was to use to obtain his value of e/m in his Classical 1897 paper "Cathode Rays" which will be discussed in chapter 5. It is at this point that Schuster made a number of assumptions which in hindsight were wrong. He first assumed that the energy equation could be used to obtain only an upper limit for the value of e/m. Secondly he assumed that the velocity of the particles could be determined from the kinetic theory of gases. As is known today the particles emitted at the cathode are actually accelerated through the electric potential reaching speeds far in excess those of gas molecules at room temperature. Thirdly he assumed that the lower limit of e/m could be obtained by measuring the smallest radius of curvature which can with certainty be traced in the glow and applying this radius of curvature to the force equation. This led to a value of e/m which lay in the range $10^3 \langle e/m \langle 1.1 \times 10^6$ [38]. The units which Schuster used were in the c.g.s. system however it is not clear from Schuster's paper whether the charge e was measured in esu or e.m.u., a more detailed discussion on these units and their modern equivalents will be made in chapter 5.

In January 1897, Schuster published a paper in the "Philosophical Magazine" on "The Magnetic Force Acting on Moving Electrified Spheres" in which he discussed the calculation of the effects of magnetic forces on moving charged particles. Schuster compared the work carried out in this area by J.J.Thomson and Heaviside. Schuster states "*the question of the magnetic field produced by a moving sphere ... was first attacked by J.J.Thomson (1881). Sometime afterwards it was reopened by*

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38 p 546-7

Heaviside (1889) who whilst agreeing with J.J.Thomson in the fundamentals was unable to corroborate some of his details."[39] Schuster then compares the results obtained by Thomson in two papers, one in 1881 and the other in 1889. While the bulk of the paper has little relevance to this present discussion, a comment made by Schuster as a footnote at the end of his article is of import. The significance of this comment becoming apparent in chapter 5 where a more detailed discussion of Thomson's work will be made. Schuster stated, *"reference should have been made to a second paper by J.J.Thomson (Phil Mag 1889 vol xxviii p1) in which possible effects are taken into account, for which there is at present no experimental evidence. The above investigation shows that the difference between the results of Heaviside and J.J.Thomson's original paper are not due to the effects discussed in his second paper*." [40] Thus Schuster is calling into doubt Thomson's work in this area, firstly by questioning his experimental methods and then the manner in which Thomson reaches his conclusions. It appears that Schuster was possibly the first person to question some of Thomson's results; however he was not the last. The issue of Thomson's experimental methods and his empirical results in some of his papers will be discussed more fully in chapters 5 and 6.

One wonders whether Schuster would ever have managed to actually obtain a better estimate of e/m if he had done further work in the area. Schuster seems to have shown a great deal of insight in developing his ideas on the conduction of electricity in gases. Unfortunately there have been few references to him and his work from his contemporaries.

3.3. Later European Experiments

At the same time as Schuster in England was putting forward his suggestions on the particulate nature of cathode rays, Hertz and his student Lenard were proceeding on their experiments to show that these rays were waves in the aether. Heinrich Hertz

[39] p 1 Schuster 1897
[40] p 11 Schuster 1897

(1857-94) was the son of a lawyer and senator of Hamberg. In 1880 Hertz completed a doctorate in physics at Berlin. It was here that he came to the attention of Hermann von Helmholtz (1821-94) who made Hertz his assistant. By 1889 Hertz had established the electromagnetic nature of light which had been predicted by Maxwell. In that year Hertz was appointed Professor of Physics at the University of Bonn where he and Lenard worked on gas discharges.[41]

Helmholtz had a long and distinguished career in experimental physics. At the time that Hertz commenced work at Berlin, Helmholtz was studying the nature of electric charge. He advocated an atomistic view as to the nature of this charge probably based on his extensive work in electrochemistry. Stoney quotes Helmholtz as stating that "*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.*"[42] Helmholtz had made this statement in a lecture to the Chemical Society in London in 1881. During this lecture Helmholtz also suggested that his atomistic view was in agreement with those of Faraday on whose work Maxwell had based his theory.[43]

An interesting situation now arose, Helmholtz was advocating his atomistic view of electricity while he was encouraging both Schuster and his own assistant, Hertz in their work on gas discharges. Schuster and Hertz proposed two diametrically opposed views on the nature of cathode rays and amazingly not one of Schuster, Hertz or Helmholtz discovered or even suggested any connection between an atom of electricity and cathode rays. In hindsight, it appears that these individuals were tantalisingly close to discovering that cathode rays were actually the "atoms of electricity" which Helmholtz had hypothesised.

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[41] p 185-6 Shamos 1959
[42] p 419 Stoney 1894
[43] p 354 Whittacker 1951

In 1883, Hertz published his paper on "Experiments on the Cathode Discharge" which he was encouraged to undertake by E.Goldstein. This paper is extremely detailed, giving excellent descriptions of all his apparatus and methodology. Unfortunately, his results suggested several erroneous conclusions which include "*the cathode rays are only a phenomenon accompanying the discharge, and have nothing directly to do with the path of the current... These cathode rays are electrically indifferent, and amongst known agents the phenomenon most nearly allied to them is light.*" [44] Finally, Hertz indicated that his results come in close agreement with those of both Goldstein and Wiedemann. It was on this base that Hertz would later return to his studies of cathode ray discharges in the early 1890's.

In 1891 Hertz discovered that cathode rays could be transmitted through a thin leaf of metal. He had placed a thin leaf of metal in the path of the cathode rays, reduced the gas pressure until it was sufficiently small that the glow inside the discharge tube was reduced and found that cathode rays passed through the metallic leaf, producing a phosphorescence on the glass wall of the tube. He found that this phenomenon occurred with all metal leaves but that aluminium produced the most intense phosphorescence hence indicating that it was the most transparent to the cathode rays. Hertz also noted that the rays observed after passing through the metallic leaf were diffused in much the same manner as light is diffused when transmitted through a translucent medium. [45]

In 1894 Philipp Lenard (1862-1947), stimulated by his mentor's work, produced vacuum tubes which contained small metallic apertures of thin foil. These apertures were named Lenard Windows. After observing the rays passing through this window, Lenard discovered that these rays could then continue on into the air outside the tube. [46] Lenard reported that in a darkened room the diffuse light is seen to spread

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[44] p 254 Hertz 1896
[45] p 328-331 Hertz 1896
[46] p 81 Pais 1986

from the window where it is brightest and after about 5 cm from the window the light finally ceases.[47]

The properties of these rays resembled those of the cathode rays within the discharge tube, consequently in order to distinguish between the two types of rays, the term Lenard rays was used for those rays which had passed through a Lenard window. If the aluminium window opposite the cathode opens onto another evacuated tube, then these Lenard rays can be studied in much the same way as cathode rays. Lenard studied these rays for a number of years, finding that Lenard rays:-

1) have similar properties to cathode rays
2) affect sensitised paper and photographic plates
3) cause an electrified body to lose its charge in an effect similar to Röntgen rays
4) have a constant absorption regardless of the gas provided the respective gas density is constant
5) are sensitive to gas pressures, being able to travel large distances when the gas pressure was low and being absorbed readily when pressures were increased
6) are absorbed by solid bodies on the basis of their density and not their chemical composition.
7) are deflected by magnetic fields[48]

These are all properties which in modern experience, are associated with a beam of electrons. Nevertheless these experimental results lead Lenard finally to the conclusion that these cathode rays which travel through a solid window are waves in the aether. However, this was not the only possible conclusion. A few years later

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[47] p 184 Thomson, J.J. 1908
[48] p 185-9 Thomson, J.J. 1908

J.J.Thomson cited Lenard's results as part of his argument for the corpuscular nature of cathode rays.[49]

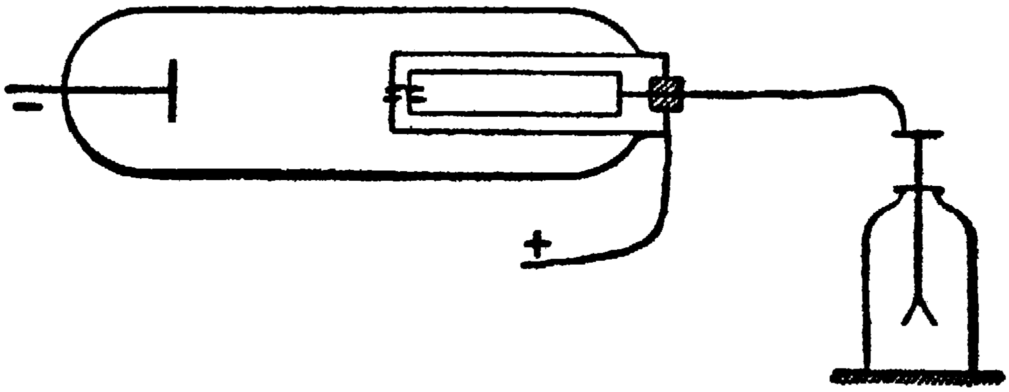

Diagram 3 C (p162 J.J.Thomson -1908)

1895 marked the year of Röntgen's discovery of what are now known as X-rays. It was also in this year that J.B.Perrin (1870-1942) performed an experiment which showed that a current of negative electricity flowed along the path of the cathode rays. (See diagram 3-C) The cathode is a disc and the anode which is earthed is a metal cylinder with a hole on the end which faces the cathode. The two holes are aligned with each other and at right angles to the cathode, so that the cathode rays can penetrate the inside of the inner cylinder. The inner cylinder was connected to a gold leaf electroscope. When the cathode rays penetrated to the inner cylinder, the gold leaves of the electroscope diverged with a negative charge. When the cathode rays were deflected by a magnetic field so that they didn't penetrate the inner cylinder, the gold leaves on the electroscope did not diverge. Perrin thus concluded that the cylinder receives a negative charge when the cathode rays enter it, and none when they do not.[50] Perrin also found that the negative charge captured from these cathode rays was quite large. Thomson later stated that *" in one of his (Perrin) experiments the charge sent into the inner cylinder for each interruption of the coil was sufficient to raise a capacity of six hundred electrostatic units to a potential of three hundred volts"*.[51]

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[49] p 194-9 Thomson, J.J. 1908
[50] p 162-3 Thomson, J.J. 1908
[51] p 163 Thomson, J.J. 1908

Thus by the end of 1895 most of the properties of cathode rays had been discovered, measured and speculated upon. The great debate as to their nature still raged with the continental physicists maintaining their *"waves in the aether"* explanation, while British physicists were firmly convinced of the particular nature of these rays. Two years later in 1897, J.J.Thomson, was to lay these controversies to rest and demonstrate conclusively that these rays were particles.

However before proceeding with the discussion of J.J.Thomson's contribution, it would be well to summarise the properties of cathode rays and the explanation of these properties according to the two then current theories.

1) The phosphorescence produced by cathode rays may be regarded as being analogous to the phosphorescence produced by ultra violet light by the aether theory. The corpuscular theory suggests that this is the result of the sudden stoppage of an electrified body. [52]
2) The thermal effects are explained by the particulate theory as the heating due to the conversion of kinetic energy of the particles into heat. The aether theory explains this as the absorption of radiant energy and its transformation into heat. [53]
3) The mechanical effects are the result of the impact of the moving particles. The aether theory describes it as the secondary effect of the thermal effects. [54]
4) Deflection of the rays in the presence of a magnetic field could be explained by the particulate theory as the path of negatively charged particles but the aether theory could not adequately explain this phenomenon. [55]
5) The ability to penetrate solid substances has its explanation in the analogy of the penetration of solids by Röntgen or X rays. The particulate theory could not at this time adequately explain this phenomenon. [56] J.J.Thomson would

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[52] p 192-3 Thomson, J.J. 1908
[53] p 191-2 Thomson, J.J. 1908
[54] p 192 Thomson, J.J. 1908
[55] p 190 Thomson, J.J. 1908
[56] p 190 Thomson, J.J. 1908

later develop an explanation in terms of the particulate theory for this ability of cathode rays to penetrate solid substances.

In 1897 J.J.Thomson wrote his famous paper "Cathode Rays" in which he proposed this particulate theory. He continued work in this area during the years 1898 and 1899. These later two papers were based on experiments carried out using equipment developed by his students and associates in the Cavendish Laboratory. Specifically, Thomson's work on determining the magnitude of the charge carried by the corpuscles utilised an experimental method and equipment developed by C.T.R.Wilson who utilised Townsend's discovery that charged particles could form nuclei around which supersaturated water vapour could condense. This empirical technique resulted in the development of devices which would later be referred to as "cloud chambers".

4. Cloud Chambers

4.1. Cloud Formation

Cloud chambers had their birth in the early meteorological studies of water vapour in the atmosphere. Terms such as cloud, fog, mist and rain had been in popular use but in the 1880s these terms began to be defined by a comparison in the size of water droplets. *"The particles comprising a fog, for instance, are so fine they scarcely fall through the air, a cloud is a little coarser in grain while a mist is coarser still in texture, and rain is any of these while falling."*[1] In 1880 John Aitken investigated the differences in atmospheric conditions which would give rise to fogs, mists and clouds. He had observed that in the Scottish Highlands water vapour did not condense to form fogs, mist or rain even if the air was supersaturated with water vapour and cooled far below the dew point. However in the industrial urban centres fogs were a frequent occurrence.

In 1883 Aitken published his paper in which he investigated the conditions required to produce a fog he found that *"Molecules of vapour do not combine with each other, and form a particle of fog or mist; but a 'free surface' must be present for them to condense upon. The vapour accordingly condenses on the dust suspended in the air, because the dust particles form 'free surfaces'. Where there is abundance of dust there is abundance of 'free surfaces', and the visible condensed vapour forms a dense cloud; but where there are no dust particles present there are no 'free surfaces' and no vapour is condensed into its visible form, but remains in a supersaturated vaporous condition till the circulation brings it into contact with the 'free surfaces of the receiver, where it is condensed."*[2] These 'free surfaces' were in fact the dust particles found in air.

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1 p 338 Aitken 1883
2 p 340 Aitken 1883

When Aitken filtered the water saturated air through cotton wool thus removing most of the dust, he found that *"when there is dust in the air the vapour condenses out in a visible form, but when no dust is present it remains in a supersaturated vaporous state"*.[3] Further he found *"that if there is an enormous number of these dust particles in the air, so that they are very close to each other, then each particle will only get a very small amount of water vapour condensing on it. It will therefore become a little heavier, and will float easily in the air. To this light and dense form of condensation we give the name of fog."*[4]

Further if the number of dust particles on which water can condense becomes smaller and hence each condenses a greater amount of vapour, the drops thus become bigger and not nearly as close together, resulting in a mist.[5] Consequently Aitken was able to conclude that *"when water vapour condenses in the atmosphere, it always does so on some solid nucleus"* and that *"the dust particles in the air form the nuclei on which it condenses"*.[6]

The next stage in the development of cloud chambers came from the observation of chemical reactions. During the 18th Century both Laplace and Lavoisier had observed that the hydrogen gas produced from the dissolution of a metal in an acid carries with it an electric charge.[7] This phenomenon was little studied until the latter part of the 19th Century and had little overall impact. In 1887 J. Enright, from St Mary's College Hammersmith, enthused by Helmholtz's Faraday Lecture on the atom of electricity (see chapter 1) conducted a series of experiments to determine the "*equality or inequality of the atomic charges"*[8]

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[3] p 341 Aitken 1883
[4] p 352 Aitken 1883
[5] p 80 Lodge 1906
[6] p 342 Aitken 1883
[7] p 244 Townsend 1897
[8] p 365 Nature 1887

Enright's result did indicate that the hydrogen he produced in this manner did carry a charge, but the sign of the charge varied according to the metal or metal salt used. Enright believed that this charge on the hydrogen was due to the reaction itself while Oliver Lodge disagreed, suggesting that the charge was produced when "*the escaping spray was electrified by friction.*"[9] Enright finally published his paper in 1890 in which he set out to "*ascertain whether or not the hydrogen carried a charge, and if so, to determine its sign.*"[10] As well as producing hydrogen by the dissolution of metals in acid, he also used other methods of producing hydrogen, consequently he was able to suggest that the sign carried by "*hydrogen is positive to acids but negative to salts.*"[11] Finally he concluded that *"I had proved beyond a doubt that hydrogen holds a charge with amazing tenacity, and that it only gives it up when each molecule individually come into contact with a conducting body"*.[12] Unfortunately, despite his own views on the matter, Enright's results were inconclusive.

4.2. Townsend

Seven years later in 1897 John Townsend (1868-1957) working in the Cavendish Laboratory, published his paper *"On Electricity in Gases and the formation of clouds in Charged Gases"*, in which he investigated the *"properties of gases having an electrostatic charge"* and *"an account of the electrification of gases which are given off when a liquid is decomposed by an electric current"*.[13]

Stokes (1819-1903), the Irish mathematical physicist had in 1850 given a formula for the force on a sphere of radius a, moving with velocity v through a medium with viscosity μ : $F = 6\pi\mu av$. When this is applied to the terminal velocity of a sphere falling under gravity, $F = \frac{4}{3}\pi a^3\rho$ and the terminal velocity becomes $v = \frac{2}{9} \times \frac{ga^2\rho}{\mu}$.

This formula became the basis for a whole series of famous experiments to determine the charges on liquid drops. It was used by J.J.Thomson and by

9 p 412 Nature 1887
10 p 59 Enright 1890
11 p 67 Enright 1890
12 p 76 Enright 1890
13 p 224-5 Townsend 1897

R.A.Millikan, but it is Townsend who must be given the credit for first suggesting its use.

Townsend at this time was a young research student working at the Cavendish where he had been admitted in 1895. He had been born in Galway, Ireland into an Anglo-Irish family. He was educated at Trinity College Dublin taking his degree in Mathematics and Physics in 1890. He then lectured in Mathematics until 1895. In 1900 Townsend became the first occupant of the Wyckham Chair of Physics at Oxford, a position he held until his retirement in 1941. He died in Oxford in 1957.

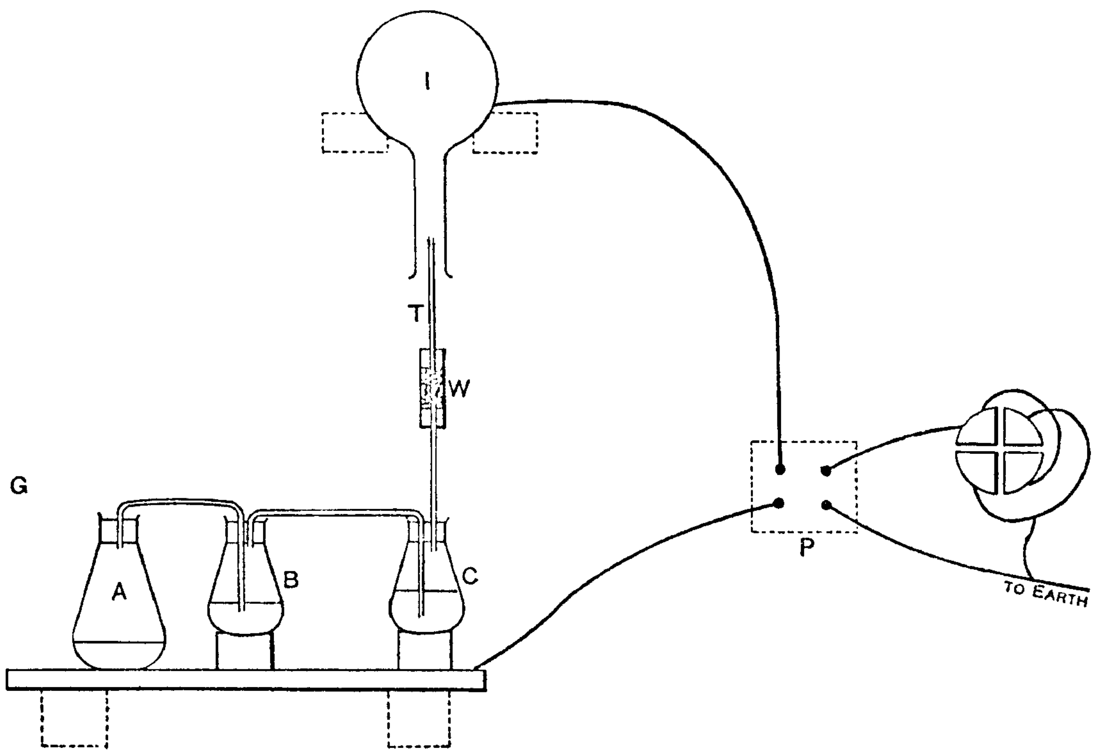

Diagram 4 A. (p246 Townsend -1897)

Returning to the 1897 paper, Townsend obtained charged gases by two methods. In the first (see diagram 4-A) he produced hydrogen gas by dissolving iron wire in sulphuric acid in flask A. The hydrogen was then bubbled through permanganate of potash in flask B, then through sulphuric acid in flask C, before finally drying it in glass wool W. The hydrogen was then collected in an insulated vessel I. An electrometer was used to determine the electric charge of the gas. This was in effect a duplication of Enright's work which Townsend duly acknowledges. [14]

The second method Townsend employed was that of electrolysis. Until Townsend had performed his experiment, it had been assumed that the gases which were produced by electrolysis were not electrically charged. Townsend found that when he passed an electric current through a dilute solution of sulphuric acid, both the oxygen and hydrogen gases produced had a positive charge. This phenomenon occurred even at relatively low currents. When he bubbled these charged gases through water he found that a cloud was formed which *"can be completely removed by bubbling the gas through sulphuric acid, but when they get into the atmosphere of the room they condense the moisture and form a stable cloud in an unsaturated atmosphere"*. [15] The behaviour of these gases was similar to that of the hydrogen produced by the dissolution of a metal in acid. On further investigation Townsend found that *"the gas retains its charge for a considerable time"* and that *"these gases form a dense cloud when they come into contact with moisture. The density of the cloud increases with the density of the charge."* [16]

In determining the charge carried by each gas particle or ion, Townsend took the following five steps:-

1) He assumed that in saturated water vapour each charged ion acted as the nucleus for a water droplet and hence the number of ions was the same as the number of droplets.
2) He determined the total electrical charge per cubic centimetre carried by the gas.
3) He found the total weight of the cloud by passing it through drying tubes and determining the increase of weight of these tubes.

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[14] p 246-7 Townsend 1897
[15] p 248-9 Townsend 1897
[16] p 245 Townsend 1897

4) He found the average weight of the water droplets constituting the cloud by observing their rate of fall under gravity and computing their mean radius. This was possibly the first use of Stokes's formula.
5) He determined the number of droplets by dividing the weight of the cloud by the average weight of the droplets, hence knowing the number of droplets he was able to calculate the number of ions and hence the charge on each ion. [17]

By the preceding method Townsend found that *"for positive oxygen the charge on each carrier is* 2.8×10^{-10} *esu and for negative* 3.1×10^{-10}*."*[18] From later experiments he conclude that *"the two charges might be considered equal and approximately* 3×10^{-10} *electrostatic units"*. [19] It should be noted that the gases were actually molecular in form but carrying a charge, hydrogen was H_2^+ and oxygen was O_2^+ or O_2^- .

4.3. C.T.R.Wilson

In April of that same year another young research student from the Cavendish, C.T.R.Wilson (1869-1959) published his investigations into the condensation of water vapour in dust free gases and air. Wilson was born in Scotland, the youngest of eight children but at the age of four his father died and the family moved to Manchester. He was educated at Greenheyes Collegiate School and at fifteen entered Owens College, Manchester, the same College that J.J.Thomson had attended. At eighteen after being awarded a B.Sc. Wilson won a Scholarship to Sidney Sussex College, Cambridge and in 1896 he was awarded the Clerk Maxwell studentship. In 1927, after receiving his Nobel Prize for the development of the cloud chamber, Wilson stated "*in September 1894 I spent a few weeks in the Observatory on the summit of Ben Nevis. The wonderful optical phenomena shown when the sun shone on the clouds surrounding the hill top and especially the coloured rings surrounding the sun or surrounding the shadow cast by the hilltop or observer on*

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[17] p 45-6 Millikan 1917 and p 252-7 Townsend 1897
[18] p 257 Townsend 1897
[19] p 47 Townsend 1897

mist or cloud, greatly excited my interest and made me wish to imitate them in the laboratory."[20]

Wilson commenced his work on the condensation of water in dust free air in 1895, publishing his rather lengthy paper "Condensation of Water Vapour in the Presence of Dust-free Air and Other Gases", in 1897. Wilson initially discusses the work of his predecessors, in particular he states Aitken's result that when a *"sudden expansion of saturated air was produced by means of air pump, a very quick stroke of the pump was found to produce a shower of drops even in filtered air, while a slow steady one had no such effect"*.[21]

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20 Dictionary of Scientific Biography
21 p 265-6 Wilson, C.T.R. 1897

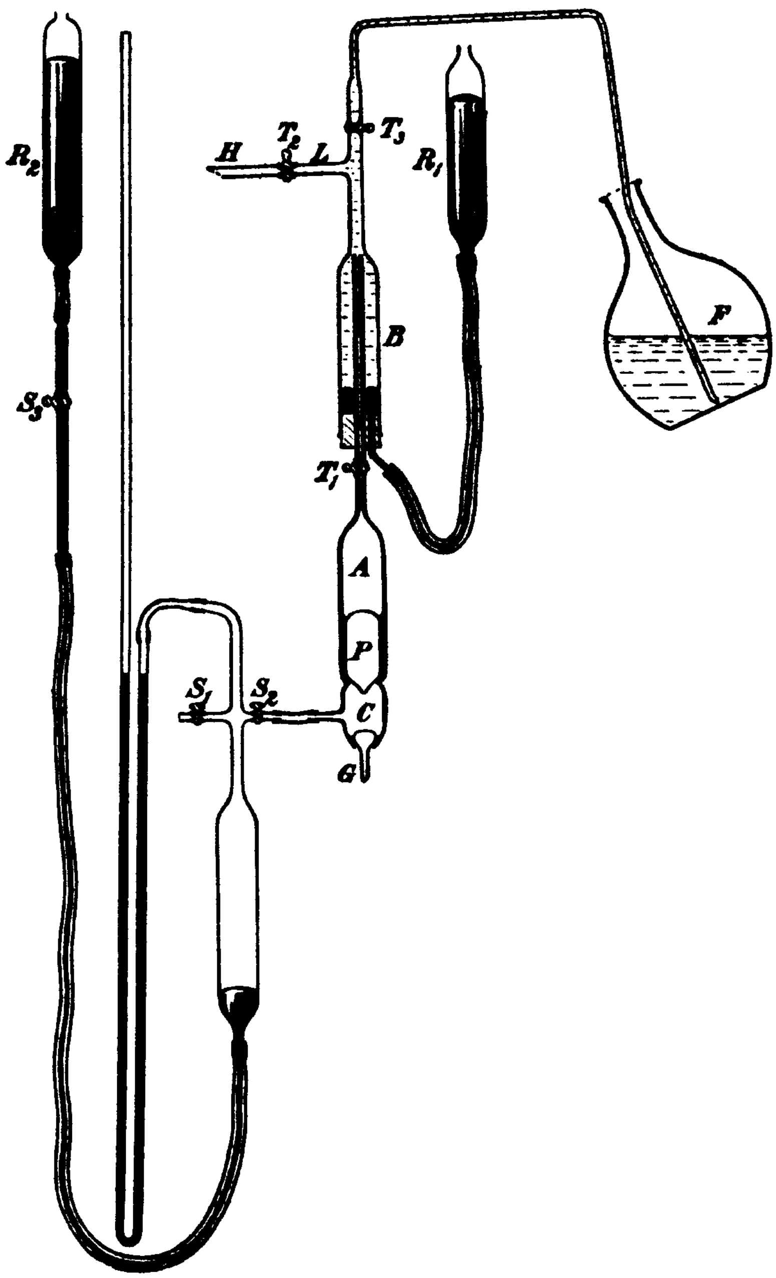

Diagram 4 B (p276 C.T.R.Wilson-1897)

To achieve this sudden expansion Wilson developed an apparatus (see diagram 4-B) in which two test tubes, one inside the other, act as a piston (A and P). Air was pumped into space C, below the piston, using the mercury pump on the left. The increased air pressure pushes the piston P up thus compressing the gas in A to any desired volume. Then by removing or opening plug G, the air pressure in C is suddenly reduced dragging the piston down, thus producing a sudden expansion in A. The apparatus above space A was to provide pure water under sufficient pressure to drive the water into A covering it with a thin film of water to lubricate the piston. This had the advantage of being able both to achieve the sudden expansion required as well as measure it. A reasonable accuracy in determining the expansion achieved was required so as to calculate *"the lowest temperature and maximum supersaturation reached with as small an error as possible"*. [22] Thus, the greater the sudden expansion the lower the gas temperature and hence the greater the supersaturation of the gas. The dust free air which Wilson required for his work was produced by expanding *"repeatedly the same sample of moist air"*. [23] As a result of this process Wilson found that *"the first expansion always produced a fog. This was allowed to settle completely before allowing the air to contract to its original volume. In this way a considerable proportion of the dust was removed, the particles being carried down by drops which condensed upon them into the water below. When this process was repeated several times the resulting fog became by degrees coarser grained. The fog passed at length into a fine rain. One more expansion was generally sufficient to remove the remainder of the dust particles and any further expansion was without visible effect."* [24]

Wilson observed that once all the dust was removed from the saturated air, if the vessel experienced a sudden expansion, no visible effect is produced until the ratio between the final and initial volumes, $^{v_2}\!/_{v_1} = 1.25$. When this ratio is exceeded, Wilson observed a rain-like condensation and the number of drops in the shower did not appear to depend on the size of the expansion nor on the number of previous expansions. Wilson did not try to explain this phenomenon, but merely used it. [25]Wilson had thus shown that *"the cloud does not form until the temperature has been lowered to such a point that the supersaturation is about eightfold. When, however, this temperature is reached, a thick fog forms even in dust free air"*. [26] He also attempted to get an estimate of the size of the droplets, however this was difficult and the results were inconclusive. [27]

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[22] p 267 Wilson, C.T.R. 1897
[23] p 267 Wilson, C.T.R. 1897
[24] p 271 Wilson, C.T.R. 1897
[25] p 272 Wilson, C.T.R. 1897
[26] p 12 Thomson, J.J. 1907
[27] p 84 Lodge 1906

Wilson then investigated whether Röntgen Rays had any effect on the condensation. He placed a source of X-rays 10 cm from the vessel in which the sudden expansion occurred. He found that *"if expansion was made when the bulb was in action, or within a second or two after switching off the current from the induction coil, the number of drops produced was greatly increased"*, if the expansion was enough to produce a *"rain like condensation in the absence of the rays. Instead of a shower settling in one or two seconds, a fog lasting for more than a minute was produced."*[28] Wilson reasoned that if the gas is ionised it will contain charged particles each of which would become the nucleus around which a drop of water forms. When the particles are negatively charged, condensation occurs at a lower supersaturation than for positively charged particles. Thus a smaller expansion is required to make a cloud form about the negative particles than about the positive particles. Further, if the expansion increased the volume of the gas in a ratio between 1.25 and 1.3 both positive and negative ions act as nuclei.[29]

C.T.R.Wilson's original cloud chamber consisted of an expansion mechanism which was used to cool the saturated air sufficiently to produce trails of condensation, a chamber in which the saturated air condensed on the ionising particles and a source of illumination so that the interior of the chamber could be made visible.

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[28] p 301-2 Wilson, C.T.R. 1897
[29] p 46 Millikan 1917 and p 342 Thomson, J.J. 1936

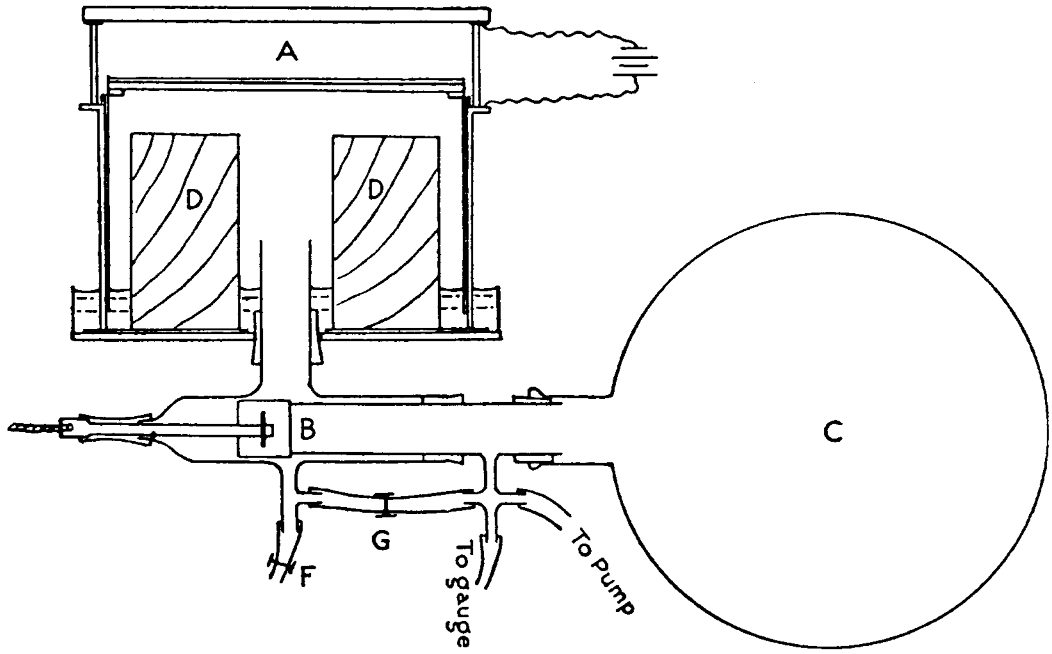

Diagram 4 C - The Wilson Cloud Chamber. (p278 C.T.R.Wilson-1912)

Wilson describes his equipment (diagram 4-C) as consisting of a cylindrical chamber of 16.5cm diameter and 3.4cm high. The roof, walls and floor were made from glass and coated inside with gelatine. The gelatine on the roof and sides was 1mm thick and was made from a solution of 4% gelatine and .1% boracic acid. The gelatine on the floor was blackened with india ink and consisted of a solution containing 15% gelatine, 2% boracic acid and 3% india ink. The gelatine on the floor provided both a dark background against which the illuminated condensation trails could be seen as well as acting as a cement between the cloud chamber and the expansion cylinder. Finally this thin gelatine layer acted as the sealant for the chamber.

The glass floor of the chamber was fixed on top of a thin walled brass cylinder which acted as a plunger. This cylinder was 10cm high, open below and was able to slide freely within an outer brass cylinder, the expansion cylinder, which was the same height as the first cylinder and about 16cm in internal diameter. The expansion cylinder supports the walls of the cloud chamber and rests on a thin sheet of india rubber lying on a thick brass disk which forms the bottom of a shallow receptacle containing water to a depth of about 2cm. The water is used to separate the air in the cloud chamber from that below the plunger.[30]

When valve B is opened, the plunger is opened into the vacuum chamber C. Thus the floor of the cloud chamber drops suddenly until it is stopped by the india rubber-covered base plate. The plunger remains firmly fixed by the air pressure in the chamber. The wooden cylinder D in the air space below the plunger reduced the volume of air passing through the connecting tubes at each expansion.[31]

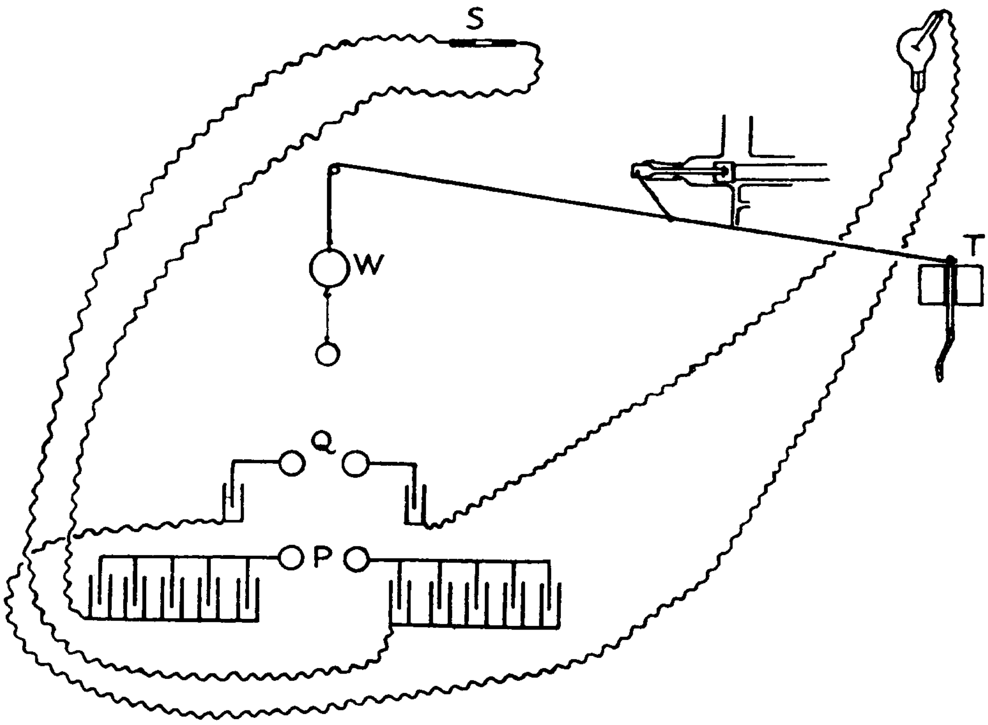

Diagram 4 D (p281 C.T.R.Wilson -1912)

The valve B is opened by the fall of weight W which is released by a trigger arrangement T (see diagram 4-D). This weight also operates the lighting mechanism. When the valve is closed and pinch-cock F open, the plunger rises thus reducing the volume of the air in the cloud chamber. Thus the two pinch-cocks can be adjusted to give any desired initial volume v_1. The final volume v_2 was always the same and set at 750cc. Thus the expansion ratio v_2/v_1 depends only on the initial volumes which were readily measured from the dimensions of the cloud chamber.[32]

30 p 277 Wilson, C.T.R. 1912
31 p 278 Wilson, C.T.R. 1912
32 p 278 Wilson, C.T.R. 1912

In setting up the apparatus, Wilson placed the plunger on the rubber covered base plate and slipped the expansion cylinder over it. A hole in the side of the cloud chamber was opened at this stage allowing the imprisoned air to escape. The plunger was driven up to the desired height by blowing air through F. The aperture in the wall of the chamber was then closed and the mass of the imprisoned air remains constant.[33]

Between the roof and the cylindrical walls of the chamber a ring of tin foil was cemented into the gelatine layer. This foil was connected with one terminal of a battery of cells, the other terminal of this battery was connected to the blackened floor of the chamber through the brass expansion cylinder and plunger. Thus a constant electric field of any desired intensity was maintained in the chamber.[34]

The chamber was illuminated by discharging a Leyden Jar through mercury vapour at atmospheric pressure. A horizontal silica tube of 15cm in length was filled with mercury and enclosed by a close-fitting silver tube with a 1mm slot extending down its length. When the silver tube is heated by a small flame the enclosed portion of the silica tube may be kept at a nearly uniform temperature which is high enough to vaporise the mercury. Platinum wires were fused through the ends of the glass tube and acted as the external connection with the Leyden Jars.[35]

To fire a spark the outer coatings of two sets of 4 or 5 *"gallon"* Leyden Jars were connected to the terminals of the mercury vapour tube. The inner coatings were connected to the terminals of a Wimshurst machine and two brass balls separated by a space of about 5cm (see diagram 4-D). This forms a primary spark gap. The jars are charged to almost sparking potential. A spark results when a metal ball falls between the primary spark gap. This ball is attached by a fine thread to weight W

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[33] p 278 Wilson, C.T.R. 1912
[34] p 279 Wilson, C.T.R. 1912
[35] p 279 Wilson, C.T.R. 1912

which is connected to the trigger T by a string. A second string is attached to this string, connecting it with the valve in the cloud chamber and hence operating the expansion apparatus.[36]

When the trigger is pulled the cord is released and the weight falls until the second string is stretched tight. This opens the valve causing an expansion in the chamber. The fine string now breaks releasing the metal ball to fall through the primary spark gap producing an illuminating spark in the mercury vapour tube. The upper spark gap Q was used only in experiments using X-rays.[37]This apparatus required great precision in producing an illumination of the cloud chamber at the exact instant that condensation tracks became visible. This achievement and subsequent studies earned C.T.R.Wilson a Nobel Prize.

Using this method Wilson was able to observe and photograph the condensation trails left by $\alpha-$rays, $\beta-$rays, $\gamma-$rays and X-rays. The $\alpha-$rays which Wilson observed were described as *"remarkably sharply defined lines, about 1/10mm wide"*.[38] Wilson describes the $\beta-$rays as being *"absolutely straight thread-like lines of cloud"*.[39] Wilson later observed that *"these* $\beta-$ray *endings are indistinguishable from the Cathode rays produced in air by Röntgen Rays"*.[40]

$\gamma-$rays were described as producing *"a cloud entirely localised in streaks and patches and consisting mainly of fine, perfectly straight threads, traversing the vessel in all directions"*.[41] X-rays also produced a region *"filled with minute streaks and patches of cloud"*. Another photograph showed *"cloudlets to be mainly small thread-like objects not more than a few millimeters in length. Few of them are straight, some of them showing complete loops. Many of them show a peculiar*

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36 p 280 Wilson, C.T.R. 1912
37 p 281 Wilson, C.T.R. 1912
38 p 286 Wilson, C.T.R. 1911
39 p 287 Wilson, C.T.R. 1911
40 p 286 Wilson, C.T.R. 1912
41 p 287 Wilson, C.T.R. 1911

beaded structure ... there are also minute patches of cloud which may be merely foreshortened threads."[42]

Wilson was finally able to conclude that *"when ionisation by X-rays occurs corpuscles are liberated, each with energy sufficient to enable it to produce a large number of lines along its course"*.[43]

Wilson's development of the cloud chamber deservedly earned him the Nobel Prize. For the first three decades of this Century, the cloud chamber was one of the major experimental tools in particle physics. For the first time researchers could see the effects of ionising particles and rays and even witness interactions between particles. This method was also ideal for photography enabling researchers to keep permanent records of their discoveries. Modern bubble chambers were based on this same principle, except in these devices, one observes bubbles of gas which are released from a superheated liquid. When an ionising particle or ray enters the bubble chamber, the charged particle acts as a nucleus for bubble formation. Finally the thick photographic emulsions were also developed, in which an ionising particle would travel through the emulsion and the trail of this particle would "expose" the emulsion producing a record of its journey. The Wilson cloud chamber, while no longer used as a research tool, is used as an educational aid. Secondary physics students can now observe the tracks of α-rays in the class room on a simplified version of this device.

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[42] p 287 Wilson, C.T.R. 1911
[43] p 288 Wilson, C.T.R. 1911

5. J.J.Thomson and the Electron

J.J.Thomson (1856-1940) was born in Manchester where he was educated. At the age of 14 he was sent to Owens College in Manchester to study engineering which he completed but since his father died, the family was unable to provide him with an apprenticeship to complete and continue his engineering career.[1] He won a number of small scholarships which enabled him to continue with his studies in mathematics and physics. In 1876, on his second attempt he was admitted to Trinity College Cambridge on a studentship.[2]

Immediately after taking his degree in 1880, Thomson began work in the Cavendish Laboratory where four years later he would succeed Lord Rayleigh. Thomson commenced his work "*by attempting to detect the existence of some effects which I thought would follow from Maxwell's Theory that changes in electric forces in a dielectric produced magnetic forces."*[3] He does not specify which effects he was hoping to observe but he was one of a number of Physicists who were attempting to show empirical evidence to support Maxwell's Theory. Thomson was probably introduced to Maxwell's work by Arthur Schuster who gave a course of lectures on "Maxwell's Treatise on Electricity and Magnetism" at Owens College at the time Thomson was a student there. In 1881, Thomson was unsuccessful in his application for the Chair of Applied Mathematics at Owens College. The successful candidate was his former teacher and colleague, Arthur Schuster.[4]

5.1. The Deflection Experiment and the Determination of e/m

In October 1897 Thomson published his now classical paper "*Cathode Rays"* which had earlier that year been communicated twice, first at the Cambridge Philosophical Society and later in a Friday Evening Discourse at the Royal Institution. He states

[1] p 30 Thomson, J.J. 1936
[2] p 30-1 Thomson, J.J. 1936
[3] p 97 Thomson, J.J. 1936
[4] p 22, 97 Thomson, J.J. 1936

that "*the following experiments were made to test some of the consequences of the electrified particle theory.*"[5] Thomson started by repeating Perrin's experiment (previously discussed in chapter 3) in a slightly different form in an attempt to show that the cathode rays were actually electrified particles. His equipment consisted of two coaxial cylinders with slits in them and were placed in a bulb connected to a discharge tube (see diagram 5-A). "*The cathode rays from the cathode A pass into the bulb through a slit in a metal plug fitted into the neck of the tube; this plug is connected with the anode and is put to earth. The cathode rays thus do not fall upon the cylinders unless they are deflected by a magnet. The outer cylinder is connected with the earth, the inner with the electrometer. When the cathode rays (whose path was traced by the phosphorescence on the glass) did not fall on the slit, the electrical charge sent to the electrometer when the induction-coil producing the rays was set in action was small and irregular; when, however, the rays were bent by a magnet so as to fall on the slit there was a large charge of negative electricity sent to the electrometer.*"[6] Thomson concludes *"this experiment shows that however we twist and deflect the cathode rays by magnetic forces, the negative electrification is indissolubly connected with the cathode rays"*.[7]

[5] p 293-4 Thomson, J.J. 1897
[6] p 294-5 Thomson, J.J. 1897
[7] p 295 Thomson, J.J. 1897

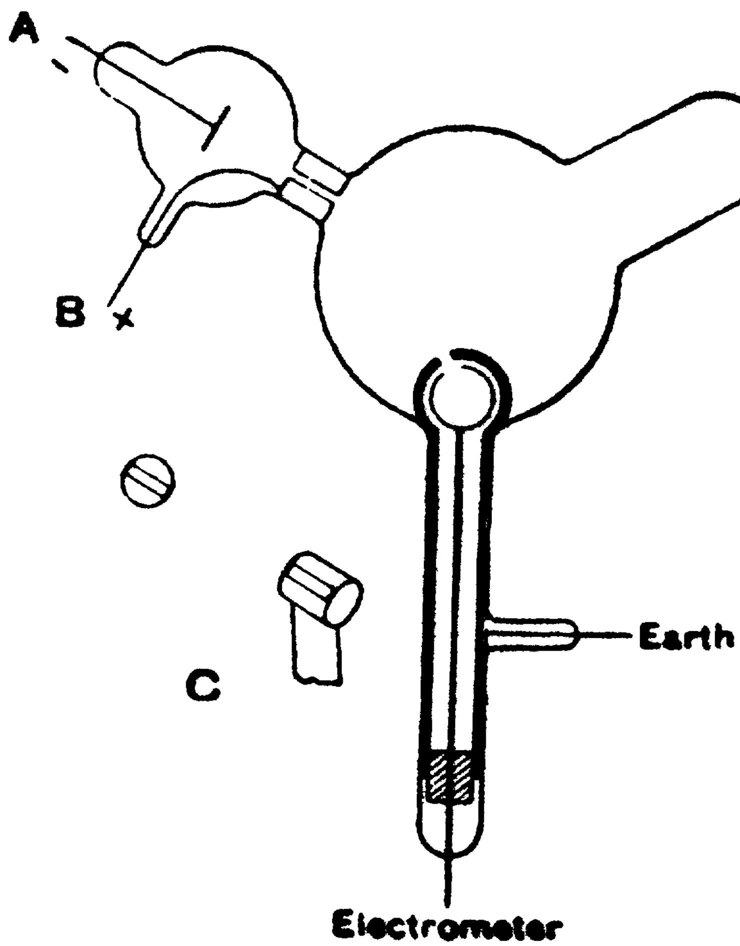

Diagram 5 A (p295 J.J.Thomson-1897)

Next Thomson set out to discover whether the cathode rays could be deflected by a small electrostatic force. Thomson repeated Hertz' experiments in which the rays travel between two parallel plates of metal placed inside a discharge tube.[8] *"The rays from cathode C pass through a slit in the anode A, which is a metal plug fitting tightly into the tube and connected with the earth; after passing through a second slit in another earth-connected metal plug B, they travel between two parallel aluminium plates about 5 cm. long by 2 broad and at a distance of 1.5 cm apart; they then fall on the end of the tube and produce a narrow well-defined phosphorescent patch. A scale pasted on the outside of the tube serves to measure the deflection of this patch."*[9] (see diagram 5-B)

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8 p 296 Thomson, J.J. 1897
9 p 296 Thomson, J.J. 1897

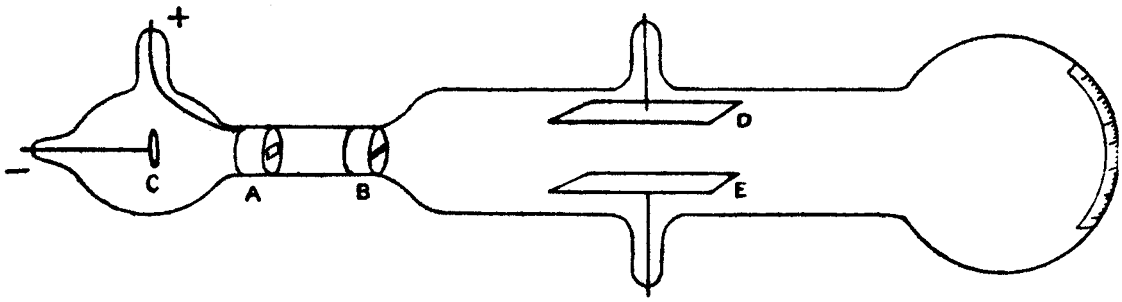

Diagram 5 B (p296 J.J.Thomson-1897)

After these two sets of experiments, Thomson believed that the deflections of the cathode rays were both proportional to the magnitude of the electric field and to the magnetic field that produced these deflections. Since he had tested the effects of the electric and magnetic fields independently, Thomson was now convinced that these rays were indeed particles. "*I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter."*[10] Thomson then speculated as to the nature of these particles concluding that a determination of the mass to charge ratio would give some indication as to whether these particles were atomic or molecular or even something smaller.[11]

Thomson used two independent methods to obtain his values of m/e. In the first method he used the deflection of a magnetic field, in the second he used the deflection of both an electric field and a magnetic field. He assumed that each particle had a mass m and charge e. At this time the units used for mass was grams and for charge, the esu, the electrostatic unit (esu) for charge was called the statcoulomb and when compared to the modern S.I. Units
$1 \text{ coulomb} = 2.997925 \times 10^9$ statcoulombs or e.s.u.. Another unit frequently quoted in the literature of the time was the e.m.u., the electromagnetic unit. The unit of charge in this system was the abcoulomb and when compared to modern S.I. Units
$1 \text{ coulomb} = 1 \times 10^{-1}$ abcoulombs or e.m.u.. He assumed that at a given time the total charge Q carried by these particles could be determined from $Q = Ne$ where N is the

10 p 302 Thomson, J.J. 1897
11 p 302 Thomson, J.J. 1897

total number of particles carried by the beam in this time. Thomson believed he could measure Q by using an electrometer. [12]

Thomson now reasoned that when these cathode rays strike against a solid object, the temperature of this object increases. He assumed that all the kinetic energy lost in this collision with an object was converted to heat and hence by measuring the temperature increase of the object and knowing the thermal properties of this object, the kinetic energy of these particles could then be directly equated to the increase in energy due to the increase in temperature of the body. Thus $W = \frac{1}{2}mv^2$ where W could be directly measured from the change in temperature. [13]

Finally, Thomson considered the forces acting on the individual particles equating the centripetal force on the particle to the force produced by the applied magnetic field. Stated in modern notation as $mv^2/r = evB$ where B is the magnetic field strength and r is the radius of curvature. [14]

The magnetic field strength was held constant for all his trials, resulting in a constant radius of curvature. By the use of simple algebra Thomson concluded that for a single charged particle in the beam of cathode rays, $m/e = \frac{QB^2}{2Wr^2}$ where all the variables could now be measured. [15]

Thomson also attempted to obtain a value for this ratio using the deflection produced by an electric field. He assumed that if the cathode rays passed through a region of space in which a perpendicular electric field was acting over a length l, then the angle through which these rays were deflected from their original path was $\Theta = \frac{Ee}{m}\frac{l}{v^2}$ where E is the electric field strength Θ is the angle of deflection. [16]

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[12] p 302 Thomson, J.J. 1897
[13] p 302 Thomson, J.J. 1897
[14] p 302 Thomson, J.J. 1897
[15] p 303 Thomson, J.J. 1897
[16] p 308 Thomson, J.J. 1897

Thomson now assumed that if a perpendicular magnetic field acted in this same region of space, the angle through which these rays were deflected from their original path was $\Phi = \frac{Be}{m}\frac{l}{v}$. He now adjusted the magnetic field so that the deflection due to the magnetic field was exactly equal and opposite to the deflection due to the electric field, thus $\Theta = \Phi$ obtaining $v = {}^{E}\!/\!_{B}$ and ${}^{m}\!/\!_{e} = \frac{B^2 l}{E\Theta}$.[17]

From both these methods Thomson obtained values that were independent of the residual gas in the vacuum tube. His results for different gases and different magnetic and electric field strengths were presented in table form. Thomson made no attempt to determine the mean velocity of the rays, stating only that "*the velocity of the cathode rays is variable, depending upon the potential difference between the cathode and anode, which is a function of the pressure of the gas- the velocity increases as the exhaustion improves; the measurements show that at all the pressures at which the experiments were made the velocity exceeded* 10^9 *cm/sec"*.[18] His actual tabled values for velocity lay in the range $2.2 \times 10^9 \mathrm{cm/sec}$ and $3.6 \times 10^9 \mathrm{cm/sec}$. This table also contained determinations of m/e, the values of which lay in the range 1.1×10^{-7} and $1.5 \times 10^{-7} \mathrm{g/e.s.u.}$ (i.e. in S.I. Units this range becomes 3.7×10^{-12} and $5 \times 10^{-12} \mathrm{kg/C}$). The modern accepted value is $5.686 \times 10^{-12} \mathrm{kg/C}$. Again, Thomson made no attempt to determine the mean value for m/e stating only "*from these determinations we see that the value of m/e is independent of the nature of the gas, and that its value* 10^{-7} *is very small compared with the value* 10^{-4}*,which is the smallest value of this quantity previously known, and which is the value for the hydrogen ion in electrolysis."*[19]

Thomson excuses these vague values for both the velocity of the cathode rays and their m/e ratio by stating *"no allowance has been made for the magnetic force due to*

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[17] p 308 Thomson, J.J. 1897
[18] p 315 Thomson, J.J. 1897
[19] p 310 Thomson, J.J. 1897

the coil in the region outside the plates".[20] The coil, one on each side of the discharge tube, was used to provide the magnetic field and was considerably larger than the area occupied by the electrodes placed in the tube. According to Thomson this extraneous field acted on the cathode rays for a longer path length and in the opposite direction, deflecting the rays less and consequently the effective value of the magnetic field was considerably smaller than that used in the equations.[21] However, Thomson makes no attempt to quantify this effect, being merely content to quote an order of magnitude value as seen above.

Thomson published his results in his now classical paper *"Cathode Rays"* in October 1897, having first presented some preliminary results at a lecture at the Royal Institution on 30th April 1897.[22] By this stage Thomson was the Cavendish Professor at Cambridge and a Fellow of the Royal Society. Consequently when Thomson concluded that cathode rays were in fact particles of a subatomic nature, his contemporaries were probably more receptive to his arguments and finally more willing to accept them. Thomson later wrote of these events *"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 lecture that he thought I had been `pulling their legs'. I was not surprised at this, as I myself came to this explanation of my experiments with great reluctance, and it was only after I was convinced that the experiment left no escape from it that I published my belief in the existence of bodies smaller than atoms. "*[23]

In January 1897 E. Weichert (1861-1928) in East Prussia presented the results of his work on cathode rays in which he concluded *"that we are not dealing with the atoms known from chemistry because the mass of the moving particles turned out to be 2000-4000 times smaller than the mass of hydrogen atoms".*[24] Weichert is clearly

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20 p 309-10 Thomson, J.J. 1897
21 p 310 Thomson, J.J. 1897
22 p 85 Pais 1986
23 p 341 Thomson, J.J. 1936
24 p 82 Pais 1986

stating that contrary to the then held view of his German contemporaries these *"rays"* were actually particles. Further these conclusions were made public five months before J.J.Thomson's paper actually appeared, however it is most probable that J.J.Thomson reached his conclusions independently without any knowledge of Weichert's lecture.

At this meeting, Weichert demonstrated his experimental apparatus which bore some resemblance to Thomson's equipment. Weichert placed a vacuum tube in a magnetic field, with strength B, which was applied perpendicular to the direction of cathode ray propagation. When the field was applied, the rays described a circular path such that $\frac{mv^2}{r} = Bev$. Thus $m/e = \frac{Br}{v}$, Weichert believed that this term provided an upper estimate for this ratio. When Weichert considered the energies of these particles/rays he found that $eV = \frac{1}{2}mv^2$ where V is the potential difference between the electrodes. This value then produced the relationship $m/e = \frac{2V}{v^2}$ which provides the lower estimate of the ratio. Consequently, Weichert believed that the ratio of e/m lay in the range $\frac{v}{Br}$ and $\frac{2V}{B^2r^2}$ and the values of V, B and r could be measured from the experiment. Weichert used an estimate for the velocity of these particles/rays of one tenth the velocity of light which he obtained by comparing the transit times of the rays with the period of a Hertzian oscillator.[25] These relationships had been used in 1890 by Schuster in England (see chapter 3). Weichert's estimates of e/m were far more accurate than Schuster had obtained because Weichert had used a much higher estimate for the cathode ray velocity.

Weichert's conclusions were dependent on his assumption that the charge carried by these particles was the same as the unit of charge obtained in electrolysis or as Weichert states *"the charge is assumed to be one electron"*.[26] Thus the first subatomic particles to be identified were also named not *"corpuscles"* as

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[25] p 82-3 Pais 1986
[26] p 82 Pais 1986

J.J.Thomson their official discoverer had referred to them, but *"electrons"*, a name first coined by G.J.Stoney some twenty years earlier.

Walter Kaufmann (1871-1947) experimented with vacuum tubes to determine whether the motion of cathode rays in the presence of electric and magnetic fields is dependent on either the pressure of the residual gas or the nature of the gas itself. Kaufmann used the energy equations employed by Weichert and Schuster, but now he also used another relationship to determine the deviation of the rays in the presence of a perpendicular magnetic field, thus equating the forces he obtained $m\frac{d^2z}{dt^2} = Bev$ where v is the velocity of the particles/rays travelling in the x-direction with an applied perpendicular magnetic field B directed along the y-direction producing a deviation in the path of the rays perpendicular to this plane. This deviation was obtained by $z = Bx_0^2\sqrt{\frac{e}{2mV}}$ where x_0 is the path length of the cathode rays in the x-direction.[27]

This relationship indicated that the deviation of the cathode rays due to the magnetic field was determined by the strength of the magnetic field and the potential across the two electrodes in the vacuum tube. Further the ratio e/m appeared to be constant and independent of the residual gas in the tube. Kaufmann now reasoned that if the e/m ratio was constant, it could not be assumed that the deflected beam was composed of molecular ions but something much smaller. Finally in April 1897 Kaufmann published his results on the determination of e/m for cathode rays. Further he found that the value of e/m was about 10^7 emu/g while that of the hydrogen ion was 10^4 emu/g. However Kaufmann did not speculate on the nature of cathode rays or the implication of his results.[28]

Thus within the space of twelve months Thomson, Weichert and Kaufmann, independently obtained results that indicated that cathode rays were subatomic

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27 p 83 Pais 1986
28 p 84 Pais 1986

particles carrying a negative charge. Of these only Thomson produced experimental results which were thorough and could be reproduced. Further Thomson had the courage to suggest that contrary to popular opinion, these rays were particles, using his results as the basis of this conclusion.

5.2. Thomson's Determination of e

By the end of 1897, Thomson was in a position to determine the charge carried by these corpuscles of cathode rays. The experimental techniques and apparatus required by Thomson had that year been developed in the Cavendish Laboratory by his research students. As previously discussed in chapter 4, Townsend had discovered that charged particles could act as nuclei around which water could condense. Townsend had also used Stokes' s formula to estimate the size of these water drops and consequently to determine the charge carried by these drops. C.T.R.Wilson had developed a method by which a charged cloud could be produced in an enclosed vessel. Thomson used this charged cloud to continue his work on the determination of the fundamental electric charge e.

Thomson now left his cathode ray experiments for a year while he investigated ionised gases. In 1898, Thomson set out to "*determine the magnitude of the charge of electricity carried by ions which are produced when Röntgen rays pass through a gas."*[29] He believed that "*by measuring the current passing through a gas exposed to Röntgen rays and acted upon by a known electromotive force, he could determine the value of the product nev, where n is the number of ions in unit volume of gas, e the charge on an ion and v the mean velocity of the positive and negative ions under the electromotive force to which they are exposed."*[30] Thus $I = nev$.

The mean velocity which Thomson employed was a measure of the mobility of the charged gas ions. Ionic mobility is defined as the average velocity of the ion as it moves towards an electrode under the influence of an electric field. In modern terms

[29] p 528 Thomson, J.J. 1898
[30] p 528 Thomson, J.J. 1898

it is determined from a measure of the conductance of the ion divided by the value of the Faraday constant, F

i.e. $F = Ne$ where $F = 96{,}490\ C/mole$ and $N = 6.0222 \times 10^{23}$ (see Chapter 3). The conductivity of these ions is dependent on the charge carried by these ions and the fraction of the total current that these ions carry. If the conductance of the solution is defined by Λ, then $\Lambda = \lambda_+ + \lambda_-$ where λ_+ and λ_- are the conductance of the positive and negative ions respectively and $\lambda_+ = t_+\Lambda$ and $\lambda_- = t_-\Lambda$ where t_+ and t_- are the fractions of the current carried by the positive and negative ions respectively. Thomson used the mean mobilities which, at this time, had recently been calculated by Ernest Rutherford (1871-1937).

In November 1897, Rutherford published a paper in which he attempted to determine the velocity of the individual charged ions in a gas by measuring the duration of the conductivity of the gas after exposing it to Röntgen radiation. He did this by two methods each of which gave results consistent with the other. In the first method he blew air at a known velocity along a tube of known length and tested the conductivity of the air at different distances from the point at which the air had been exposed to the radiation. By measuring the dimensions of the tube, the volume of air moved and the time taken for the air to move from one electrode to the next, Rutherford could determine the conductivity of the gas. [31]

In the second method Rutherford first exposed the gas to Röntgen rays for a short period of time. When he ceased the irradiation, he applied an e.m.f. to the gas across predetermined intervals, by measuring the current that passed through the gas he could determine the velocity of the ions. Rutherford found that each gas had its own unique value of ionic velocity and this was independent of the exposure time to the radiation. [32]

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31 p 422-3 Rutherford 1897
32 p 425-35 Rutherford 1897

Returning to the discussion of Thomson's 1898 paper, Thomson now set out to determine the number of ions, n, present in a unit volume of gas. He decided to use the earlier discoveries of C.T.R.Wilson that ions produced by exposure to X-rays act as nuclei around which water could condense forming droplets which comprise a cloud or fog. If the size of the water droplet is known and the mass of the water deposited per unit volume of gas is known, then the number of droplets could be determined. Further if each droplet was centred on an ion, the number of ions present could then be calculated, and hence the charge carried by each ion. [33]

To measure the size of these drops, Thomson employed Sir George Stokes's formula where

$\text{Force} = \frac{4}{3}\pi a^3 \rho g = 6\pi\mu a v$ producing the following relationship

$$v = \frac{2}{9}\frac{g a^2 \rho}{\mu}$$

where v = the velocity at which the drop falls
a = the radius of the drop
g = the acceleration due to gravity
μ = coefficient of viscosity of the gas
ρ = density of the drop

George Stokes had developed this formula in 1849 to describe the motion of solids in a streamline non-turbulent flow through a viscous fluid. A sphere such as a water drop falling slowly, controlled by viscosity alone, soon reaches its terminal velocity, *"the speed at which the viscous resistance exactly balances its own weight. At this speed, it is subject to no resultant force and simply obeys the first law of motion."* [34] It is this terminal velocity that is calculated using Stokes's formula. It should also be noted that this is exactly the same method used a year earlier by Townsend to determine the charge carried by ionic gases produced in chemical reactions (see Chapter 4).

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33 p 529 Thomson, J.J. 1898
34 p 86 Lodge 1906

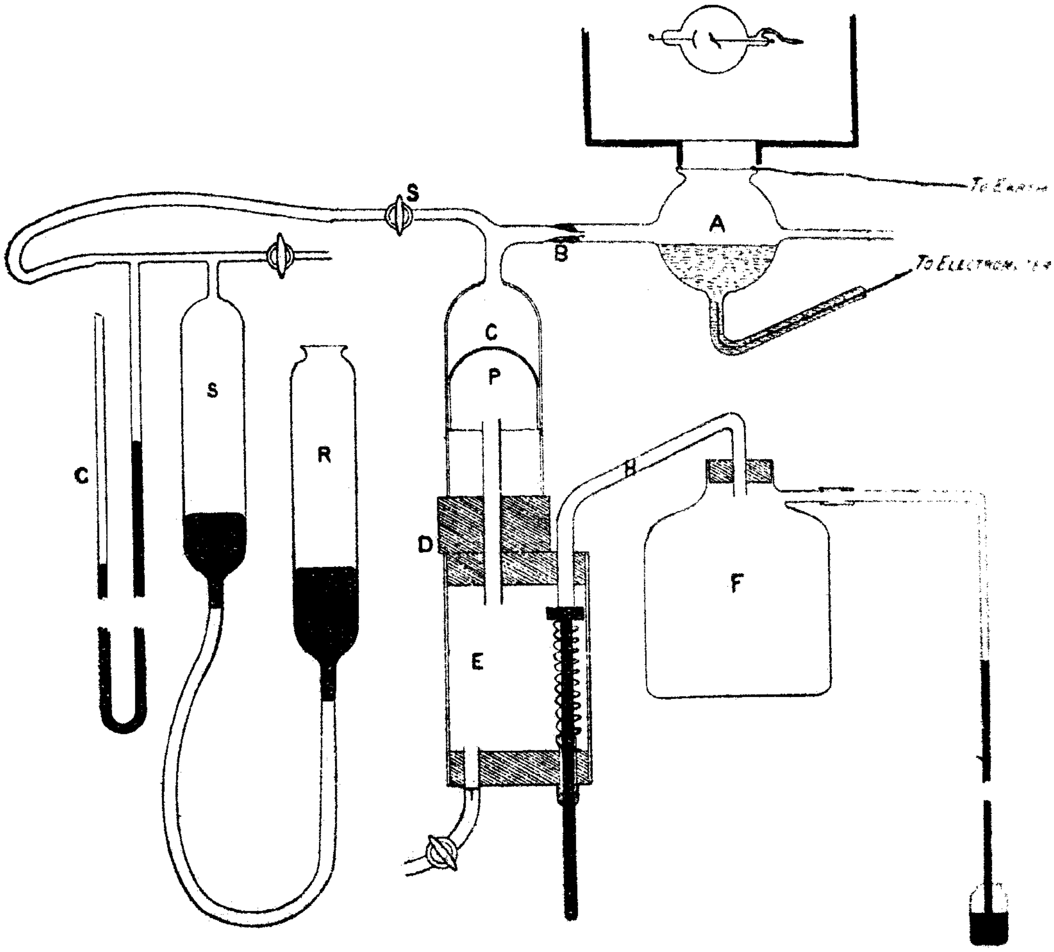

Diagram 5 C (p534 J.J.Thomson-1898)

To measure this velocity, J.J.Thomson produced clouds using C.T.R.Wilson's expansion apparatus (see diagram 4-B and chapter 4 for a description of how it functions) to which he added vessel A (see diagram 5-C). Vessel A contains the gas which is to be exposed to the X-rays and it is also where the cloud is formed and where the electrical conductivity of the gas is tested. Vessel A is a *"glass tube about 36mm in diameter the top of which is covered by an aluminium plate; a piece of blotting paper is placed on the lower side of the plate and the current of electricity passed from the blotting paper to the horizontal surface of the water in this vessel."*[35] The bulb producing the X-rays was placed above A and layers of aluminium sheets were placed between the bulb and A to control the intensity of the X-rays.

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35 p 535 Thomson, J.J. 1898

The aluminium plate on the top of A was connected to earth and a pair of quadrants of an electrometer. The other pair of quadrants were connected with the water surface as shown in diagram 5-C. This surface was charged up by connecting it to a battery of two Leclanché cells. Once charged, the battery was disconnected and the surface insulated. When the X-rays were turned on, the charge began to leak. By measuring the rate of leakage, the quantity of electricity per second crossing the gas which had been exposed to the rays could be determined if the capacitance of the system is known i.e. $Q = C \times V$.[36] Hence this apparatus enabled Thomson to both calculate the size of the drops and the current passing through the exposed gas.

Thomson assumed that the individual water drops would be of an identical size and fall at the same rate as the cloud as a whole. Thus he was able to calculate this rate of fall *"by observing the time the top layer of the cloud took to fall a given distance."* This velocity varied with the temperature of the air, the expansion ratio of the apparatus, the air pressure and whether the gas had been exposed to X-rays during the expansion. Thomson found that the velocity of the drops was 0.14 cm/sec when exposed to X-rays and 0.41 cm/sec when not exposed to X-rays.[37]

Having obtained a value for the size of the individual water drops, Thomson then set out to determine the mass of the water deposited by the cloud. Thomson assumed that q *"the mass of the water deposited from a cubic centimeter of the gas is*

$$q = \frac{4}{3} n a^3 \pi$$

where $a =$ radius of the drop".[38]
$n =$ number of drops

The quantity stated in this relation is actually the volume of the water drops. It is unclear from the paper whether Thomson assumed that the density of water was $\rho = 1$, or that his readers would simply make the same assumption without specifically referring to it.

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36 p 536 Thomson, J.J. 1898
37 p 540 Thomson, J.J. 1898
38 p 538 Thomson, J.J. 1898

This quantity q, could not be directly measured using the apparatus, so Thomson used a method developed by C.T.R.Wilson in his 1897 paper on the formation of clouds in dust free air. This method required the use of the latent heat of vaporisation of water, the specific heat at constant volume of the gas in which the cloud is formed, the mass of the unit volume of this gas, the temperature of the gas both before and after expansion, the air pressure before and after expansion and the ratios between the volumes of the gas before and after expansion. The latent heat to form this quantity, q g of liquid must be taken from the gas which will consequently be at a lower temperature after the expansion than it would be if the water vapour were not present. Following some lengthy computations, Thomson found that at a temperature of 1.2°C the drops were at their maximum size or as Thomson states "*fully grown*"[39] and he estimated that the amount of water deposited per unit volume expanded gas is 47.7×10^{-7} g.[40]

Having found the velocity of the droplets and the amount of water deposited per unit volume of gas, Thomson applied the following values to Stokes's formula:-

$$v = 0.14 \text{ cm/sec}$$
$$g = 981 \text{ cm/sec}^2$$
$$m = 1.8 \times 10^{-4}$$

obtaining a value for the radius of the water drop of $a = 3.39 \times 10^{-4}$ cm. Hence using the formula

$$n = \frac{3}{4}\frac{q}{a^2\pi} \text{ where } q = 47.7 \times 10^{-7}.$$

Thomson found that $n = 2.94 \times 10^4$ in 1cc of gas after expansion and $n = 4 \times 10^4$ in 1cc of gas before expansion.[41]

39 p 538 Thomson, J.J. 1898
40 p 540 Thomson, J.J. 1898
41 p 541 Thomson, J.J. 1898

Thomson now considered the electrical part of the experiment. The electrometer deflection for the two Leclanché cells was *"90 scale divisions"*, Thomson states that "*the capacity of the system consisting of the cell containing the gas exposed to the rays, the connecting wires and the quadrant was 38, on the electrostatic system of units."*[42] Thomson further stated that *"if E is the electromotive force of a Leclanché cell, the quantity of electricity passing through a cross-section of the discharge tube (i.e. vessel A) is equal to* $\frac{38}{300}E$*."*[43]

But this is

$$q = Aneu_0E$$

$$\begin{aligned} \text{where } A &= \text{the area of the electrodes } [\pi(1.8)^2 \text{ cm}^2] \\ n &= \text{number of ions per cc } [4\times10^4] \\ u_0 &= \text{the mobility of the positive and negative ions} [1.63\times10^2 \text{cm/sec}] \\ E &= \text{uniform potential gradient} \end{aligned}$$

The mobility had been determined by Rutherford in 1897 and discussed earlier in this chapter. As the result of this long experimental and deductive argument, Thomson, at last was able to quote a value of $e = 6.3\times10^{-10}$esu (i.e. 2.1×10^{-19}C).[44]

Thomson then added a correction to this to account for the cloud which formed in the absence of X-rays and to account for the conductivity of the walls of vessel A due to the film of moisture with which it was coated. As a result of these corrections, Thomson concluded that the value of $e = 6.5\times10^{-10}$ esu.[45]

Towards the end of this paper, Thomson compares his results with those obtained from electrolysis. He states that his value of e *"is greater than that usually given for the charge on the hydrogen atom in electrolysis."*[46] Finally Thomson points out *"that Prof H.A.Lorentz has shown that the charge on the ions whose motion causes those*

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42 p 541 Thomson, J.J. 1898
43 p 541 Thomson, J.J. 1898
44 p 541 Thomson, J.J. 1898
45 p 543 Thomson, J.J. 1898
46 p 544 Thomson, J.J. 1898

lines in the spectrum which are affected by the Zeeman Effect is of the same order as the charge on a hydrogen ion in electrolysis."[47]

Having determined a value of e for the charge carried by ions produced by exposing supersaturated water vapour to X-rays, Thomson now used a different method to obtain charged particles, and he again measured both e and the mass to charge ratio (m/e) of *"negative electricity carried by charged particles."*[48] Thus, Thomson's 1899 paper *"contains an account of measurements of m/e and e for the negative electrification discharged by ultra violet light, and also of m/e for the negative electrification produced by an incandescent carbon filament in an atmosphere of hydrogen."*[49]

Thomson observed that the escape of the negatively charged ions from a negatively charged metallic surface exposed to ultraviolet light is diminished by a magnetic force if the field producing this force is perpendicular to the electric field applied to the metallic surface. Thomson now stated that if both the electric and magnetic fields were constant and both were perpendicular to the direction of current drift, one could determine the path of any moving ion in these fields. Thus Thomson found that a negatively charged particle would execute a spiral path with a circular component of radius $r = \frac{m}{e}\frac{E}{B^2}$.[50] This method has some resemblance to the method Thomson used in "Cathode Rays" in 1897. This more recent method is a refinement on the previous one since it does not require the two fields to cancel each others effects and hence produce an identical and opposite deflection of the particle.[51]

47	p 545	Thomson, J.J. 1898
48	p 548	Thomson, J.J. 1899
49	p 548	Thomson, J.J. 1899
50	p 549	Thomson, J.J. 1899
51	p 308	Thomson, J.J. 1897

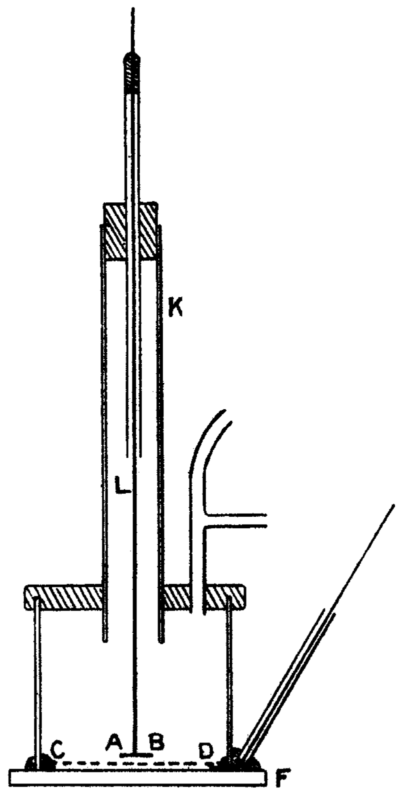

Diagram 5 D (p550 J.J.Thomson-1899)

Thomson applied this method by using the following apparatus (diagram 5-D). A 1cm diameter zinc plate AB was attached to a handle and passed out of the tube K. AB was thus connected to the negative terminal of a battery of small storage cells, the other terminal of this battery was earthed. This plate could be moved so that the distance between AB and the perforated electrode CD could be varied. The electrode CD is actually a grating of fine wires, was placed parallel to AB and rested on a thin quartz plate. This grating was carefully insulated and connected to two quadrants of an electrometer, the other quadrants were earthed. Any leakage of current between AB and CD could thus be measured. This was then enclosed in a glass tube which was connected to a vacuum pump. Beneath the quartz plate was a box containing the zinc terminals and induction coil which produced the ultra violet light. Thus exposing plate AB to ultra violet light. The magnetic force was applied across the area between AB and CD using a horseshoe type of electromagnet.

The negative particles produced by ultra violet exposure of the electrified plate travelled down to the perforated plate and the current was measured as a deflection on the electrometer. When the magnetic field was applied to this situation there would be no change in the current reaching the perforated plate until the distance between the two electrodes was equal to the radius of curvature of the charged particle exposed to both magnetic and electric forces.[52]

Thomson obtained a mean value for e/m of 7.3×10^6. He compared this to his own value of e/m for cathode rays of 5×10^6 (this value is actually quoted by Thomson in his 1899 paper, however, he does not indicate when or how he obtained it). He could thus conclude *"the value of e/m in the case of the convection of electricity under the influence of ultra violet light is of the same order as in the case of cathode rays, and is very different from the value of e/m in the case of the hydrogen ions in ordinary electrolysis when it is equal to 10^4."*[53]

Thomson next examined the *"case in which we have convection of electricity at low pressures by means of negatively electrified particles - that of the discharge of electricity produced by an incandescent carbon filament in an atmosphere of hydrogen."*[54] Thomson essentially used the same equipment as before, but replaced the two electrodes with two parallel aluminium discs of 1.75 cm in diameter. Between these plates and located close to the upper disc, Thomson placed a small semi circular carbon filament which was raised to red heat by applying a current from a battery of storage cells. The lower disc was connected to an electrometer as before.[55] Using the same methods as before Thomson obtained a mean value for $e/m = 8.7 \times 10^6$.[56]

In 1898 C.T.R.Wilson *"discovered that the ions produced by ultra violet light act like those produced by Röntgen rays, in forming nuclei around which water will condense*

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52 p 550-2 Thomson, J.J. 1899
53 p 554 Thomson, J.J. 1899
54 p 554 Thomson, J.J. 1899
55 p 555 Thomson, J.J. 1899
56 p 556 Thomson, J.J. 1899

from dust-free air."[57] It appeared that ultraviolet light could ionise air only in some circumstances. A cloud could be formed by ionisation produced by ultraviolet light, however this cloud could only be formed in the presence of an electric field. If there was no electric field, the negative ions remain close to the surface of the illuminated plate and do not diffuse out to the region of cloud formation.[58]

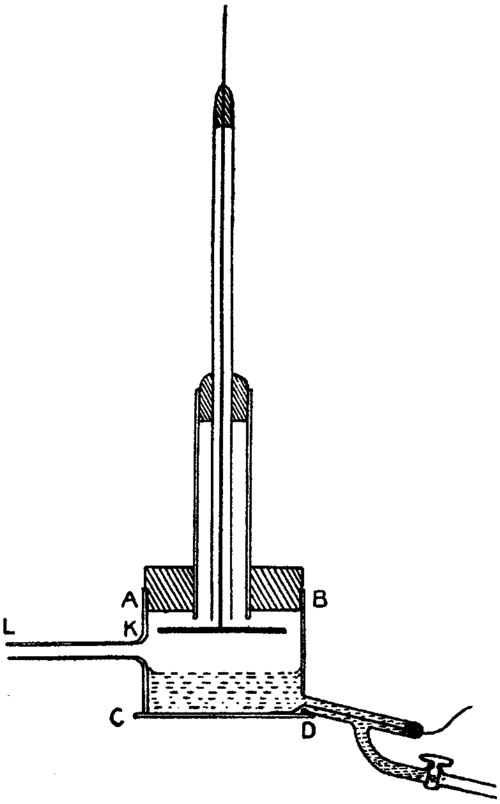

Diagram 5 E (p559 J.J.Thomson-1899)

Thomson used the following apparatus (diagram 5-E) connected to the expansion apparatus he had previously used. The vessel in which expansion occurred was a glass tube 3.6cm in diameter with a quartz base through which the ultra violet light could penetrate and pass through the water illuminating a zinc plate of 3.2cm diameter located 1.2cm above the surface of the water. The electrical connections were similar to those in his 1898 paper.[59]

57 p 557 Thomson, J.J. 1899
58 p 558 Thomson, J.J. 1899
59 p 559-60 Thomson, J.J. 1899

Using similar calculations as in 1898, Thomson obtained a mean value of $e = 6.8 \times 10^{-10}$ esu.[60] This second value of e is in good agreement with Thomson's previously obtained values of e, hence Thomson concluded *"that e for the ions produced by ultra-violet light is the same as e for the ions produced by the Röntgen rays; and as Mr. Townsend has shown that the charge on these latter ions is the same as the charge on an atom of hydrogen in electrolysis"*.[61] It was also found to be the same as the charge carried by cathode rays, *"the magnitude of this negative charge is about* 6×10^{-10} *esu"*[62]

Thomson next states that *"in gases at low pressures these units of negative electric charge are always associated with carriers of a definite mass. This mass is exceedingly small, being only about* 1.4×10^{-3} *of that of the hydrogen ion, the smallest mass hitherto recognised as capable of a separate existence."*[63] He then states what was still at that time a revolutionary thought, *"the production of negative electrification thus involves the splitting up of an atom, as from a collection of atoms something is detached whose mass is less than that of a single atom."*[64]

Finally, Thomson puts forward his conjecture which is now commonly referred to as the *"plum pudding"* model of the atom. It should be noted that Thomson uses the term *"corpuscle"* for the charge carrying part of the atom. This same term was used by Thomson when he later referred to the particles in cathode rays and $\beta-$rays. The term now used for these corpuscles is the *"electron"*. The *"electron"* was the term used by Stoney some time earlier to refer to the unit of negative electricity (see chapter 2).

Thomson states *"I regard the atom as containing a large number of small bodies which I will call corpuscles; these corpuscles are equal to each other; the mass of a*

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60 p 562 Thomson, J.J. 1899
61 p 563 Thomson, J.J. 1899
62 p 563 Thomson, J.J. 1899
63 p 563 Thomson, J.J. 1899
64 p 563 Thomson, J.J. 1899

corpuscle is the mass of a negative ion in a gas at low pressure. In the normal atom, this assemblage of corpuscles forms a system which is electrically neutral. Though the individual corpuscles behave like negative ions, yet when they are assembled in a neutral atom the negative effect is balanced by something which causes the space through which the corpuscles are spread to act as if had a charge of positive electricity equal in amount to the sum of the negative charges on the corpuscles. Electrification of a gas I regard as the splitting up of some of the atoms of the gas, resulting in the detachment of a corpuscle from some of the atoms. The detached corpuscles behave like negative ions... while the part of the atom left behind behaves like a positive ion."[65]

Thomson had now calculated that the mean value of this unit charge on an ion was $(6.8 \pm 1.5) \times 10^{-10}$ e.s.u., the commonly accepted modern value for e is 4.8026×10^{-10} e.s.u. Earlier in this 1899 paper, Thomson quoted the mean charge to mass ratio to be $e/m = (8.7 \pm 2.6) \times 10^{6}$ for ions produced by a carbon filament and $e/m = (7.3 \pm 1.5) \times 10^{6}$ for ions produced by ultraviolet light. The error ranges were obtained from calculations using the tables which Thomson included in this paper, Thomson did not give any indication or estimate of the magnitude of any errors in his determinations. Further in none of these cases does Thomson state the units which he uses, i.e. esu or e.m.u.

Returning to the concluding pages of this 1899 paper, Thomson, in his discussion on the nature of the corpuscle, stated the mass of these negative ions in a gas at low pressure was "3×10^{-26} *of a gramme".*[66] The modern accepted value for the mass of an electron (corpuscle) is 9.109×10^{-28} g. Thomson makes no explanation of how he obtained his value for the mass of these corpuscles. While Thomson's value for the fundamental charge, e, is in some agreement with the modern value, Thomson's

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[65] p 565 Thomson, J.J. 1899
[66] p 565 Thomson, J.J. 1899

determination of the mass is far too large. Further, using Thomson's measurements of e and e/m to obtain the mass gives

$$m = \frac{e}{e/m} = \frac{6.8\times10^{-10}}{8.7\times10^{6}} = 7.8\times10^{-17}\,\text{g or } m = \frac{e}{e/m} = \frac{6.8\times10^{-10}}{7.3\times10^{6}} = 9.3\times10^{-17}\,\text{g.}$$

Assuming that the e/m ratio was measured using the esu, this value for the mass is very much higher than either Thomson's stated value or the modern value. If, however, Thomson measured the charge component in his e/m ratio in e.m.u. which may also be used in the c.g.s. system of measurement, the mass of these particles would now become 2.6×10^{-27}g or 3.1×10^{-27}g which is still out by a factor of 10 but is a somewhat better estimate for the mass. The value of 3×10^{-26}g quoted by Thomson appears to conform with the later supposition, however his determination is still out by a factor of ten. The modern accepted value for the mass of the electron is 9.109×10^{-31}kg.

At the conclusion of this article, Thomson refers to the Zeeman effect (see chapter 7) which he uses to propose that the atom contains more corpuscles than the one or two that can be removed by ionisation or electrolysis. Thomson states *"the ratio of the mass to the charge, as determined by the Zeeman effect, is of the same order as that deduced from our measurements on the free corpuscles; and the charges carried by the moving particles, by which Zeeman effect is explained, are all negatively electrified."*[67]

Thomson then concludes with *"if there were only one or two of these corpuscles in the atom, we should expect that only one or two lines in the spectrum would show the Zeeman effect. ... As, however, there are a considerable number of lines in the spectrum which show Zeeman effects comparable in intensity, we conclude that there are a considerable number of corpuscles in the atom of the substance giving this spectrum*."[68] The explanation of the Zeeman effect to which Thomson refers,

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[67] p 567 Thomson, J.J. 1899

[68] p 567 Thomson, J.J. 1899

was proposed by Lorentz to explain the splitting of spectral lines in the presence of a magnetic field which was first reported by Zeeman but previously sought unsuccessfully by Faraday. Lorentz based his theory on Maxwell's work on electromagnetism.

6. The Cavendish Laboratory and the Determination of *e*

6.1. H.A.Wilson's Water Drop Experiment

Harold Albert Wilson (1874-1964) arrived in Cambridge in 1897 as an 1851 Exhibition Scholar, from York where he had been born and educated. In 1901 he became a Fellow of Trinity College and a Clerk Maxwell Student in the Cavendish Laboratory. In 1903 H.A.Wilson conducted a series of experiments based on the discoveries of cloud formation made by C.T.R.Wilson. It should be noted that H.A.Wilson and C.T.R.Wilson were not related but they worked together at the Cavendish Laboratory as research students. H.A.Wilson used the same expansion apparatus as had previously been used by C.T.R.Wilson, in fact H.A.Wilson states that "*the expansion apparatus used was kindly lent to me by Mr C.T.R.Wilson.*"[1] While using the equipment and discoveries of his predecessors, H.A.Wilson used a different theoretical approach to obtain a measured value for e. He assumed that the individual droplets in the cloud contained one or more ions and hence a droplet having one ion would carry a charge e and have a mass m. The rate at which this droplet fell in air would be v_1. Now if a vertical electric field E is applied to this drop, then the total force acting on this drop would be

$$F = Ee + mg$$

"Now the rate of steady motion of a sphere in a viscous fluid is proportional to the forces acting on it."[2] Which in this case is firstly, the force due to gravity, i.e. $F = mg$ and secondly the force due to both the electric field and gravity, i.e. $F = mg + Ee$. Thus $\frac{v_1}{v_2} = \frac{mg}{mg + Ee}$ where v_1 is the velocity due to gravitational acceleration and v_2 is the velocity due to both gravity and the applied electric field.

1 p 432 Wilson, H.A. 1903
2 p 430 Wilson, H.A. 1903

Wilson next used the relationship between mass and velocity which J.J.Thomson utilised in 1899, ie Stokes's equation (see Chapters 4 and 5) $mg = \frac{4}{3}\pi a^3 \rho g = 6\pi \mu a v$

which produces a value for the radius of the drop of

$$a = \left(\frac{3}{4\pi\rho} m\right)^{\frac{1}{3}}$$

which in turn produces this expression

$$m^{\frac{2}{3}} = \left\{\frac{6\pi\mu}{g}\left(\frac{3}{4\pi\rho}\right)^{\frac{1}{3}}\right\} v_1.$$

The terms in the braces are all constants and hence a value for the mass could be determined in terms of the velocity of the drop. Thus Wilson determined that $m = 3.1 \times 10^{-9} v_1^{\frac{3}{2}}$ where all the constant terms were based on the cgs units. Finally by substituting this expression of the mass in the earlier force equation, Wilson obtained the following relationship

$$e = 3.1 \times 10^{-9} g (v_2 - v_1) v_1^{\frac{1}{2}} / E$$

Wilson could now determine the value for e by simply measuring the electric field and the two velocities with which the cloud fell.[3] Wilson believed that *"the principal advantages of my method are that it is not necessary to estimate either the number of drops in the cloud or the number of ions present at the moment of its formation or to make the assumption that each droplet contains only one ion"*.[4]

3 p 430 Wilson, H.A. 1903
4 p 430 Wilson, H.A. 1903

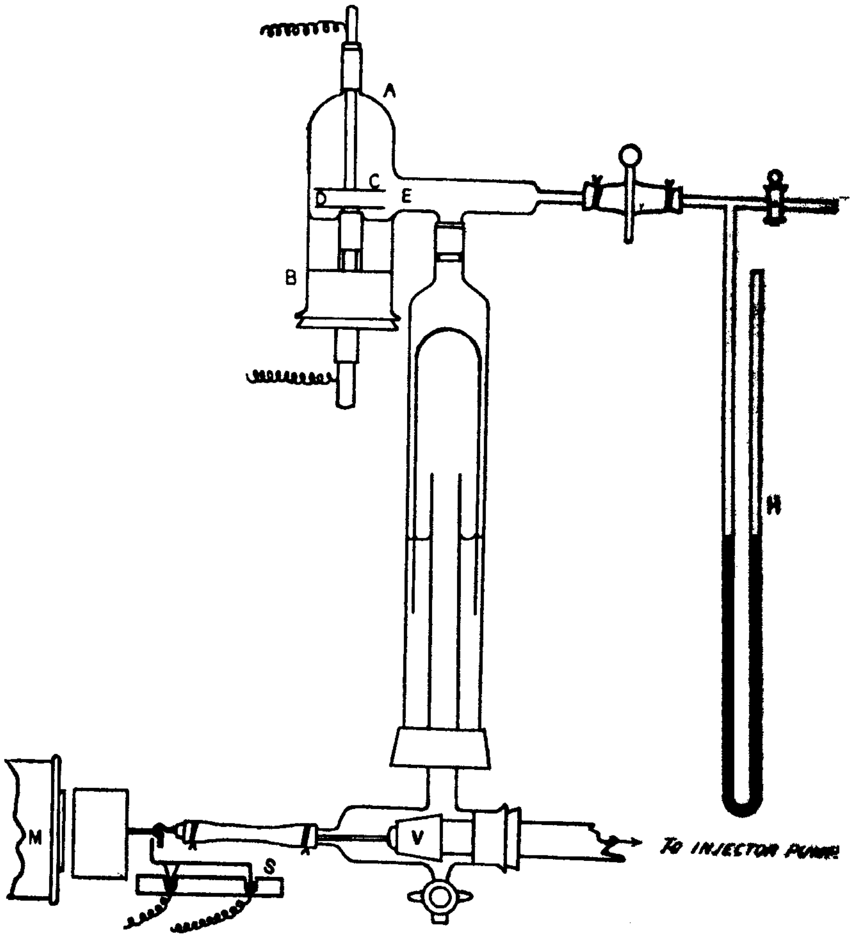

Diagram 6 A (p431 H.A.Wilson-1903)

To enable him to obtain his value of e, H.A.Wilson developed a new cloud chamber device (see diagram 6-A) in which two circular brass discs C and D of 3.5 cm in diameter are supported one above the other. The cloud on which the observations were made was formed between them and a potential difference of up to 2000 volts could be maintained by a battery of small secondary cells. This was enclosed in a glass tube AB which was 4 cm in diameter and 10 cm long. Attached to AB was a glass tube E which acted as a connection between AB and the expansion apparatus. A mercury manometer was used to measure the expansion.

When a cloud was formed between the discs, Wilson using a stop watch measured the time taken for the upper surface of the cloud to fall to the lower disc. This gave the velocity v_1 without an electric field. This procedure was then repeated with an applied electric field on the cloud, timing the fall of this cloud gave the velocity v_2.

Wilson found that the value of e lay between 2×10^{-10} and 4×10^{-10} esu.[5] In a footnote, Wilson states that "*since this paper was written Prof Thomson.. has lately made a fresh determination of e by his original method but with an improved apparatus."*[6] Thomson's value of e is stated as being 3.8×10^{-10} esu and Wilson further states that "*it appears that in his (J.J.Thomson) earlier experiments the cloud was formed mainly on the negative ions and not on both positive and negative ions as was supposed at the time, consequently the result obtained was nearly twice too big."*[7] It should be noted that in the original papers, Thomson specifically spoke of the "*negative ions"* and had calculated the e/m of these negative ions. Hence this comment of Wilson's in the footnote at the start of his paper appears quite baffling. Perhaps Thomson's improved value of e lay in the improved "apparatus" that he used and not in an error in his hypothesis.

6.2. J.J.Thomson's Water Drop Experiments

Thomson's 1903 paper "On the Charge of Electricity carried by a Gaseous Ion", describes the new apparatus which included a more sensitive electrometer. Thomson used essentially the same expansion apparatus that he used in 1899 however he utilised radium as his radiation source instead of X-rays. The innovation in these experiments, the parallel plate capacitor is only described but not actually shown in the apparatus(see diagram 6-B). Thomson measured the time of fall of the fog in an electric field and hence was able to calculate the velocity, u, of the ions under the applied electric field. He assumed that the ions each had a charge of e and the total number of ions in a cc of air was n. If the area of the lower plate was A, then Thomson concluded that "*the quantity of electricity received by the lower plate in unit time was neuA"*[8]

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5 p 441 Wilson, H.A. 1903
6 p 429 Wilson, H.A. 1903
7 p 429 Wilson, H.A. 1903
8 p 352 Thomson, J.J. 1903

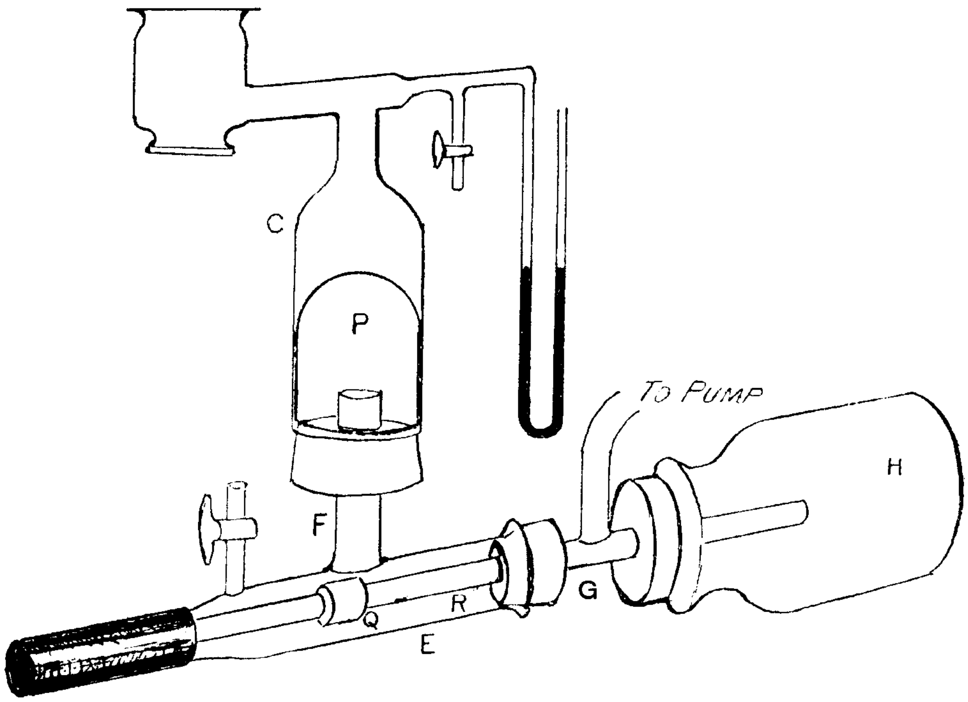

Diagram 6 B (p349 J.J.Thomson-1903)

When Thomson referred to the ions he specifically mentions both positive and negative ions and assumes that n is "*the number of ions (positive and negative) per c.c. of the air".* This assumption will of course lead to some very wrong conclusions since the contribution to the total electric charge gained by the lower plate could only be due to either positive ions or negative ions depending on the direction of the field. Hence Thomson's reasoning seems obscure. Next Thomson assumes *"if C is the capacity of the electrometer and its connections, this quantity of electricity will produce a potential difference of neuA/C between the quadrants."*[9] To obtain a measure of the capacitance C, Thomson measured the deflection of the electrometer using this capacitor then by connecting this capacitor with another of known capacitance, he compared this new deflection of the electrometer with the previous deflection. Thomson now made an estimate of the number of ions per cc in the air and obtained two different values which depended on the distance that the source of radiation (in this case Radium) was placed above the cloud chamber. When the radiation source was 10 cm from the cloud chamber, Thomson determined

[9] p 352 Thomson, J.J. 1903

that the number of ions $n = 6.25 \times 10^4$. When the radiation source was located further away, 15 cm from the cloud chamber, the estimated number of ions was 16.75×10^4. [10] From these results, Thomson was able to conclude that $e = 3.3 \times 10^{-10}$ esu for the first case and $e = 3.5 \times 10^{-10}$ esu for the second, producing an average value of $e = 3.4 \times 10^{-10}$ esu [11]

Thomson's 1903 paper preceded H.A.Wilson's paper by only a couple of months. H.A.Wilson's paper had been communicated to the "Philosophical Magazine" by J.J.Thomson. In 1988, in a taped interview to Prof Robert Crompton, Sir Leonard Huxley who had been acquainted with H.A.Wilson, J.J.Thomson and J.Townsend, stated "*that Wilson had ... given his manuscripts to Thomson to communicate to the Phil. Mag. and nothing happened for some months and he (Wilson) went to Thomson's office and there was the manuscript still ... on the table."*[12] Huxley continued "*in the meantime Thomson had been repeating his (i.e. Wilson's) stuff, having abandoned it for his a couple of years, and had actually published his new value which was the same as Wilson's and Wilson's paper wasn't communicated until after that."*[13] While this statement has not as yet been supported by documentary sources, an examination of both Thomson's and H.A.Wilson's 1903 papers would tend to support Huxley's comment.

As has already been stated Thomson's paper preceded H.A.Wilson's paper by only a matter of months and Thomson had in fact sent Wilson's paper to the "Philosophical Magazine". The comments in the footnote of Wilson's paper comment on Thomson's results indicate that at the very least, Thomson and Wilson were working on this new determination of e at the same time. While Huxley's allegations may at first seem somewhat extreme, there is a distinct possibility that Thomson may have been inspired by Wilson's work. The evidence for this proposition comes from

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[10] p 353 Thomson, J.J. 1903
[11] p 354 Thomson, J.J. 1903
[12] p 2 of cassette 2 ref 59
[13] as above

a comparison of the two papers. The distinct change and probably the major advance in the experimental apparatus was the inclusion of the parallel plate capacitor within the cloud chamber unit. Wilson includes this in his description and diagram but Thomson only mentioned it and failed to include it in the diagram of his apparatus, instead he focused on the well documented expansion apparatus (see diagrams 6A and 6B). It was this parallel plate capacitor that Millikan utilised in his famous oil drop experiment (see chapter 7).

6.3. Huxley's Accusations

In April 1933 an unsigned article appeared in "Nature" entitled "Early History of the Determination of Atomic Charge" [14] This article was written by Prof Huxley, who was at this time a young academic and held the position of head of the Physics Department at the University College Leicester. The article had been deliberately unsigned because it largely contradicted the then accepted version of events in the determination of e. Thomson from his position as head of the Cavendish Laboratory and the discoverer of the electron, had written a number of books and papers on the history of Cathode Rays and the experiments by him and others which first determined the value of e. It was and still is Thomson's version which is accepted. While Thomson won a Nobel Prize for his work on proving that Cathode Rays were actually charged particles, he was as has already been discussed in Chapter 5, the third scientist to make this observation, Wiechert being the first in January 1897 and Kaufmann the second in April 1897.

The bulk of this 1933 article by Huxley focuses on J.Townsend's contribution, the determination of the charge on an ion. At the time the article was written, Huxley and Townsend were close friends while the initial minor conflicts between Townsend and Thomson had degenerated to a deep personal resentment on the part of Townsend. While these factors may explain why the article was written, they do not detract from the evidence it presents. As has already been stated in Chapter 5, Townsend was the first person to apply Stokes's formula to the charged cloud so as to determine the

[14] p 569 (Huxley) 1933

size of the droplets in the cloud from the rate at which the cloud fell. While Thomson uses this formula, he never acknowledges from where he obtained it.

Although Thomson freely acknowledges, in his papers, the contributions made by Rutherford and C.T.R.Wilson, he never mentioned the contributions made by H.A.Wilson and Townsend. Townsend's contributions not only allowed Thomson , but also H.A.Wilson and finally Millikan to determine the value of electronic charge, e. H.A.Wilson's contribution of the parallel plate condenser allowed both Thomson to make a new determination of e and Millikan to utilise this method in his oil drop experiment. One cannot completely excuse Thomson from neglecting to mention the pioneering contributions of two of his students. Thomson was at this time the head of the Cavendish Laboratory and reasonably secure in his academic appointment. Unfortunately, he did not appear to be as mathematically talented as Townsend and hence may not have even considered utilising Stokes's equation in the determination of e. Further, in the 1890's Thomson appeared to be a prolific experimenter on a wide range of topics and seemed to fall into the habit of working in an area then neglecting it for a time and then returning to it shortly after a new discovery, or experimental method was developed or a new determination was made.

As has already been discussed in Chapter 3, in 1897 Arthur Schuster commented on the lack of consistency in Thomson's arguments and conclusions. Specifically, when Schuster compared Thomson's most recent work in a specific area with his earlier work in the area and that of others, Thomson's conclusions did not appear to be consistent. This inconsistency was so noticeable that Schuster was forced to comment. Further, as has already been noted in this chapter, Thomson failed to recognise the importance of the parallel plate capacitor in his own work. Surely, if Thomson had engaged in this original research he would have emphasised the latest equipment and not an item that had already been described both by himself and C.T.R.Wilson some four years earlier.

If Huxley's allegations are correct, and the evidence seems to indicate this, Thomson appears to work in a particular area then leave that area of research, only to return to it sometime later, often after one of his research students has made a major contribution to that area. Further one could even be so bold as to say that Thomson acknowledged the work of those he respected (e.g. C.T.R.Wilson and Rutherford) and ignored the work of those he considered to be students under his direction (e.g. H.A.Wilson and J.Townsend). It may be worth speculating that perhaps Thomson was somewhat jealous of those whose came from comfortable or academic backgrounds such as the later two students, while at the same time trying to encourage and assist those from more impoverished or less established backgrounds, such as the former two students. Further, Thomson, Rutherford and C.T.R.Wilson all won Nobel Prizes for their work, Townsend and H.A.Wilson conspicuously did not. Further, Millikan who used both Townsend's and H.A.Wilson's contributions was another Nobel Prize winner. It is little wonder that by 1933 Townsend should have become somewhat bitter. However both Townsend and H.A.Wilson continued successfully in their academic careers, Townsend in Oxford and H.A.Wilson in Houston.

In "Inward Bound", Abraham Pais makes a number of comments concerning Thomson's work on the electron and his subsequent development of the "plum pudding" model. In 1913, Thomson published a paper in which he attempted to refine his previous thought on the subject. Pais comments on this paper are as follows

"*there is no word about the hydrogen atom;*
there is no word about Rutherford;
there is no word about Niels Bohr.
Now Thomson read his paper before the September 1913 meeting of the British Association. Yet two years before, Rutherford had discovered the nucleus while, earlier in 1913, Bohr had cracked the Hydrogen atom".[15]

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[15] p 187-8 Pais 1986

A second reference by Pais described what occurred after the final acceptance of the atomic model presented by Bohr. Pais notes that as late as 1923 Thomson was still expounding his own classical model of the atom "*without using or mentioning the quantum theory or the names of Rutherford and Bohr".*[16] This tendency of not acknowledging the work of others seemed to continue during most of his working life and is only obvious when his published papers are critically examined. However not all his published papers suffer from this tendency, His classical "Cathode Rays" appears to fully acknowledge the work of others.

One concluding point must be made on J.J.Thomson as head of the Cavendish Laboratory, a position to which he was appointed at the relatively young age of 28. Lord Rayleigh in retrospect, states of his successor "*My doubt was whether Thomson should be professor of experimental Physics. He had done very little experimenting at the time, though enough to show he could do it."*[17] Was Thomson, at the age of forty, attempting to prove that he was indeed a worthy successor to both Maxwell and Lord Rayliegh at the Cavendish? Thomson certainly had the talent to attract the best young minds of his day to the Cavendish. The reputation of the Cavendish is so great that even today, almost a hundred years after Thomson's "Cathode Rays " it is still held in awe. Unfortunately, there appears to be a body of evidence that suggests that J.J.Thomson's work may not be entirely his own. As has been stated in Chapters 3 and 4 and earlier in this Chapter, Thomson's papers appear to contain a number of inconsistencies either in the use of formulae, calculations or in understanding the developmental changes to a piece of equipment. Some of his arguments and determinations appear to be casual or even sloppy by modern standards. Thomson also seems to return to previous areas of research very shortly after a new determination or discovery is made, often failing to acknowledge the assistance of his students. Further, Thomson's peers and superiors

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16 p 210 Pais 1986
17 p 85 Pais 1986

initially doubted his abilities in both experimental and theoretical/mathematical areas of Physics. However once Thomson had established his reputation and that of the Cavendish Laboratory as being at the forefront of original research, Thomson became the accepted authority in his areas of research. No one, until Huxley, had ever dared to question Thomson's version of events.

7. The Accurate Determination of e

7.1. Millikan's First Experiments

Continuing from H.A.Wilson's 1903 paper, the next attempt to determine the value of e was made in the U.S.A. by R.A.Millikan, in 1910. At this time the U.S. was a physics backwater. Most serious physics students travelled to Europe or Britain for further study and obtained much of their inspiration from here. R.A.Millikan (1862-1953) the son of a clergyman, grew up in the small rural towns of the mid-western United States. He attended Oberlin College, then Columbia University from where he obtained a Ph.D in 1895. Later that year, Millikan travelled to Germany for further study returning to the United States to work as A.A.Michelson's assistant in Chicago. [1]

Millikan's interest in the discovery of the fundamental unit of electric charge appears to come from two separate areas. The first came from the weekly seminars which he was required to organise as Michelson's assistant. On one particular occasion he was presenting a review of J.J.Thomson's paper on *"Cathode Rays"*. This particular paper so greatly impressed Millikan that he wrote *"it put together in matchless manner, the evidence for the view that cathode rays consist not of aether waves as Lenard and the Germans were maintaining but rather material particles carrying electric charges, each particle possessing a mass of about a thousandth of that of the lightest known atom ... this paper impressed me greatly and started me on the researches which have been my life work"*. [2]

The second influence appears to come from his great admiration for the pioneer work in electricity of his fellow countryman Benjamin Franklin whose work Millikan quotes in the early part of his book *"The Electron"*. For Millikan electric charge not

[1] p 189 Segre 1980
[2] p 38 Holton 1978

only existed but it was of fundamental importance for him to find its value. Millikan, it should be noted, was not the only physicist to have noted the connection between Franklin's ideas of electricity being particulate in nature and the emerging modern theory of electricity. Lord Kelvin and Rutherford had also observed this [3] (see chapter 2). Thus in 1908 Millikan started to find the magnitude of e and in 1910 he published the first of two major papers on the determination of e.

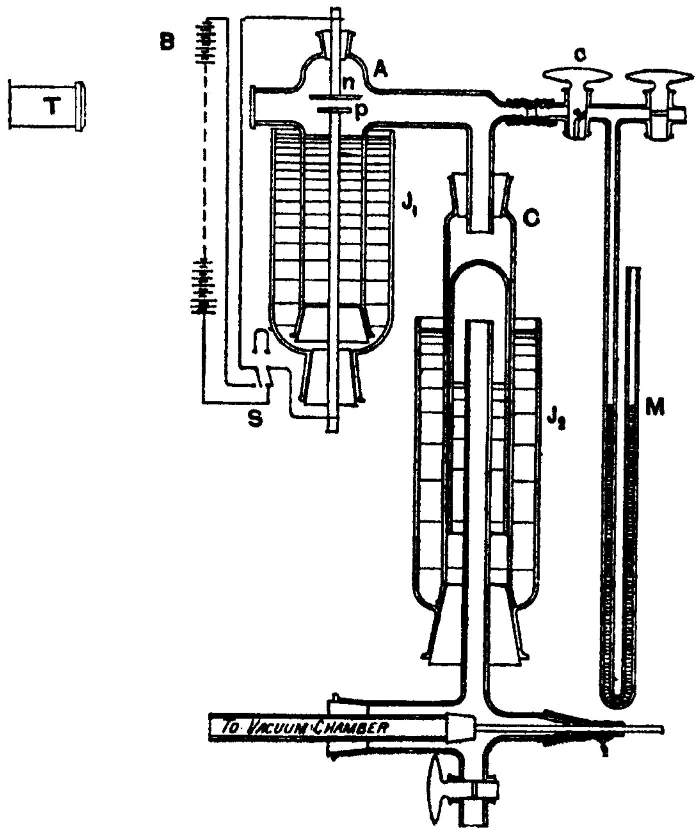

Diagram 7 A (p212 Millikan-1910)

He used H.A.Wilson's modification of Thomson's cloud method to determine e including the use of a copy of the apparatus developed by H.A.Wilson and C.T.R.Wilson, (see diagram 7-A). Millikan's first published results for the value of $e = 4.06 \times 10^{-10}$ e.s.u. (the modern value is 4.803×10^{-10} e.s.u.) appeared in a preliminary report in 1908. During the early decades of the Twentieth Century, numerical results were frequently stated without any estimates of possible error ranges; also these quantities were stated without reference to the units of measure used. At this stage, Millikan was still replicating the Wilson-Thomson experiments. [4]

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3 p 40 Holton 1978
4 p 211 Millikan 1910

However, while replicating this work, Millikan modified this method in an attempt to correct the many sources of error which he believed existed in this method. Millikan stated that,

"*1) There is an experimental difficulty involved in obtaining clouds which fall without any distortion of the upper surface because of air currents.*

2) The upper surface of a cloud falling in an electrical field is exceedingly difficult to follow on account of the scattering of the cloud which is usually produced by throwing (i.e. switching) on the field.

3) The method necessitates the assumption that it is possible to obtain in successive expansions exactly identical drops, so that v_1 *and* v_2 *can be used in the equation* $e = 3.1\times10^{-9}\dfrac{g(v_2 - v_1)v_1^{\frac{1}{2}}}{E}$ *as though they applied to the same drop."*[5]

This equation was derived from Stokes's equation and the relationship between the velocity of the drops under gravity alone and the velocity of the drop under both gravity and an applied electric field as was developed by H.A.Wilson (see chapter 6). The value 3.1×10^{-9} was the numerical expression of the constants involved in this equation.

"4) The assumption is made that the cloud falls uniformly and that there is no appreciable evaporation during the time of observation.

5) The assumption is made that the temperature of air through which the cloud falls is the equilibrium temperature after condensation."[6]

Millikan now attempted to eliminate all these areas of uncertainty. The temperature of the cloud chamber shortly after expansion "*in say two or three seconds after expansion, was not appreciably different from the temperature of the room."*[7] Millikan further determined that for "*the sort of fog chamber here used the temperature*

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5 p 211 Millikan 1910 and p 43 Holton 1978
6 p 211 Millikan 1910 and p 43 Holton 1978
7 p 213 Millikan 1910

existing midway between the plates six seconds or more after expansion does not differ appreciably from that of the room."[8]

The next source of error addressed by Millikan was that of the viscosity of air saturated with water or alcohol at $26°C$ which was the temperature of the room during these experiments. While the viscosity of dry air was well known at this time, Millikan required the viscosity of saturated air which he obtained from a Mr Fred Allison from the Ryerson Laboratory at the University of Chicago. The viscosity of air saturated with water vapour was $1904\times10^{-7}P$ and saturated with alcohol was $1878\times10^{-7}P$. From these values for viscosity, Millikan found that the constant 3.1×10^{-9} became 3.422×10^{-9} for water vapour and 3.353×10^{-9} for alcohol. Consequently when e was determined using the new constant terms, Millikan obtained a mean value of 4.5×10^{-10} e.s.u.[9]

Millikan now attempted to eliminate the evaporation error by obtaining *"an electric field strong enough to exactly balance the force of gravity upon the cloud ... and to vary the strength of this field so as to hold the cloud balanced throughout its entire life"*,[10] thus allowing Millikan to study its evaporation rate. He modified his equipment by using a 10kV battery to produce this field.[11]

When Millikan turned on the field the cloud dissipated, leaving only a few individual droplets in view. Millikan believed that those drops "*which have charges of the same sign as that of the upper plate or too weak charges of the opposite sign, rapidly fall, while those which are charged with too many multiples of sign opposite to that of the upper plate were jerked up against gravity to this plate.*"[12]Although he was unable to hold the cloud stationary *"it was found possible to do something very much better, namely, to hold individual charged drops suspended in the field for periods varying*

8	p 213	Millikan 1910
9	p 215-6	Millikan 1910
10	p 216	Millikan 1910
11	p 44	Holton 1978
12	p 216-7	Millikan 1910

from 30 to 60 seconds" [13] Millikan also found that *"the drops which were balanced by an electric field always carried multiple charges"*. [14] Finally, to vary the conditions of the experiment he used *"alcohol drops instead of water"*. [15]

Millikan found that the value of a single charge as deduced from this work lay in the range of 4.56×10^{-10} e.s.u. to 4.87×10^{-10} e.s.u. with a mean of 4.65×10^{-10} e.s.u. In discussing his results Millikan stated that *"we did not succeed in balancing any singly charged drop*" and that *"big drops and heavily charged drops are those which are most easy to hold stationary*." [16] Millikan finally concluded that *"the only possible elementary charge of which the observed charges are multiples is* 4.65×10^{-10} e.s.u." [17]

7.2. Contemporary Values of e

In his first paper Millikan compared his result with other contemporary values of e. Planck had determined a value for Boltzmann's constant k from the shape of the black-body radiation curve and from this constant derived a value for the Avogadro number N, using the relationship $R = Nk$ where R is the gas constant. Planck now applied the Avogadro number N to the Faraday constant, $F = Ne$ where e is the unit electric charge. The Faraday constant refers to the amount of electricity required to electrolyse one mole of a monovalent element such as hydrogen, which had at that time been accurately determined. From his calculations, Planck obtained a value of $e = 4.69 \times 10^{-10}$ esu. [18]

In 1908, Rutherford and Geiger obtained a value for e of 4.65×10^{-10} esu which they had obtained by "*counting the number of α particles emitted by a known quantity of radium and measuring the total electric charge carried by these particles."* [19]

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13 p 216 Millikan 1910
14 p 216 Millikan 1910
15 p 221 Millikan 1910
16 p 223 Millikan 1910
17 p 224 Millikan 1910
18 p 225 Millikan 1910
19 p 225 Millikan 1910

Rutherford and Geiger found that the charge on an α particle was 9.3×10^{-10} e.s.u. By this time, Rutherford had realised that the charge carried by the α particles was twice that of the electron.

Regener, in 1909, obtained a value of 4.79×10^{-10} e.s.u. by what was essentially a repeat of the Rutherford-Geiger experiment, i.e. counting the number of scintillations produced by the α particles emission from polonium. He then measured the total charge carried by these particles and hence made his determinations.[20] Begeman obtained a value of 4.67×10^{-10} esu using Millikan's method. It should be noted that Begeman was Millikan's assistant for much of his early work on the determination of e.[21]

Ehrenhaft obtained a mean value of 4.6×10^{-10} e.s.u. using a method similar to Millikan's except that he first observed the fall of the drop under gravity and then observed the fall by the action of an electric field.[22] This method will be more fully discussed later in this chapter.

M.de Broglie obtained a value of 4.5×10^{-10} e.s.u. by measuring the velocities of charged particles of tobacco smoke in an electric field. This method required *"the mean radius of these particles being obtained from kinetoscopic records of the mean displacement which they undergo in a given time because of their Brownian movements."*[23] This method required the use of a value of Avogadro's number (N), the value used was Perrin's which lay in the range 5.6×10^{23} to 7.1×10^{23}.

Finally Moreau had obtained a value of 4.3×10^{-10} e.s.u. by measuring the *"charge carried by ions in flames."* This value was also obtained using Perrin's value of N.[24]

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[20] p 225 Millikan 1910
[21] p 225 Millikan 1910
[22] p 226 Millikan 1910
[23] p 227 Millikan 1910
[24] p 227 Millikan 1910

7.3. Millikan's Later Experiments

The use of both water and alcohol still had the major problem of evaporation. As the drop evaporated the mass of the drop decreased making it impossible to observe a given drop for more than 5 or 6 seconds. Other possible sources of error which Millikan acknowledged included *"the lack of stagnancy in the air through which the drop moved; the lack of perfectly uniformity in the electric field used ... and the assumption of the validity of Stokes' equation"*.[25]

Prior to publishing these results Millikan presented them at a meeting of the British Association for the advancement of Science which was meeting in Winnipeg in August 1909. At this meeting Rutherford suggested that Millikan had failed to account for the evaporation of the cloud, this resulted in an overestimation of the number of ions present and hence producing a lower value for e.[26] Millikan recalled that the use of oil drops occurred to him while he was on the train to Chicago returning from this meeting. [27]

He thus attempted to overcome at least some of these problems by using oil instead of water or alcohol. He obtained the minute droplets of oil required for this process from a commercial oil atomiser. The oil which was atomised in the atomiser had been rendered dust free by passing it through a container of glass wool. The air was sprayed into a large chamber at the bottom of which were located two conducting plates set a small distance apart. The top plate had a pin hole which allowed an occasional oil droplet to fall into the region between the conducting plates (see diagram 7-B).

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25 p 64 Millikan 1917
26 p 43 Holton 1978
27 p 50 Holton 1978

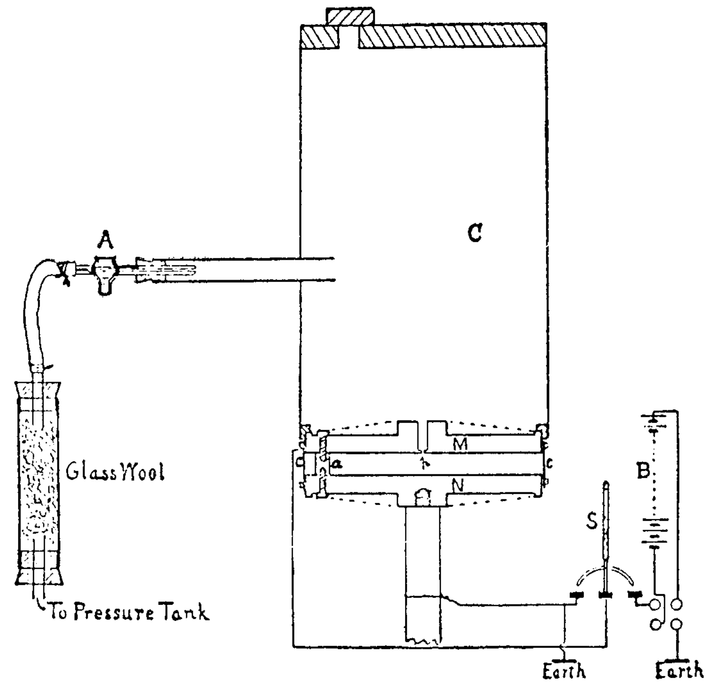

Diagram 7 B (p65 Millkan-1917)

The conducting plates had a potential difference of between 0 and 10,000 V. The oil drops were illuminated in this region by a powerful beam of light, enabling observation of individual droplets to be made. The frictional process involved in producing the spray had produced a charge on these oil drops.

These charges were sufficiently strong to allow the drop to fall freely under gravity and also to move upward if the field was applied between the plates. Millikan was thus able to observe a single drop for some minutes while timing its rate of fall or rise by an ordinary stop watch.

Millikan assumed *"that the velocity with which the drop moves is proportional to the force acting upon it and is independent of the electrical charge which it carries".* [28] Thus using his predecessors' formula of, $\frac{v_1}{v_2} = \frac{mg}{Ee + mg}$

Millikan argued that the charge captured by an oil drop in its fall to be:-

[28] p 68 Millikan 1917

$$q = \frac{mg}{E}\left(\frac{v_2' - v_2}{v_1}\right)$$

where v_1-velocity due to gravity

v_2'-velocity of the drop with a captured charge in the electric field

v_2-velocity of the drop due to the electric field

q-the captured charge

Millikan stated *"I have observed, all told, the capture of many thousands of ions in this way, and in no case have I ever found one the charge of which did not have either exactly the value of the smallest charge ever captured or else a very small multiple of that value. Here, then, is direct unimpeachable proof that the electron is not a `statistical mean', but rather the electrical charges found on ions all have exactly the same value or else small exact multiples of that value."* This value was first determined to be 4.917×10^{-10} esu [29]

When Millikan exposed the region between the plates through which the oil drops fell to an X-ray source or Radium, he found that he could control to some extent the charge that the drops captured, either positive or negative. From this experiment he was able to conclude *"that the charge carried by an ion in gases is the same as the charge on the beta or cathode ray particle ... and ... that there are no differences between the positive and negative electrons"*.[30] This value of the charge on the electron was thus determined to be 4.774×10^{-10} esu.[31]

In 1917, Millikan published another paper in which he made "*a new determination of e, N, and related constants.*" This paper was an attempt to refute Felix Ehrenhaft's results and subsequent conclusions (this will be discussed in more detail in the next section of this chapter). Millikan used the same equipment and the same oil drop

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[29] p 70 Millikan 1917
[30] p 78-83 Millikan 1917
[31] p 79 Millikan 1917

method which he had employed previously. He states that "*the only remaining element of uncertainty was the value of the coefficient of viscosity of air".*[32] Since Millikan's 1913 paper, E.L.Harrington had made a new determination of the viscosity of air which Millikan now used. This new value of viscosity of air was $\eta = 1822.7 \times 10^{-7}$ poise, while the previous value for viscosity that Millikan used was 1824×10^{-7} poise. [33] It should be noted that the oil drop method required the viscosity of dry air. Millikan's first experiments were the only experiments which required the corrections for the addition of water vapour or alcohol.

From this experiment, Millikan found that the values of e and N (Avogadro's Number) agreed exactly with his previous results of $e = 4.774 \times 10^{-10}\,\mathrm{e.s.u.}$ and $N = 6.062 \times 10^{23}$. [34] This can be a hardly surprising result since it is now accepted that Millikan was somewhat selective as to which oil drops he used in his final calculations. From these results Millikan determined the values of other constants which could be calculated using e or N, which included,
Planck's constant $h = 6.547 \times 10^{-27}$, the modern value is (in cgs units) 6.626×10^{-27} [35].

Millikan was a man who enjoyed speaking about both science and religion. While he was at Cal. Tech., where he had moved in 1921, a religious group hung a large sign with the words *"Jesus Saves".* A group of students added *"And Millikan takes the credit"*. [36]

In his book "The Discovery of Sub Atomic Particles", Steven Weinberg refers to a posthumous publication by Harvey Fletcher (1884-1981). Fletcher was a postgraduate student at the University of Chicago and worked with Millikan on measuring the value of e. According to this article, Fletcher claimed that he was the

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[32] p 9 Millikan 1917
[33] p 9-10 Millikan 1917
[34] p 13 Millikan 1917
[35] p 16 Millikan 1917
[36] p 189 Segre 1980

first to perform the oil drop experiments and was also the first to measure the charge on a single oil drop. [37]

7.4. Sub-electrons, The Dispute with Ehrenhaft

At about the same time as Millikan was obtaining his value for e in the U.S. thus confirming the particulate nature of electric charge, Felix Ehrenhaft was producing his own determination of e claiming that e is not a fundamental unit. Ehrenhaft believed that electric charge was part of a continuum in nature similar to the electromagnetic spectrum and thus it was possible for charges smaller than e to exist as free charges, these he termed sub-electrons.

Felix Ehrenhaft was born in Vienna in 1879 to a professional family. He studied at both the University and Institute of Technology of Vienna. By 1903 he became an assistant to Victor von Lang at he University of Vienna. Victor von Lang was an associate of Ernst Mach who, like many physicists on the continent, strongly held the view that electrical charge was part of a continuum and that the idea of discrete electrical charges was merely a conceptual device which did not describe the reality of their observations.

As seen previously this view that charged particles smaller than atoms existed was strongly opposed by many British and most continental physicists, including J.J.Thomson prior to his 1897 paper, and Schuster who wrote in 1884 that *"The separate existence of a detached atom of electricity never occurred to me as possible, and even if it had, and I had openly expressed such heterodox opinions, I should hardly have been considered a serious physicist."* [38]

By the turn of the century this concept of electricity as a continuous homogenous liquid was beginning to lose favour in England and the US. Continental Europe

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[37] p 95 Weinberg 1993
[38] p 41 Holton 1978 and p 59 Schuster 1911

however had not accepted the atomicity of electric charges. It was in this background that Ehrenhaft started his work.

When he commenced his work Ehrenhaft was an atomist and stated that his work was *"a new support for the molecular-kinetic hypothesis"*. [39] Ehrenhaft started his work in colloids and the observation of microscopic Brownian movement of individual fragment of metal (e.g. vapour of silver arc) or cigarette smoke. While studying Brownian motion, Ehrenhaft had noted that colloidal metal particles occasionally showed an electric charge which was detected by their motion in a horizontal field. [40]

Ehrenhaft first reported his method in March 1909 and by April 1909 had submitted three papers on his determination of the charge e. He measured the motion of these particles both with and without an electric field. By applying Stokes' equation he could obtain the mass of the particles and hence measure their electric charges. Since Ehrenhaft required two sets of particles, one for the horizontal motion when the field was applied and the other for the vertical motion when no field was applied, his value for e could only be a statistical average. [41] Ehrenhaft obtained a value of 4.6×10^{-10} e.s.u. which was closer to Rutherford's value and Plank's value than Millikan's determination. Further Ehrenhaft was the first physicist to use the paths and motions of individually charged particles to determine his value of e.

In April 1910, Ehrenhaft used "*a horizontal condenser, with a vertical electric field strong enough to make the particles rise against gravitation"*[42], which was almost the exact method used by Millikan. Ehrenhaft studied platinum and silver particles emitted from arcs reporting that *"the particles were not only singly or doubly charged but can also have charges between and below these values."* [43] In May 1910 Ehrenhaft delivered a report to the Vienna Academy in which he first use the term

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[39] p 47 Holton 1978
[40] p 47 Holton 1978
[41] p 47 Holton 1978
[42] p 56 Holton 1978
[43] p 57 Holton 1978

"sub-electron". By this time he also had access to Millikan's data, which he used in a recalculation of the value of e, obtaining values from 4.6×10^{-10} to 29.82×10^{-10} e.s.u., thus supporting the non atomist view of the nature of electricity.[44]

Ehrenhaft stubbornly held to his belief in *"sub-electrons"* and the continuous fluid theory of electric charge long after most of his contemporaries accepted the particulate nature of the electron.

Millikan, in his autobiography, summarised the possible reasons for his success and Ehrenhaft's failure *"Indeed nature was very kind. She left only a narrow range of field strengths within which such experiments as these are possible. They demand that the droplets be large enough so that the Brownian movements are nearly negligible, that the droplets be round and homogenous, light and non-evaporable, that the distance of fall be long enough to make the timing accurate and that the field be strong enough to more than balance gravity by its upward pull on a drop carrying but one or two electrons. Scarcely any other combination of dimensions, field strengths and materials could have yielded the results obtained."* [45]

7.5. The X-ray Method of Determining e

In 1928, E.Backlin in Sweden used an entirely different approach from that of Millikan to determine the value of e. Backlin determined the wavelength of X-rays which were reflected at very shallow angles from a ruled grating. The angular positions of the maximum intensities of the reflected X-rays could then be measured. The method used was similar to that employed to determine the optical wavelength from a diffraction grating. Now ,

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[44] p 57 Holton 1978
[45] Holton 1977

$$n\lambda = D(\sin\Theta_1 - \sin\Theta_2)$$

where D = separation between the gratings
Θ_1 = incident angle
Θ_2 = angle of the scattered ray
n = constant

It had been widely observed that the faces of calcite crystals will reflect X-rays but only at certain angles of incidence. The angle at which reflection occurs is dependent on the wavelength of the X-rays and the separation of the atoms in the crystal. The separation of the atoms could be determined from the geometric arrangement of the atoms in the crystal and from the value of N, the Avogadro Number which could be obtained from the Faraday constant and unit charge, e (i.e. $F = Ne$).[46]

When Backlin measured the wavelength of the X-rays by these two different methods he expected identical results. However, the discrepancy between the two methods was much greater than could be accounted in the experimental uncertainties. Consequently, Backlin assumed that the direct measure of the wavelength using the grating to be correct. He then substituted the correct value for wavelength and found that a discrepancy arose in the three constants, Avogadro's constant, the Faraday constant and the value for unit charge. Finally it became evident that the actual source of the error was in the value used for e. In his initial calculations Backlin had used Millikan's value of 4.774×10^{-10} e.s.u. As a result of his calculations and measurements, Backlin found that e was 4.794×10^{-10} e.s.u.[47]

In 1932, K.Shiba suggested that the discrepancy between Millikan's results and those found by the X-ray method arose not from the differences in experimental method but from an incorrect value for the viscosity of air. Shiba suggested that the viscosity of air was actually higher than the value used by Millikan. When Shiba

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[46] p 57 Stranathan 1946
[47] p 58 Stranathan 1946

combined the higher value for viscosity of air with Millikan's original oil drop data, the value of e obtained was 4.803×10^{-10} e.s.u. [48]

Following on from Shiba's suggestion, G.Kellstrom in 1935 made careful determinations of the viscosity of air finding it to be somewhat higher than that used by Millikan. Kellstrom determined the viscosity of air to be 1832.9×10^{-7} poise(P) while Millikan had used the value obtained by Harrington of 1822.6×10^{-7} P. [49] Using his own value for the viscosity of air and Millikan's original oil drop data, Kellstrom found e to be 4.818×10^{-10} e.s.u. [50] The poise(P) is the unit for viscosity in the cgs system of units, the S.I. unit for viscosity is the poiseuille(Pl) and 1P=0.1Pl.

The following year, E.Backlin and H.Flemberg again attempted to determine the value of e. They believed that *"the variations in the velocity of the drops between the condenser plates are real, and therefore a long series of observations are necessary to get the mean value free from the influence of Brownian motion."*[51] Consequently some of these observations lasted as long as 3 hours on a single drop. Using Kellstrom's new value for the viscosity of air, Backlin and Flemberg obtained a mean value of e to be 4.800×10^{-10} e.s.u. [52]

7.6. The Melbourne Experiments

The last serious determination of e was carried out in Australia at the University of Melbourne by T.H.Laby and V.D.Hopper. Laby was then Professor of Natural Philosophy and Hopper his assistant. Laby was born in 1880 at Creswick Victoria. In 1883 the family moved to New South Wales where young Thomas was educated. He passed the Senior Public Examination in mathematics and history, but failed to matriculate. However, 1901 he became a junior demonstrator in chemistry at the University of Sydney and attended evening classes in chemistry, physics and mathematics as well as undertaking some research. In 1905 after being awarded an

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48 p 59 Stranathan 1946
49 p 61 Stranathan 1946
50 p 61 Stranathan 1946
51 p 656 Backlin & Flemberg 1936
52 p 656 Backlin & Flemberg 1936

1851 Exhibition Scholarship to study at the Cavendish Laboratory under J.J.Thomson, Laby left Australia. He received his BA in 1907.[53]

In 1909 Laby took up a new chair in physics at the then Victoria College, Wellington (now Victoria University). It was here that he completed a project that he had started in Cambridge with G.W.C.Kaye. This work resulted in the publication in 1911 of their *"Tables of physical and chemical constants with some mathematical functions."* which has been reprinted and sold world wide for decades. This work keeps generations of physicists familiar with his name.[54]

Laby returned to Australia in 1915 taking the chair of Natural Philosophy at Melbourne University which he held until 1942. The University retitled the department as Physics after the Second World War. By the time Laby started his work on the determination of e, he was already a fellow of the Royal Society (being elected in 1931). In August 1939, Laby also became the foundation president of the Australian branch of the Institute of Physics. In short, Laby was a well respected member of the Physics fraternity both in Australia and abroad.[55]

During the years 1939-1941, Laby and Hopper conducted a number of experiments in which they attempted to reconcile the discrepancies in the results between the *"X-ray"* method and the *"oil drop"* method of determining e. Laby states that he modified H.A.Wilson's drop method by changing the direction of the electric field.[56] It is of interest to note that Laby gave recognition to H.A.Wilson's contribution to the oil drop method rather than to Millikan to whom this method is commonly attributed. Laby and H.A.Wilson were contemporaries at the Cavendish Laboratory, Wilson being senior to Laby at the time.

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[53] p 640 Australian Dictionary of Biography
[54] p 640 Australian Dictionary of Biography
[55] p 640-1 Australian Dictionary of Biography
[56] p 157 Laby & Hopper 1939

Laby applied the electric field in a horizontal direction rather than the vertical direction used previously. In this way he was able to note the deflection of the charged particle as it fell between the parallel plates forming the condenser. Thus he could initially measure the motion of the drop falling without an electric field and then measure its deflection when the field was applied. Observation times for individual drops were thus greatly reduced and were in fact photographed.[57]

Laby states that this method together with a photographic record used to measure the velocity of the drop *"has the advantage that departures from Stokes' equation, the presence of convection currents in the air, a change in the charge of the drop and any error in the direction of the field can be detected."*[58] Further, by using a photographic record Laby also attempted to eliminate the errors due to timing the fall of the drop.[59]

Laby obtained his photographs by intermittently illuminating the oil drops for an exposure time of 1/1500 sec every 1/25 sec, similar to photographing motion using a strobe light. His photographs showed a series of white dots set against a black background, these photographs produced an image that had been magnified by 12.[60]

The condenser plates were made of glass which was silver plated in the middle but not at the edges which act as an insulation. These plates were separated by a distance of 0.4985 cm.[61] A potential of 3000 V across the plates was obtained by rectifying an alternating current *"from the public supply"*[62] This produced an electric field of 6000 V/cm.

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[57] p 158 Laby & Hopper 1939
[58] p 244 Laby & Hopper 1941
[59] p 245 Laby & Hopper 1941
[60] p 261 Laby & Hopper 1941
[61] p 258 Laby & Hopper 1941
[62] p 258 Laby & Hopper 1941

Since the observation times were extremely short, Laby was not concerned with the evaporation of the oil. Instead he used oil which produced drops capable of carrying a large charge, castor oil and apiezon oil were his choices.[63] Drops with radii in the range 3 to 10 μm were required but atomisers produced much larger drops. Laby obtained the oil drops required by covering lightly the wires of a fine steel brush. The wires were then slowly pushed back and then suddenly released producing a shower of oil drops.[64]

Using a value for viscosity of air $\eta = 1830 \times 10^{-7}\,\mathrm{P}$, Laby obtained a value of $e = (4.8020 \pm 0.0013) \times 10^{-10}\,\mathrm{e.s.u.}$ When Laby applied the same value for viscosity of air to Millikan's data, a value of $e = 4.7992 \times 10^{-10}\,\mathrm{e.s.u.}$ was obtained.[65] The X-ray method for determining charge quoted by Laby was
$e = (4.8044 \pm 0.0007) \times 10^{-10}\,\mathrm{e.s.u.}$[66]

Thus Laby believed that finally the two methods for determining e were reconciled and gave almost identical results.[67] However, Laby concludes that *"the main uncertainty in the value of e as found by the drop method is in the value for the viscosity of air."*[68] The value for e from the X-ray method does not suffer from this source of error.

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63 p 259 Laby & Hopper 1941
64 p 260 Laby & Hopper 1941
65 p 265 Laby & Hopper 1941
66 p 271 Laby & Hopper 1941
67 p 649 Laby 1942
68 p 270 Laby & Hopper 1941

8. Zeeman Effect

At the same time as Thomson and his associates at the Cavendish Laboratory were working with cathode rays and attempting to find the value of the fundamental unit charge carried by these rays, a Dutchman, Pieter Zeeman (1865-1943) was observing the effects that a magnetic field could produce on the plane of polarisation of emission spectral lines of various elements. The effect he discovered carries his name, the Zeeman Effect, and describes the phenomenon of the splitting of a spectral line into three or more components.

Pieter Zeeman was born in 1865 in Zonnemaire, Zeeland in the Netherlands, the son of a Lutheran minister. He was educated locally until he entered the University of Leide in 1885. By 1890 he had become an assistant to H.A.Lorentz with whom he was to later share the 1902 Nobel Prize for their work on magneto-optics. Zeeman was awarded his doctorate in 1893. From January 1897 until his retirement in 1935, Zeeman was associated with the University of Amsterdam where he became Professor in 1900. In 1908 he succeeded J.D.van der Waals as director of the Physical Institute.

In 1854, Michael Faraday found that a relationship existed between light and magnetism. He succeeded in demonstrating that the plane of polarisation of polarised light is rotated when the light is passed through a piece of glass which has been placed in a magnetic field. [1] This phenomenon has been termed by Zeeman as the Faraday Effect. [2] For the remainder of his life Faraday continued to investigate the relationships between light, electricity and magnetism. In fact the last piece of experimental work carried out by Faraday was an attempt to detect the effects of a magnetic field on the line spectrum of a flame. In an article on Faraday, Maxwell

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1 p 24 Zeeman 1913 and p 244 Macmillan Dictionary of History of Science
2 p 24 Zeeman 1913

states " *in 1862, he (Faraday) made the relationship between electromagnetism and light the subject of his very last experimental work. He endeavoured but in vain, to detect any change in the lines of the spectrum of a flame when this flame is acted on by a powerful magnet."*[3]

In another biography on Faraday, Bence Jones (quoted in Zeeman's paper of 1897) gives a brief account of Faraday's experiment. "*Steinheil's apparatus for producing the spectrum of different substances gave a new method by which the action of magnetic poles upon light could be tried. In January (1862) he made himself familiar with the apparatus, and then he tried the action of the great magnet on the spectrum of chloride of sodium, chloride of barium, chloride of strontium and the chloride of lithium."*[4] In March of that year, using 10 pairs of voltaic batteries for the electromagnet, Faraday found that *"the colourless gas flame ascended between the poles of the magnet, and the salts of sodium, lithium etc. were used to give colour. A Nicols's polariser was placed just before the intense magnetic field, and an analyser at the other extreme of the apparatus. Then the electromagnet was made and unmade, but not the slightest trace of effect on or change in the lines in the spectrum was observed in any position of polariser or analyser. Two other pierced poles were adjusted at the magnet, the coloured flame established between them, and only that ray taken up by the optic apparatus which came to it along the axis of the poles i.e. in the magnetic axis, or line of magnetic force. Then the electromagnet was excited and rendered neutral, but not the slightest effect in the polarised or unpolarised ray was observed."*[5]

It should be noted that Faraday was working 38 years prior to Zeeman's discovery of changes in spectral lines of vapour exposed to strong magnetic fields. Also this particular biography was written some 16 years before Zeeman's discovery. One wonders whether Faraday would have been successful in this area of

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[3] p 74 Pais 1986
[4] p 236 Zeeman 1897, Vol 43
[5] p 236 Zeeman 1897, Vol 43

experimentation had he had equipment such as the Rowland grating which became available in 1880s.

Prof. Tait in 1875 published a paper *"On a Possible Influence of Magnetism on the Absorption of Light and some correlated subjects"*, in which he states *"The explanation of Faraday's rotation on the plane of polarisation of light by a transparent diamagnetic requires, as shown by Thomson (Lord Kelvin), molecular rotation of the luminiferous medium. The plane polarised ray is broken up, while in the medium, into its circularly polarised components, one of which rotates with the aether so as to have its period accelerated, the other against it in a retarded period. Now, suppose the medium to absorb one definite wavelength only, then - if the absorption is not interfered with by the magnetic action - the portion absorbed in one ray will be of a shorter, in the aether of a longer, period than if there had been no magnetic force; and thus what was originally a single dark absorption line might become a double line, the components being less dark than a single one."*[6]

This theoretical paper predicted the Zeeman Effect on absorption spectra which was observed 21 years later. In 1885 and 1886 M. Fievez carried out a number of experiments on the effects of magnetic fields on spectral lines. Unfortunately his results were inconclusive but *"he has observed with a flame in a magnetic field not only widening but reversal and double reversal of the lines of the spectrum."*[7]

John Kerr (1824-1907), discovered, in 1876, the second magneto-optic effect. He found that when plane polarised light was reflected from the poles of a magnet, the plane of polarisation of this reflected light was perpendicular to the plane of polarisation of the incident light. Zeeman referred to this phenomenon as the Kerr Effect.[8] However in modern Physics the Kerr Effect refers to the phenomenon in which a long bipolar molecular liquid experiences birefringence in the presence of an

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6 p 237 Zeeman 1897, Vol 43
7 p 238 Zeeman 1897, Vol 43
8 p 331 Whittacker 1951

electric field. Birefringence refers to the ability of some materials to have one refractive index for light plane polarised in one direction and another refractive index for light plane polarised perpendicular to the first.

Zeeman was actually investigating the phenomenon first observed by Kerr when Zeeman decided to deviate from this research and study the effects on emission spectra of a magnetic field. When Zeeman started his work on the effects of magnetic fields on spectral lines, he was unaware of the previous work in this area. However, after his first negative results, Zeeman was made aware of Faraday's work in this area. Zeeman states in his paper of 1897 *"If Faraday thought of the possibility of the above mentioned relation, perhaps it might be yet worthwhile to try the experiment again."*[9] Which is precisely what he did and obtained the results which are now referred to as the Zeeman Effect and was the third magneto-optic effect.

Part of Zeeman's success lies in his use of a newly acquired Rowland grating. In 1882 Henry Rowland at the Johns Hopkins University developed a machine which was capable of producing fine equidistant gratings on concave mirrors. This machine could place 400-800 lines per mm with a separation accuracy better than 1/400 th of a mm.[10] Zeeman used a "*Rowland grating with a radius of 10 ft and with 14,938 lines per inch"*[11] (i.e. 598 lines per mm) to analyse the light spectrum under observation.

To produce a sufficiently strong magnetic field, Zeeman employed a Ruhmkorff coil. A Ruhmkorff coil was a greatly improved version of an induction coil and could produce a magnetic field of approximately 10 kilogauss or approximately 1 Tesla.[12] Zeeman described it as producing a "*magnetising current which was in most of the cases 27Amps and could be raised to 35Amps."*[13]Finally the spectra were observed using a micrometer eyepiece with a vertical cross wire. Zeeman then placed a

[9] p 226 Zeeman 1897, Vol 43
[10] p 75 Pais 1986
[11] p 227 Zeeman 1897, Vol 43
[12] p 76 Pais 1986 and p 4 Segre 1980
[13] p 226-7 Zeeman 1897, Vol 43

Bunsen burner between the poles of the electromagnet and *"a piece of asbestos impregnated with common salt was put in the flame in such a manner that the two D-lines were seen as narrow and sharply defined lines on the dark ground. If the current was put on, the two D-lines were distinctly widened. If the current was cut off they returned to their original position."*[14]

After observing a widening of the lines in an emission spectrum of sodium, Zeeman now attempted to observe whether absorption spectra were similarly effected by a magnetic field. Zeeman placed a water cooled porcelain tube containing a piece of sodium over a bunsen burner, heating it until some of the sodium had vaporised. Zeeman stated that "*the absorption lines are rather sharp over the greater part of their length.*[15] When he applied the magnetic field, Zeeman found "*the lines widened and are seemingly blacker."*[16] Zeeman could repeat this until all the sodium had vaporised. He notes "*the disappearance of the sodium is chiefly attributed to the chemical action between it and the glazing of the tube"*.[17] In his later experiments he used unglazed porcelain tubes.

Zeeman originally thought to explain this broadening phenomenon by using explanations developed by Maxwell and Kelvin. This assumes *"that in a magnetic field a rotating motion of the aether is going on, the axis of rotation being in the direction of the magnetic forces and if the radiation of light may be imagined as caused by the motion of the atoms, relative to the centre of mass of the molecule (in circular orbits) then the period ... will be determined by the forces acting between the atoms, and then deviations of the period to both sides will occur through the influence of the perturbing forces between aether and atoms."*[18]

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14 p 227 Zeeman 1897, Vol 43
15 p 228 Zeeman 1897, Vol 43
16 p 228 Zeeman 1897, Vol 43
17 p 228 Zeeman 1897, Vol 43
18 p 230-1 Zeeman 1897, Vol 43

Zeeman next successfully applied Lorentz's theory to this phenomenon. This theory assumes *"that in all bodies small electrically charged particles with a definite mass are present, that all electric phenomena are dependent upon the configuration and rotation of these ions. Then the charge, configuration and motion of the ions completely determine the state of aether. The said ion, moving in a magnetic field experiences mechanical forces and these must explain the variation of the period."*[19]

When Zeeman communicated his findings to Lorentz, Lorentz suggested methods by which to calculate the motion of these ions, as well as suggesting that if his theory was applicable then *"the edges of the lines of the spectrum ought to be circularly polarised"* and *"the amount of widening might then be used to determine the ratio between the charge and mass"* of the *"particle giving out the vibrations of light"*.[20]

In 1895 Lorentz reformulated his 1892 paper in which he produced an atomistic interpretation of the Maxwell equations in terms of charges and currents carried by fundamental particles which he called ions. These ions were later, in 1899, called electrons. Lorentz introduced the assumption that an ion with the charge e and velocity v is subject to a force K such that $\tilde{K} = e(\tilde{E} + \tilde{v} \times \tilde{B})$ where E and B are the electric and magnetic fields respectively. This force K was later called the Lorentz force.[21]

The Zeeman effect was one of the first applications of this new force. In addition to the Lorentz force, it was considered that these ions were also bound by harmonic forces, which Zeeman described mathematically by assuming that the ion is vibrating in the x-y plane and a uniform magnetic field is applied perpendicular to the plane of vibration. In this situation, the equations representing the forces acting on this ion of mass m and charge e are:-

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19 p 231-2 Zeeman 1897, Vol 43
20 p 232 Zeeman 1897, Vol 43
21 p 76 Pais 1986

$m\frac{d^2x}{dt^2} = -k^2x + eB\frac{dy}{dt}$ and $m\frac{d^2y}{dt^2} = -k^2y + eB\frac{dx}{dt}$ where k is a constant.

The terms $-k^2x$ and $-k^2y$ refer to the elastic forces acting on the ion causing it to return to its equilibrium position and the terms $eB\frac{dy}{dt}$ and $eB\frac{dx}{dt}$ refer to the mechanical force due to the magnetic field.

If no magnetic field is applied, B=0, then the period for the vibration of the ion would be $T = \frac{2\pi\sqrt{m}}{k}$. Now if a magnetic field is applied, the period for vibration changes to $T' = \frac{2\pi\sqrt{m}}{k}\left(\pm\frac{eB}{2k\sqrt{m}}\right)$. This expression gives two periods of vibration and hence two possible frequencies for the light that may be emitted.[22] These three periods would later account for the triplets occurring in the Zeeman Effect. In modern terminology the change in frequency is given by

$$\nu = \pm\frac{\mu_B|\tilde{B}|}{h}$$

where μ_B (the Bohr magneton) $= 9.2732 \times 10^{-24}\,J/T$

h (Planck's constant) $= 6.6261 \times 10^{-34}\,Js$

$|\tilde{B}|$ = absolute value of the magnetic field strength

The Bohr magneton $\mu_B = \frac{e\eta}{2m_e}$ is the magnetic moment of the spinning electron. Thus the energy of this orbiting electron in a magnetic field is $E = \bar{\mu}_B \cdot \bar{B}$ and if the magnetic moment of the electron and the applied magnetic field are aligned, the energy of this electron becomes $h\nu$.

Lorentz's theories enabled Zeeman to utilise the widening of the spectral lines of sodium to determine the charge to mass ratio of these vibrating ions. Zeeman found that when he applied a magnetic field of 10^4 cgs units or 1 Tesla, the spectral lines were widened by about "*1/40 of the distance between the lines.*"[23] Lorentz's theory suggests that when the difference between the period of vibration in a magnetic field

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22 p 232-3 Zeeman 1897, Vol 43

23 p 230 Zeeman 1897, Vol 43

and the period of vibration without a magnetic field could produce the following relationship

$$\frac{T_M - T}{T} = \frac{e}{m}\frac{BT}{4\pi}$$

where T = natural frequency of vibration

T_M = period of vibration in a magnetic field

B = magnetic field strength in cgs-emu units.

By applying these measurements of spectral broadening to the expressions of the periods of vibration of the ions, Zeeman found that the e/m ratio was about $10^7\,\mathrm{emu/g}$[24] which compares well to the modern value of $1.76\times10^7\,\mathrm{emu/g}$ (i.e. $1.76\times10^{11}\ \mathrm{C/kg}$). This result was very similar to that published by J.J.Thomson later in 1897 (see chapter 5).

A similar analysis is found in J.J.Thomson's book *"Corpuscular Theory of Matter"* (pages 34-39). However, Thomson uses the conical pendulum as the model on which to base his equations. Further Thomson made reference to Zeeman's results in his papers of 1898 and 1899. In the first paper Thomson states *"Professor H.A.Lorentz has shown that the charge on the ions whose motion causes those lines in the spectrum which are affected by the Zeeman effect is of the same order as the charge on a hydrogen ion in electrolysis."*[25]

In his second paper, Thomson states that *"A reason for believing that there are many more corpuscles in the atom than the one or two that can be torn off, is afforded by the Zeeman effect. The ratio of mass to charge, as determined by this effect, is of the same order as that we have deduced from our measurements on the free corpuscles, and the charges carried by the moving particles, by which the Zeeman effect is explained, are all negatively electrified. ... As however, there are a considerable number of lines in the spectrum which show Zeeman effects*

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24 p 235 Zeeman 1897, Vol 43

25 p 545 Thomson, J.J. 1898

comparable in intensity, we conclude that there are a considerable number of corpuscles in the atom of the substance giving the spectrum."[26] Thus Thomson used these results to develop his *"plum pudding"* model of the atom which was thought to contain a diffuse positive charge neutralised by a number of negatively charged corpuscles or electrons.

In the latter part of his first 1897 paper, Zeeman attempted to prove the correctness of Lorentz's theory that this broadening was caused by the vibrating ions interacting with a magnetic field. Zeeman now used a polarising material which he placed between the sodium producing the spectrum and his eye piece. He could now analyse the relative polarisation between the upper and lower parts of the broadened sodium spectrum, he had not as yet seen the line resolve into three. According to theory the upper and lower bands would be plane polarised but at 90° to each other. Zeeman found that this was indeed the case, agreeing with Lorentz's predictions.[27]

Lorentz further predicted that spectral lines placed in a magnetic field should be split into either triplets or doublets according to whether the light is emitted in a direction perpendicular or parallel to the lines of magnetic force.[28] If the light is emitted perpendicular to the lines of magnetic force the light produced is linearly polarised with period $T + \delta T$ and $T - \delta T$ as well as light with period T. This gives rise to a triplet. The central line is polarised normal to the lines of magnetic force. If the light is emitted parallel to the lines of magnetic force then the original line splits into two components with period $T + \delta T$ and $T - \delta T$ and the light in this case is circularly polarised in opposite directions.[29]

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26 p 567 Thomson, J.J. 1899
27 p 235 Zeeman 1897, Vol 43
28 p 77 Pais 1986
29 p 34, 42 Zeeman 1913

Later in 1897 Zeeman set out to observe the splitting of spectral lines into doublets and triplets according to Lorentz's theory. Zeeman estimated that the strength of the magnetic field required to produce these distinct lines, as opposed to a general broadening of the spectral line would have to be large enough to separate the individual lines with a distinct dark band in between them. He estimated that to produce a triplet he required twice the magnetic field strength than that needed to produce a doublet.[30] In this experiment, Zeeman used cadmium to produce his spectral lines, but the rest of his equipment was similar to that already described earlier in this chapter.[31] Zeeman was able to report that the expected splitting of the blue line in the cadmium spectrum had occurred.[32]

Later that same year Zeeman produced a third paper in which he described his observation of a triplet of a line in the cadmium spectrum, he later made a similar observation for the sodium spectrum. For the third time that year, Zeeman used a completely different set of equipment for his experiments. In the course of this set of experiments, Zeeman also found that the plane of polarisation of light emitted from the central band was vertical, while the side bands emitted light polarised in the horizontal direction, thus supporting Lorentz's theory.[33] Finally at the end of this paper, Zeeman concludes that the e/m ratio of these charged ions is 1.60×10^{-10} measured in cgs units.[34] This seems a somewhat ridiculous value compared to his previous value for e/m which appears to be a misprint. In his 1913 publication "Magneto-optics", Zeeman quotes this value of e/m to be 1.6×10^{7} emu/g.[35] This later value is close to the modern accepted value quoted earlier in this chapter i.e. 1.76×10^{7} cgs units and is close to his first value of e/m, $10^{7}\,\mathrm{emu}/\mathrm{g}$.

[30] p 56 Zeeman 1897, Vol 44
[31] p 58 Zeeman 1897, Vol 44
[32] p 77 Pais 1986
[33] p 255 Zeeman 1897, Vol 44(II)
[34] p 256 Zeeman 1897, Vol 44(II)
[35] p 39 Zeeman 1913

According to Lorentz's theory, if the lines of magnetic force were directed towards the observer and the motion of the ion was clockwise, the period of the rotation increased if the ion was negatively charged, but decreased if the ion was positively charged. Zeeman concluded from his observations that when the lines of magnetic force were directed towards the observer, the right hand circularly polarised component of the doublet had a greater period than the original line, the ions causing the radiation of light must therefore be negatively charged.[36]

Zeeman had shown that not only was Lorentz's theory correct, but he went on to prove that the vibrating ions in the atom were negatively charged and had an e/m ratio similar to both cathode rays and $\beta-$rays. The latter two similarities would become more obvious during the next few years, as has already been discussed in chapter 5.

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[36] p 38 Zeeman 1913

9. Lorentz

The next part of the story in the development of the modern theories of the electron comes from Holland. At about the same time as Thomson and his collaborators in the Cavendish Laboratory were discovering some of the properties of the electron a quiet isolated Dutchman, H. A. Lorentz (1853-1928) was writing his theories which he based on the work of another Englishman, James Clerk Maxwell.

It was Lorentz, more than any other physicist of his day who married Maxwell's mathematical theories of electromagnetism to the empirical results from the Cavendish Laboratory and others from Germany and Austria. Lorentz went further by proposing his own theory of the electron which in turn led to the questioning and subsequent demise of the concept of the aether. Finally Lorentz's work anticipated many aspects of Einstein's Special Theory of Relativity. Thus in many ways Lorentz may be regarded as the bridge between the classical Newtonian physics of forces and macroscopic phenomena and the brave new world of modern relativistic quantum physics.

H. A. Lorentz's story can be told in a purely biographical or chronological manner but perhaps it would be better to take a specific area of his work, describing its development and final conclusion. Lorentz's story and the development of his theories are made up of as many intertwining and intermeshed threads as the complicated yet beautiful laces of the Dutch.

Lorentz was born in 1853 at Arnhem, a small town in eastern Holland. Although of humble origins (his father was a nurseryman) Lorentz's talents were recognised relatively early, since he was always at the top of his class during his school years. In 1870 Lorentz commenced his studies at the University of Arnhem where he wrote his thesis *"On the Reflection and Refraction of Light"*. While writing his thesis

Lorentz taught at the local high school. In December 1875 Lorentz was awarded his doctorate from the University of Leyden.

Lorentz's theory of electrons which had its origins in his doctoral thesis was developed over a number of years. Notably in 1892 when he applied his ideas to some optical phenomena, in 1895 when he introduced the Lorentz transformation which preceded relativity and finally, in 1896 when he used this model to explain the Zeeman effect (as has been discussed in the previous chapter).

Lorentz was appointed Professor of Theoretical Physics in 1878 at Leyden where he distinguished himself as a gifted teacher whose lectures were both lucid and inspiring, often incorporating the latest researches. As an accomplished linguist, Lorentz was able to communicate with a number of his foreign colleagues through their mutually published papers. He seemed to make little effort to meet his contemporaries, apparently content with disseminating and interpreting their findings as well as including his own.

Without diminishing the importance of many of Lorentz's contributions, this section will deal with only that aspect of Lorentz's work which led him to develop his theory of the Electron. The conception of this theory lay in Lorentz's doctoral thesis "*On the Reflection and Refraction of Light"* in which Lorentz made a critical investigation of Fresnel's theory of light and introduced Maxwell's electromagnetic theory of light. [1]

9.1. The Aether

Before one can discuss the development of Lorentz's electron theory, some discussion must be made of the theoretical background within which this theory was developed. The most significant theoretical construct within which Lorentz's theories were developed was that of the aether. The concept of the aether had developed over the centuries and had different interpretations over this period. A more thorough

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1 p 48 De Haas-Lorentz 1957

discussion of the development of this concept of the aether may be found in E.Whittaker's "A History of the Theories of the Aether and Electricity".

In 1675, the Danish astronomer Olaf Romer (1644-1710) discovered that light was not transmitted instantaneously but required a certain amount of time to reach the earth. His conclusions were based on his observations of the eclipse of one of Jupiter's satellites. The Dutch astronomer Christian Huygens (1629-1695) attempted to provide a theoretical explanation for this discovery by assuming that light behaved as a wave. In particular he assumed that just as water waves ripple in concentric circles and sound waves form spherical regions of compressed and rarefied air, light must also be transmitted through some gaseous medium which pervaded and filled all space. This all pervading medium was the aether.

The aether was not a new concept. The term had been used by the Ancient Greeks and Romans to signify that part of space or air located far above the earth's surface. Descartes (1596-1650) used the term aether to denote a medium which had mechanical properties and occupied the entire universe except those spaces occupied by ordinary matter. Descartes seemed to conceive of the aether as a gas of tenuous particles. The particles comprising this aether were in constant motion.[2]

Isaac Newton (1642-1727) used an aether model to explain his theory of light. Newton believed that light was transmitted as particles travelling through the medium of the aether from the source of the light. He described the aether as "*a substance in which bodies move and float without resistance and which therefore has no inertia, but acts by other laws than those that are mechanical."*[3] This particulate theory, published after Huygens' proposals, was generally adopted as the better explanation of light propagation until the early Nineteenth Century.

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[2] p 5-6 Whittacker 1951
[3] p 144 Doran 1975

Thomas Young (1773-1829) rejected Newton's corpuscular theory of light in 1800 when he published his first paper on light. Young argued that the corpuscular theory failed to adequately explain the phenomena of the simultaneous reflection and refraction of a light beam at the interface between two media. Young's later work, particularly on the interference of light reinforced his earlier ideas. As with all major concepts in Physics, the ultimate acceptance of a wave theory of light occurred after both lengthy and vigorous debates. By 1818 Young had determined that light must be transmitted, not as a longitudinal or compression wave as had previously been proposed, but was a transverse vibration of the luminiferous aether. [4]

Young's contemporary, Augustin Fresnel (1788-1827) immediately accepted Young's notion of light as a transverse wave. Fresnel had experimented with light phenomena such as diffraction, interference and polarisation. By 1821 he was engaged in observations of the double refraction that occurs to light transmitted through a crystal of calcite. The current view explained this double refraction in terms of the crystal containing two types of luminiferous aether, one for transmission of ordinary waves and one for the transmission of extraordinary waves. Fresnel suggested that the double refraction was due to two velocities of light in the crystal travelling through a simple aether. The two velocities were thought to be the two solutions of a quadratic equation derived from Fresnel's theories. Further, Fresnel's theory suggested that the aether behaved more like a solid than a gas as was the current view. The solid properties provided the aether with the ability to twist and distort in response to external forces as well as possessing the elastic properties required to resist these forces. [5]

Fresnel used Young's earlier suggestions that the refractive ability of transparent bodies depends on the concentration of the aether within it. This aethereal density was proportional to the square of the refractive index of the material. The refractive

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[4] p 100-115 Whittacker 1951
[5] p 115-120 Whittacker 1951

index of the material was defined as $n = {}^{c}\!/_{v}$ where v is the velocity of light in the material and c is the velocity of light in vacuo. Now the aethereal density of interplanetary space and that of a medium are connected by the relationship $\rho_1 = n^2\rho$ where ρ is the aethereal density of interplanetary space and ρ_1 is the aethereal density of the medium.

Further, Fresnel assumed that when a body is in motion, the part of the aether within it is carried along while the remainder remains at rest, i.e. the density of the aether carried along with the motion of the body is $\rho_1 - \rho$ or $(n^2 - 1)\rho$ while the aethereal density ρ remains at rest. Now within this moving body the centre of gravity of the aether moves forward with a velocity of $\frac{n^2-1}{n^2}u$ where u is the velocity of the body. Now if light is travelling through this body, the absolute velocity of light within the body and relative to the interplanetary aether is $v' = v + \frac{n^2-1}{n^2}u$.[6] This relationship was confirmed by the brilliant experiments carried out by A.Fizeau (1819-1896) in which he determined the velocity of light in different media.

This analysis had been developed by Fresnel to explain the phenomenon of aberration. In this phenomenon there is an observed seasonal shift in the position of stars due to the earth's orbital motion. The aberration of light was discovered in 1728 by J.Bradley (1693-1762) who detected that an annual parallax occurred in some fixed stars when they appeared near the zenith. It was from these observations that the assumption of light being propagated in space with a finite velocity was developed. Light was thought to be transmitted through a stationary aether which was not affected in any way by the earth's motion.[7]

In January 1823, Fresnel presented a theory of reflection and refraction based on Young's concept that reflection and refraction were due to the differences in the inertia of the aether in the different media. This inertia, Fresnel thought was

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[6] p 109-110 Whittacker 1951
[7] p 269-270 Richardson 1914

proportional to the inverse square of the velocity of light in that medium. [8] He then assumed that the energy carried by both the reflected and refracted light would be equivalent to the energy of the incident light. From this basis, Fresnel was able to give an accurate theory of the intensity of the transmitted and reflected intensities as a function of the angle of incidence and polarisation. This had previously been suggested by D.Brewster (1781-1868) who had also observed and described a number of other phenomena involving both reflected and polarised light. Fresnel's mathematical model demonstrated the relationships between the planes of polarisation, energies, intensities and amplitudes of reflected waves. [9] The totality of this aspect of Fresnel's work formed his theory of reflection on which Lorentz would later base his own work.

In 1846 the notion of a stationary aether , unaffected by the motion of objects in it was challenged by G.Stokes. Stokes proposed that the aether was not ordinary matter but some form of perfectly continuous substance which had both solid and liquid properties. [10] Stokes assumed that all the aether contained in the body moved with the body. This led to the assumption that as the body moved through the aether, the aether entered the body at the front, was immediately condensed and later expelled from behind and immediately rarefied i.e. the aether was dragged by the moving body. The actual nature of the aether and its properties were to be of much debate for the remainder of the Nineteenth Century. The major physical theories developed in the second half of the Nineteenth Century were all based on some notion of the properties of the aether.

It was against this background that Lorentz wrote his doctoral thesis which he publicly defended on 11th December 1875 at Leyden. Lorentz commenced his thesis with a critical investigation of Fresnel's theory of light. While Lorentz could accept Fresnel's theory of light transmitted through an elastic aether as a transverse

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[8] p 123 Whittacker 1951
[9] p 125 Whittacker 1951
[10] p 159-60 Doran 1975

vibration, Lorentz became aware of a major problem with this theory. When vibrations are transmitted through an elastic aether two types of vibrations are established, longitudinal and transverse. While Fresnel's theory could adequately explain the transverse transmissions through the aether, it gave no reasons for the total absence of light with any longitudinal vibrations in this aether.

Lorentz found that the solution to this shortcoming in Fresnel's theory lay in the work of an Englishman (or rather a Scot), James Clerk Maxwell (1831-1879) who had three years previously published his "*Treatise on Electricity and Magnetism"*. In this classical work, Maxwell explained that light waves resulted from oscillations of electric and magnetic fields. He derived his famous wave equations which not only explained the existing observations but would later predict such phenomena as the rotation of the plane of polarisation of light in a magnetic field.

At the end of his thesis, Lorentz anticipated the development of Maxwell's ideas into a unification of electromagnetic theory and molecular theory into an electron theory of matter. Lorentz states "*if it is true that light and radiant heat consist of electric vibrations, it is natural to suppose that in the molecules of the bodies, which generate these vibrations in the surrounding medium, electrical movements also take place which increase in intensity with the increase in temperature. ... Finally, the theory of light should show how the electrical motions in question are related to the physical and chemical conditions of matter."*[11]By 1878, Lorentz had developed the model that inside each molecule there existed charged harmonic oscillators and that the aether in the intermolecular spaces retains the properties it possessed in a vacuum. [12] This model would form the basis of his electron theory. Lorentz's electron theory would now gradually evolve over the next two decades, as he continuously returned to the ideas expressed and discussed in his thesis, refined them and developed them. As

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[11] p 54 De Haas-Lorentz 1957
[12] p 461-2 Mc Cormmach 1970

he thus worked, Lorentz also explored and developed other ideas which were unrelated to his electron theory.

In 1886 Lorentz concluded that Fresnel's concept of a stationary aether provided a far better model than Stokes' concept of an aether dragged along by a moving object. Lorentz had come to this conclusion from his own studies on the aberration of the light emitted by distant stars. Within five years Lorentz concluded that Maxwell's concept of a field or contiguous action to explain electrical and magnetic phenomena separated in space was far superior to the previously held notion of action at a distance. Both these conclusions while apparently unrelated were instrumental in allowing Lorentz to formulate his electron theory. [13]

The concept of action at a distance had been developed from the time of Gilbert's work on magnetism and was later extended to the phenomena related to static electricity (both were discussed in Chapter 1). Newton introduced a revolution in thought by applying this concept to an explanation of gravitational attraction. While it was well known that planets move through their orbits, the mechanisms by which objects fell to earth and the planets continued to move had not been well explored at this time. The action at a distance was now being applied to extremely large objects and not just to the smaller objects. By the late Seventeenth and early Eighteenth Century it had been observed that the three phenomena of electricity, magnetism and gravity produced an action on a body without any direct contact between the objects concerned. The concept of the aether was developed to enable such actions as attraction and repulsion to be explained in terms of a transmitting agent. Newton, in a letter written in 1675 to Henry Oldenburg, makes a speculative suggestion as to the nature of this aether "*it is to be supposed therin that there is an aethereal medium much of the same constitution with air, but far rarer, subtiler, and more strongly elastic . . . for the electric and magnetic effluvia, and the gravitating principle, seem to argue such variety."*[14] While debates raged over the nature of this

[13] p 402 Mc Cormmach 1970
[14] p 134-5 Jammer 1957

transmitting agent or aether, another set of debates started concerning this apparent action at a distance.

In the early Eighteenth Century, Newton proposed his action at a distance model to explain gravitational attraction. In this model the action (i.e. the attractive force or even a repulsive force) was transmitted, not by direct contact but, instantaneously or at least at an extremely large velocity so as to appear instantaneous. This model was accepted at this time in England. However in Europe, Leibniz (1646-1716) became Newton's greatest critic on this matter. Leibniz could not accept the notion of a vacuum or empty space, even after a vacuum could be produced in Torricelli's tube or by von Guericke's air pump (see Chapter 2). Further, Leibniz believed that matter could act on matter only by contact in accordance to the laws of mechanics. Thus, Leibniz concluded that the void was not completely empty and contained some material substance. [15] Newton's model of action at a distance was ultimately accepted in terms of corpuscles colliding in the aether. [16]

R.Boscovich (1711-1787), a Yugoslavian Jesuit priest, was the next to attempt to explain the attractive and repulsive forces of electricity and magnetism and the phenomenon of gravitational attraction at seemingly infinite distances. Boscovich was born in Dubrovnik in 1711, after entering the Society of Jesus (Jesuits) spent most of his life in Italy and France. By 1740, he was appointed Professor of Mathematics at the Collegium Romanum. He visited France and in 1760 he travelled to England, visiting Cambridge, Oxford and London where he met Benjamin Franklin. As a result of his travels and the wide circulation and respect for his work, when in 1773 the Jesuit Order was suppressed by Papal Decree, Boscovich continued to lecture and write at universities until his death in Milan in 1787.

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[15] p 160-163 Hesse 1961
[16] p 167 Hesse 1961

In 1758 he published "Philosophiae Naturalis Theoria" in which he proposed that the force exerted between two point particles was a continuous function of the distance between them. He suggested that at extremely short distances this force was repulsive and alternated between attractive and repulsive as the distance increased until at distances comparable to ordinary objects the force became attractive and tended to obey the inverse-square law. Unfortunately, Boscovich's ideas failed to explain the repulsive effects of ordinary magnetised materials. [17]

During the next fifty years a number of other proposals were suggested to explain these attractions and repulsions. As seen earlier, some suggested that these phenomena resulted from the passage of a single fluid or even a two fluid hypothesis (see Chapter 1). However, despite its apparent limitations, the concept of a force being transmitted instantaneously or acting at a distance became the accepted model for these phenomena.

9.2. Field Theories

Field theories were developed in the Nineteenth Century and are now an integral part of modern physics. The concept of the field was initially developed to provide a mechanism by which energy could be transported. The field was material in nature and possessed certain properties which allowed this propagation to take place. In modern physics the field is no longer explained in terms of matter. Field theories are found in most branches of modern physics and are essential in some areas such as quantum electrodynamics.

By the early Nineteenth Century, it became more evident, as a result of new discoveries, that the notion of a force acting at a distance could no longer adequately explain the physical phenomena for which it had been developed. As was previously mentioned in Chapter 1, in 1820 Oersted had shown that a magnetised metal needle reacted, i.e. changed its position when a current flowed

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[17] p 164 Hesse 1961

through a nearby wire. This was possibly the first empirical evidence to suggest that action at a distance can produce forces other than mere attraction or repulsion. A short time later Ampere showed that not only does a wire with an electric current affect the direction of a magnet, but that two wires carrying currents can also affect each other.

Finally, Faraday as a result of his work on electromagnetic induction, concluded that the phenomenon of action at a distance actually required a medium for propagation. Faraday's work had led him to make three conclusions, all of which seemed, to him, to indicate the existence of an active medium:-

1) the induction of an electric charge between conductors across an insulating medium depends quantitatively on the nature of the insulator.
2) If the insulator is cut and the parts separated, the opposite charges appear on the two separated surfaces.
3) The lines of induction, as well as for magnetism, are curved.[18]

Nineteenth Century thought now turned to Leibniz's old notions and the beginnings of the concept of a field developed. Leibniz's requirement for a transmission medium through which the cause and effect of a mechanical or physical action could occur reinforced the need for an aether which occupied evacuated space. Later, to account for his conclusions, Faraday independently proposed the notion that a medium must exist which allowed for magnetic interaction to take place. By 1846, Faraday had proposed that physical phenomena propagating from a source should be considered in relation to the space or medium surrounding this source. This simple statement by Faraday was the beginning of the modern concept of a field.[19]

A field may be regarded as a mathematical model in which a region of space may be characterised by a set of quantities which are functions of that space. These

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[18] p 198-9 Hesse 1961
[19] p 163 Doran 1975

quantities can then be expressed in some manner to describe this region of space and the phenomena occurring within it.[20] In 1856 Lord Kelvin developed an early field theory in his attempts to find a relationship between matter and the aether. Lord Kelvin was attempting to explain mathematically the results obtained by Faraday in his experiments on magneto optics (see chapter 8). Lord Kelvin developed the notion of a mechanical model, expressed mathematically, to demonstrate the possibility of the existence of such a phenomenon.[21] This approach motivated such scientists as Maxwell to explore this issue further.

In 1861 Maxwell developed a series of equations which he interpreted as a mechanistic model for Faraday's field. He suggested that the aether consisted of cellular vortices which became distorted as a result of the motion of an electric current. The kinetic and potential energies of the medium correspond to the magnetic and electric energies, respectively. Maxwell developed, mathematically, Faraday's ideas that the lines of force tend to contract longitudinally and to expand laterally. Maxwell's explanation suggested that in any magnetic field the medium is in rotation about the lines of magnetic force and may therefore be regarded as a vortex.[22]

Maxwell then obtained the equations of motion of his system of vortices and particles. In so doing he assumed that the medium was divided into cells made up from a stratum of particles which were electric. He further assumed that the cells were elastic and were rotating within a medium which exerted a stress similar to pressure as well as a longitudinal tension directed along the lines of the axis of rotation.[23] After obtaining his equations of motion for the system of particles and cells, he attempted to determine the rate of propagation of the disturbances through this system.

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20 p 192 Hesse 1961
21 p 135-7 Doran 1975
22 p 247-8 Whittacker 1951
23 p 250 Whittacker 1951

Maxwell invoked the concept of the aether stating that the "*aether is a material substance of a more subtle kind than visible bodies, supposed to exist in those parts of space which are apparently empty."*[24] Maxwell's theory stated *"the energy of electrification resides in the dielectric medium whether that medium be solid, liquid or gaseous, dense or rare or even what is called a vacuum, provided it be still capable of transmitting electrical action."*[25] Maxwell's electromagnetic field theory may be expressed mathematically by a set of four differential equations which relate the relative motions of the magnetic and electric fields to the medium through which transmission occurs, stated in modern terminology as:-

$$\mathrm{div}\overline{E} = \rho/\varepsilon_0 \qquad \mathrm{div}\overline{B} = 0$$

$$\mathrm{curl}\overline{E} = -\partial\,\overline{B}/\partial\,t \qquad c^2(\mathrm{curl}\overline{B}) = \partial\,\overline{E}/\partial\,t + \bar{j}/\varepsilon_0$$

In 1888 Hertz had shown experimentally that the existence of electromagnetic waves could be produced by oscillating electric charges as had been predicted by Maxwell's equations. For Hertz's contemporaries this discovery confirmed that light was a form of electromagnetic wave and confirmed also the reality of the aether.[26]

9.3. Lorentz's Theories

It was against this background of discussion and debate as to the nature of the aether and the mechanism by which forces or actions were transmitted through space, that Lorentz, in 1892 developed and published his electron theory in " La theorie electromagnetique de Maxwell et son application aux corps mouvant". Lorentz regarded the concept that electromagnetic actions were propagated through the aether at the speed of light as being the single most important aspect of Maxwell's theory.[27] Consequently, he regarded the contemporary German theories of instantaneous action at a distance as being erroneous. Lorentz, however, did not

24 p 155 Hirosige 1969
25 p 154 Hirosige 1969
26 p 156 Hirosige 1969
27 p 402 Mc Cormmach 1970

accept the British concept of a turbulent aether, preferring to use the notion of a stationary aether.[28]

Lorentz attempted to separate matter from the aether by supposing that matter was made from an aggregate of microscopic particles and that the aether pervades all intermolecular space. It could be assumed that the electromagnetic field could be borne by this intermolecular aether.[29]

Lorentz introduced his electron theory by stating six hypotheses from which he would develop his theory:-

1) Charged particles have inertial mass and weight to which the laws of motion may be applied. The aether exists in the space occupied by these particles or by uncharged molecules. An interaction can occur between the aether and the electric charges but not with ponderable molecules.
2) The electric energy of an electromagnetic system is identified as the system's potential energy.
3) Charged particles behave as rigid bodies.
4) The total electric current is related to the velocity of a given point charge, i.e. the material contribution to the displacement current in a dielectric is an infinitesimal translation of electric particles and a current in a conductor is the real migration of these particles.
5) The kinetic energy of the system is determined by the magnetic energy of the system.
6) The location of each point of the aether participating in the electromagnetic motions of the system is determined by the positions of all of the charged particles and by all the dielectric displacements of the particles.[30]

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[28] p 500 Schaffner 1968
[29] p 159 Hirosige 1969
[30] p 463-5 Mc Cormmach 1970

These six hypotheses became the basis from which Lorentz developed the equations of motion of these charged particles from the magnetic forces acting on them and their dielectric displacements in this aether. These hypotheses also incorporated Maxwell's four equations to which Lorentz added a fifth equation which gave an expression for the total force acting on these particles. This force equation included an expression for the electrostatic forces as well as an expression for the forces acting on a moving charged particle as it progresses through the aether under the influence of a magnetic field thus providing a unification of the electrostatic and electrodynamic components of action on a particle. This equation, known as the Lorentz force can be stated in modern terminology as:-

$$\overline{F} = q(\overline{E} + \overline{v} \times \overline{B}).$$

Using these five equations, Lorentz was initially able to derive Fresnel's drag co-efficient (discussed earlier in this chapter). This theory enabled Lorentz to explain the apparent dragging of the aether by the confirmation of moving charged bodies and a stationary aether. The main objection to this stationary aether assumption came from the notion that any moving body in this stationary aether should experience some form of aether wind. The aether wind could be explained as the apparent movement between the aether and the moving object in much the same way as an athlete experiences a wind from the surrounding still air when sprinting. A metaphor commonly used at the time was of a wind blowing freely through a grove of trees.

Until this time an aether wind had never been observed. In fact, the famous Michelson-Morley experiment of 1887 seemed to indicate that there was no relative motion between the earth and the aether, in contradiction with Lorentz's assumption. The accuracy of the Michelson-Morley experiment was such that even extremely small differences in the relative motion could have been detected. As a result of these observations Lorentz was forced to defend his stationary aether proposition. In

1895, Lorentz developed a treatise on the influence of the earth's motion on electrical and optical phenomena.[31]

In this paper, Lorentz abandoned the mechanical derivation of his equations. Instead he used his basic equations as a hypothesis. Lorentz further abandoned the mechanical basis of his theory by concluding that the aether was not required to obey Newton's laws of motion. Specifically, while the aether may exert a force on an object, no force may act on it. This was Lorentz's first recorded departure from the accepted laws of mechanics. During this very productive period of his life, Lorentz also developed a set of transformations which could be utilised when measuring the relative length of objects undergoing very high speed motion. These Fitzgerald-Lorentz transformations would also be developed independently and utilised by Einstein in his Special Theory of Relativity.

The treatise of 1895 enabled Lorentz to incorporate a more complete explanation of three optical effects:-

1) the aberration of light
2) the change in the speed of light observed in Fizeau's' experiment
3) the Doppler effect for light.

The aether wind effects were far more elusive, while Lorentz reintroduced his contraction transformation and employed several other transformations to this problem, he nevertheless still failed to explain an absence of aether wind.[32]

During the next four years Lorentz concentrated on developing an electromagnetic theory of matter in which he viewed matter consisted of charged particles interacting with an electromagnetic field. Lorentz based this work on the ideas first proposed by W.Weber (1804-91) in 1846 and developed by Clausius, Riemann and Carl

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31 p 466-8 Mc Cormmach 1970
32 p 469-71 Mc Cormmach 1970

Neumann. The theories of electromagnetism thus developed introduced a number of departures from the contemporary mechanical theories of this time. These included:-

1) The replacement of Newton's action at a distance with the propagation of electric force at a finite velocity (i.e. the velocity of light).
2) Electrodynamic forces did not obey Newton's law of action and reaction.
3) An upper limit for the possible relative velocities particles should exist.
4) Electrodynamic phenomena required a symmetry in time and space descriptions.
5) A separate form of energy conservation suited specifically to electrodynamics.
6) The apparent mass of electric particles was velocity dependent. [33]

In 1899, Lorentz published his electron theory in which he now called his charged particles electrons (a term which had already been used to describe a unit electric charge, see Chapter 2). He redeveloped what is now called the Lorentz transformations, predicting a contraction in the direction of motion, and suggested that it applied to all matter and not just to the position and shapes of the electrons. He suggested that the velocity dependence of mass could also be applied to all matter and not just the electrons moving through the aether as had been suggested earlier. Lorentz further suggested that forces could be determined utilising Maxwell's continuous field equations but the motion of the electrons moving as a result of these forces obeyed Newton's mechanical laws. [34] It was these departures from the accepted concepts, extensions of previously suggested ideas and attempts to synthesis the laws of mechanics and electrodynamics which now started to shake the foundations of classical physics.

In fact, Lorentz derived not only the length contraction formula but also the entire set of Lorentz equations by determining the manner in which the interatomic interactions

[33] p 472 Mc Cormmach 1970
[34] p 473-4 Mc Cormmach 1970

which determine the physical properties of a body, are affected by the motion of this body through a stationary aether. One could go so far as to say that Lorentz developed his equations from "first principles". The Lorentz transformations were later utilised by Einstein, in his Special Theory of Relativity. By assuming that the velocity of light was a constant and that the laws of physics took the same form in all inertial frames, Einstein was able to simply develop the Lorentz transformations from these two assumptions and with equal facility utilise them. [35] The Lorentz transformations, stated in modern terminology are:-

$$x' = \frac{x - vt}{\sqrt{1 - v^2/c^2}} \qquad y' = y \qquad z' = z \qquad t' = \frac{t - vx/c^2}{\sqrt{1 - v^2/c^2}}$$

Mass, once the epitome of an invariant property, was now no longer constant. It depended on the motion of the object , be it charged or uncharged. Within the context of his time Lorentz's theory was a radical departure from the concrete observable physics of his day. The theory was developed at the same time as J.J.Thomson was coming to terms with experimental results which indicated that cathode rays were particles (see Chapter 5)

As the electron moved within an atom at a velocity v, sometimes so high as to approach the velocity of light, this spherical electron would change its shape from a sphere into an ellipsoid in accordance to the length contraction formula of the Lorentz transformations. While Lorentz calculated that this electron would have a mass, he had not yet determined whether the mass was real in concrete terms, as particles, or whether the mass was the result of a mathematical construct in which the mass could be determined from the electromagnetic equations of Lorentz and Maxwell and did not exist in concrete terms. Essentially, Lorentz was unsure if an electron in an atom existed as a particle with a mass or if this property of mass was merely a mathematical property with no concrete physical significance.

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35 p 140-3 Pais 1982

Lorentz was fortunate in that the experimental results required to show that the atom housed subatomic charged particles which in some circumstances could be ejected at high speeds, was already available to him. By this time J.J.Thomson had already published his discovery that cathode rays were composed of negatively charged particles whose properties were independent of their source or the manner of their production. Zeeman had also made his discovery that spectral lines may be broadened or split in the presence of a perpendicular magnetic field (see chapter 8) Lorentz now had two pieces of evidence supporting his concept of the subatomic electron. The mass of this electron was real and calculated to be one thousandth that of a hydrogen ion. It would still be a number of years before Louis de Broglie would provide evidence to show that the electron was a wave, which in turn would lead to the concept of wave -particle duality.

Further work on the Zeeman effect produced spectral lines which could also be split into four or even six components, which was not predicted by Lorentz's theory. Lorentz attempted unsuccessfully to extend his theory to explain this phenomenon but it is essentially a quantum phenomenon. A final explanation for this splitting was provided in 1925 when Samuel Goudsmit (1902-78) and George Uhlenbeck (b1900) introduced the concept of electron spin and the spin quantum number.[36]

In 1904, Lorentz produced his final version of his electron theory in which he made the following hypotheses:-

1) A moving spherical electron becomes ellipsoid in shape as a result of the physical deformation described by the Lorentz transformation equations.
2) Non-electric forces are influenced by the motion between ponderable particles or between electrons and these particles.
3) The mass of an electron is electromagnetic in origin.
4) The influence of motion on the dimensions of electrons or ponderable particles is restricted to the dimension parallel to the direction of motion.

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36 p 79-80 De Haas-Lorentz 1957

5) The masses of all particles vary with motion.
6) These theories only apply to particles travelling with a velocity less than that of light and that the velocity of light is the upper limit at which particles may move.[37]

While Lorentz's theory could give a full mathematical description and explanation of a wide range of phenomena, it still could not explain the notion of a stationary aether. Lorentz in his desire to explain all phenomena occurring in the aether attempted to extend his theory to include the effects of gravitation. Unfortunately he, like many of his successors including Einstein, could not produce a single unified field theory to explain both electromagnetism and gravitation within the same set of mathematical expressions.

During the period 1890-1901, leading physicists were very concerned with the idea of the aether. Matter was explained as vortices in the aether or even singularities in the aether. The literature of the time carried the debate so convincingly that even now it is easy to be converted to the notion of an aether. However, this aether model would within a generation die. The Michelson-Morley experiment, because of its accuracy, showed beyond a doubt that there was no relative motion between the earth and the aether. Later developments in modern quantum mechanics and special relativity would not require an aether model as the medium of force propagation.

Lorentz and Weber, believed that chemical forces originated in the electron. The exact nature of this relationship could never be derived by Lorentz but had to wait until the model of the atom was proposed by Rutherford and refined by Bohr. These models stated that all chemical properties of matter could be explained by the electron distribution or arrangement in the atom.

[37] p 483 Mc Cormmach 1970

Lorentz was awarded the Nobel Prize for Physics for his theory of electrons and the propagation of light. In his Nobel lecture Lorentz stated "*I should like to remark that thanks to the speedy publication of research and the consequent lively exchange of views between scientists much progress must be considered as the result of a great deal of joint effort."*[38] His comment is as true today when the media for publication, discussion and dissemination of ideas are more varied but not necessarily more rapid than those 100 years ago.

Lorentz died in 1928, after an extremely distinguished career. In his later years he attended the Solvay Councils where he was depicted as the "grand old father" of Physics. With his passing came the end of the era of Classical Physics. Modern Quantum Mechanics, Special and General Relativity were conceived and developed in the later part of his life. The exciting developments of Quantum Electrodynamics and the theories describing the realm of subatomic physics lay in the future.

The story of the electron does not finish with H.A.Lorentz. The concept of the electron and the discovery of electron properties is a continuing saga. One could go so far as to say that the theory of the electron will continue to evolve. The future may hold untold new properties of subatomic particles which may be waiting for the technological developments which will make their presence observable.

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[38] p 15 Nobel Lectures

10. Epilogue-Advances in the Twentieth Century

This final chapter will take a very cursory view of the major developments in the theory and the concept of the electron that occurred during the Twentieth Century. By 1910, it was reasonably established that the atom was no longer the indivisible ball of matter as had been proposed by Dalton. The atom consisted of small negatively charged electrons nestled in some way into positive matter so as to produce a neutral atom. This is in fact a very simplistic view of Thomson's "plum pudding" model of the electron which he proposed in 1903. While students now take it for granted that an atom of atomic number Z contains Z free electrons, this was not the case in 1910. All that physicists could say with any confidence was that the mass of an electron was about 1/2000 of the mass of the mass of a hydrogen atom. At this time one could even speculate that the hydrogen atom had 2000 electrons which in some way neutralised each other and that one negative electron could be removed during ionisation producing a free electron and a positively charged hydrogen ion.

10.1. The Bohr Atom

In 1907 Rutherford returned to Britain from Canada replacing Thomson's mentor Arthur Schuster in Manchester. At this time, Rutherford started a successful collaboration with Schuster's assistant, Hans Geiger (1882-1945). Rutherford commenced his work on the scattering of α-rays in 1907, the following year he communicated two papers to the Royal Society. The second paper, written by Geiger, indicated that α-rays could "*be deflected through an appreciable angle"* when they were scattered by gold or aluminium foil.[1] Rutherford then suggested to Geiger and his assistant Marsden (1889-1970) to "*see if you can get some effect of α-particles directly reflected from a metal surface."*[2] By May 1909, Geiger and Marsden had discovered that "*of the incident α-particles about 1 in 8000 was reflected."* Rutherford's reaction to this discovery was his now famous "*it was almost*

1 p 188 Pais 1986
2 p 189 Pais 1986

as incredible as if you fired a 15 inch shell at a piece of tissue paper and it came back and hit you."[3]

Rutherford's surprise led him to develop a new atomic model. Rutherford stated "*on consideration, I realised that this scattering backwards must be the result of a single collision, and when I made calculations I saw that it was impossible to get anything of that order of magnitude unless you took a system in which the greater part of the mass of the atom was concentrated in a minute nucleus. It was then that I had the idea of an atom with a minute massive centre carrying a charge."*[4] Rutherford had shown that the nucleus was extremely small compared to the atom, the nuclear diameter was of the order of $10^{-15}\,\mathrm{m}$ and atomic diameter was of the order $10^{-10}\,\mathrm{m}$. This central positively charged nucleus was surrounded by a shell of orbiting electrons. Rutherford's scattering experiments had also shown that this nucleus had a positive charge of Ne where N was approximately half the atomic mass number for that atom.

It was only later that H.Moseley (1887-1915) in 1913 demonstrated from his work on X-ray spectra that the number of electrons in orbit about the nucleus is the same as the atomic number of that element in the periodic table.[5] It is now known that the central nucleus is made from two types of particles of similar mass, the proton which carries a positive charge and the neutron which carries no charge. The atomic mass of an atom is the sum of all the neutrons and protons in that atom, while the atomic number refers to the number of protons or electrons within that atom. For the lighter elements which tended to be used in this early work, the atomic number is approximately half the mass number.

According to classical electromagnetic field theory these negatively charged electrons should eventually collapse into the nucleus, a fact admitted by Rutherford.

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3 p 189 Pais 1986
4 p 615 Holton & Roller 1965
5 p 24 Whittacker 1951

"*I was perfectly aware when I put forward the theory of the nuclear atom that according to classical theory the electron ought to fall into the nucleus.*"[6] According to classical electromagnetic theory, an orbiting electron should continuously radiate light, thus continuously losing energy and spiralling into the nucleus. This problem was answered by the refinements developed by Niels Bohr (1885-1962) in his theory of the atom.

In October 1911, Bohr after receiving his Ph.D., arrived in Cambridge expecting to work with J.J.Thomson at the Cavendish. Shortly after his arrival, Bohr had attended a lecture presented by Rutherford on his new atomic model which had been published earlier that year. It was not long after this lecture that Bohr left the Cavendish and joined Rutherford in Manchester.

Bohr's decision to leave the Cavendish appears to be the result of an unfortunate incident shortly after his arrival there. At his first meeting with Thomson, Bohr attempted in his limited English to inform Thomson that his formula on the diamagnetism of conducting electrons was wrong. Thomson's response was to avoid Bohr, leading Bohr to comment sometime later that "*I considered Cambridge as the centre of Physics, and Thomson as a wonderful man. It was a disappointment to learn that Thomson was not interested to learn that his calculations were not correct.*"[7]

This incident seemed to indicate that Thomson did not appreciate being corrected by his juniors. While on the surface it is not an unusual response from one in such a senior position as Thomson, it was a pity that Thomson lacked the charity to humour a new and enthusiastic student who was trying to impress the great master. As discussed in Chapters 5 and 6, Thomson's mathematical abilities could well have been somewhat limited and Thomson's reputation may well have been founded to

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6 p 624 Holton & Roller 1965
7 p 195 Pais 1986

some extent on the work and creative insights of his students. Consequently, Thomson's reluctance to meet and discuss the issue with the young Bohr could only be seen as another piece of evidence against him. However, Thomson's reputation and that of the Cavendish was enough to entice young post doctoral students, such as Bohr, from all over Europe.

Before discussing Bohr's work on the structure of the hydrogen atom, it would be best to review some of the developments that had occurred and formed the background against which Bohr developed his ideas. The periodic properties of elements which later led to the development of the periodic table of elements had been well established for about fifty years. The phenomenon of radioactivity was being explored. From Rutherford's work on α -scattering, it became apparent that the nuclear charge was approximately equal to the atomic number of the element in the periodic table. Since an atom carried no resultant charge it was suggested that the number of orbiting electrons should also be equal to this atomic number. Thus the number of negative electrons orbiting the nucleus increases by one as the atomic number increases across the periodic table.[8] The spectral lines of various elements had been observed and it was found that each element had its own unique set of spectral lines. Various phenomena associated with these spectral lines, such as the Zeeman effect, were observed and described. Finally, the nature and behaviour of the negatively charged subatomic electron had by now been identified.

In 1900, Max Planck (1858-1947) developed his quantum theory after studying the emissions from blackbody radiation. Planck proposed an empirical formula which fitted with the available experimental data. Some months later he proposed a theoretical basis for this formula. His theory was based on a radical assumption that light was not emitted as a continuous spectrum but was emitted in discrete packets or quanta of energy. This quantum of energy was released by an atomic oscillator at frequencies related to its own frequency of oscillation,

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[8] p 24 Whittacker 1951

$$E = h\upsilon$$

where, h (Planck's constant) $= 6.626 \times 10^{-34}$ Js

υ = frequency of the emmitted light

It was during his collaboration with Rutherford at Manchester that Bohr developed his model of the atom which was published in a series of three papers in 1913. Using Planck's theory and classical mechanics, Bohr developed a model of the atom in which electrons orbit a central positively charged nucleus in stationary orbits. Electrons may, in some circumstances, move from one orbit to another, in which case the electron either emits a quantum of light or is required to absorb a quantum of light.

When an electron moves from one stationary orbit to another stationary orbit closer to the nucleus the quantum of light emitted by this electron may be determined directly from Planck's Theory,

$$E_1 - E_2 = h\upsilon$$

where $E_1 - E_2$ is the energy difference between the stationary orbits

There was no theory at that time which gave any idea on why an atom might have stationary orbits. Bohr was guided by the Balmer formula which explained the four visible lines of the hydrogen spectrum. J.J.Balmer (1825-1898), a teacher in a girls' school in Basel had presented his formula in his first research paper in physics in 1885, at the age of sixty![9] Bohr assumed that for electrons moving in circular orbits the angular momentum of these electrons could be quantised such that angular momentum $= mvr_n = n\frac{h}{2\pi}$ where r_n is the radius of the nth orbit and n is an integer and is called the quantum number of that orbit. This integer, n is now called the principal quantum number. Consequently, Bohr developed the relationship

$$\nu = \frac{2\pi^2 me^4}{h^3}\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right)$$ [10]

[9] p 172 Pais 1986

[10] p 9 Bohr 1913 (I)

to explain the emission frequency of light emitted as the electron moves from one orbit of quantum number n_1 to another orbit of quantum number n_2. This formula successfully explained the spectra of the 1-electron systems, H and He^+. It makes no reference to the orbital frequency, or to any resonance of the system. There was a complete break with classical ideas.

In his second 1913 paper, Bohr suggested that the electrons will fill the lowest energy orbits first and that a number of electrons can exist in each orbit simultaneously. However, since he was aware of the periodic nature of the properties of the elements, Bohr suggested that the upper limit for the number of electrons be restricted to 8.[11]

Bohr expanded his theory to include the formation of molecules and the interactions of electrons around more than one nucleus. He attempted to determine the shape and nature of molecules which share electrons (i.e. use covalent bonding). He correctly suggests that the interatomic bonds consist of two shared electrons orbiting about the two nuclei.[12] Bohr continued work on his model of the atom, publishing another two papers on this subject in 1915. While Bohr theorised that 8 electrons was the maximum number in any electron orbit and that covalent bonds required pairs of shared electrons, his theory did not even attempt to explain the reasons for either expectation.

10.2. Old Quantum Theory

In his 1913 papers, Bohr had defined two properties of atomic electrons, namely the orbit in which they were found and the angular momentum they possessed in that orbit. Bohr had found that this angular momentum increased by an integer quantity of $h/2\pi$ or $\hbar$.[13] As has already been discussed, the principal quantum number (n) signifies the orbit in which an electron is to be found. If the electron is in the innermost orbit, it has a principal quantum number n=1. If it is in the next orbit, then it

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11	p 494-7	Bohr 1913 (II)
12	p 874	Bohr 1913 (III)
13	p 875	Bohr 1913 (III)

has a principal quantum number n=2, and so on. Bohr's 1913 theory worked well for 1-electron atoms. In the years 1913-1923 there were several almost ad hoc, extensions. The first was to introduce the concept of elliptical orbits, with the cyclic variation in radial momentum also subject to a quantum condition introducing a second integer, the orbital quantum number l. This theory was developed largely by A.Sommerfeld (1868-1951) in 1915.[14]

The orbital quantum number effectively describes the nature of the elliptical orbits of electrons found in the p, d and f energy levels of each orbit. The s energy level is described by the orbital quantum number l=0. By this time each electron could now be described by the orbit in which it was located and the type of orbit it described i.e. by the quantum numbers n and l.

These relationships, however, failed to explain the presence of the multiple splitting of spectral lines found in the Anomalous Zeeman Effect. The Anomalous Zeeman Effect is the splitting of spectral lines in the presence of a magnetic field but in this case the spectral lines are split into four or even six distinct lines. This phenomenon could not be adequately explained by Lorentz's Theory of Electrons and at this time still remained a mystery. It had also been observed that line spectra were themselves made up of two or more fine lines, now referred to as the fine structure. In 1920 Sommerfeld introduced a third quantum number j, which was called the inner quantum number and was to quantify the angular momentum in a third degree of freedom which he thought of as the tilt of the orbit. These orbits are degenerate in the absence of a magnetic field.[15] This third quantum number is now designated as m_l and is referred to as the magnetic quantum number and has values of $m_l = 0, \pm 1, \pm 2, \ldots \pm l$. This quantum number describes the direction or tilt that the angular momentum, L has with respect to some defined direction. Thus the magnetic

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[14] p 132 Whittacker 1951
[15] p 134 Whittacker 1951

quantum number refers to the restricted orientation of the angular momentum of the electron, $L_z = m_l\hbar$ where L_z is the angular momentum component on the z-axis.

The following year A.Landé (1888-1975) suggested that j have half integer values in some circumstances. Landé, further, suggested that the quantum number j should have values of $j = l + R$, where l is the angular momentum quantum number of the valency electron and R was the core angular momentum quantum number and had a value of $R = \frac{1}{2}$ for the alkali metals.[16] While Landé's suggestions could completely explain the Anomalous Zeeman Effect, Landé gave no explanation of the relevance of this half integer quantity. In December 1924, W.Pauli (1900-1958) in his paper on the Anomalous Zeeman Effect, rejected Landé's concept of a core angular momentum in the atom. While he agreed that Landé's formulae fully explained the Anomalous Zeeman Effect, Pauli suggested that the quantum number R should refer to some property in the valency electron which he believed was responsible for this effect.[17]

In October 1924, E.Stoner (1899-1968) had already suggested that "*the number of electrons in each completed energy shell is equal to twice the sum of the inner quantum numbers*"[18] By taking into account the three quantum numbers, n, l and m_l, it a simple matter to determine the number of atoms in each energy shell i.e.

Principal quantum number	Orbital quantum number	Magnetic quantum number	Number of electrons	Total number of electrons
n=1	l=0	m_l=0	2	2
n=2	l=0	m_l=0	2	
	l=1	m_l=-1,0,1	6	8

16 p 271-2 Pais 1986
17 p 272 Pais 1986
18 p 273 Pais 1986

Thus the maximum number of electrons in the first shell would be 2 and in the second shell would be 8.

In January 1925, Pauli now used Stoner's proposal together with Landé's formulae to formulate his famous exclusion principal. Pauli suggested that each atomic electron could be described by four quantum numbers:-

n-principal quantum number (n=1,2,...)

l-angular momentum quantum number (l=0,1,2,...(n-1))

m_l-magnetic angular momentum $(-l \le m_l \le l)$

$m_R = \pm \frac{1}{2}$ -this was another magnetic quantum number.

He then states that "*in the atom there can never be two or more equivalent electrons for which the values of all quantum numbers coincide*".[19]

At this time Pauli had made no suggestion as to which property of the valency electron the fourth quantum number referred, except to say that it was another magnetic quantum number. The nature of this property became more clear in October 1925 when two young Dutch physicists, Samuel Goudsmit (1902-1978) and George Uhlenbeck (b1900) made a startling suggestion. This fourth quantum number, referred to the spin of the electron. The electron not only moved around the nucleus in an orbit, it also had a spin about its axis thus experiencing a magnetic field. Due to the interaction of the spinning electron moving around a central charged nucleus, the electron could orient itself in only one of two possible values for this fourth quantum number.[20]

The old quantum theory could now account for the behaviour of atomic electrons and associated phenomena. This theory, while now replaced by modern quantum mechanics is still widely taught at secondary schools and in some introductory undergraduate courses. As a theory it has the advantage that students can visualise the concepts of these various energy levels without the need to develop higher order

[19] p 274 Pais 1986
[20] p 274-80 Pais 1986

skills in mathematics. However, this model still requires the electron to behave as a particle which presumably could be observed as such in some manner.

By the late 1920's, a young theoretical physicist was developing a new model for the explanation of the behaviour of these atomic electrons. P.A.M.Dirac (1902-84) wrote a series of papers in the period from 1927 to 1930 in which he united Einstein's Special Theory of Relativity with quantum principles. These papers were the basis of modern Quantum Mechanics and more specifically, Dirac established the conceptual basis for Quantum Electrodynamics. The relativistic equation at the basis of Dirac's work is

$$E^2 = E_0^2 + p^2c^2$$

where $E_0 = m_0c^2$ and p is the momentum.

The equation suggests the possibility of negative energy solutions. By May 1931, Dirac suggested the existence of a particle with a negative energy state which behaves as an electron with the same mass but with a positive charge which Dirac called the anti-electron.[21] By December 1931, Carl Anderson (b1905) had identified the positron from tracks obtained from cosmic ray trails photographed in a cloud chamber. Thus, by the end of 1931, the first antimatter particle had not only been predicted but had also been observed. In February 1933, this positive electron or anti-electron had been named the POSITRON.[22]

10.3. Wave-particle Duality and Quantum Mechanics

The next major development in the understanding of the nature of the electron was occurring at the same time as Bohr, Pauli and Dirac were making their contributions to the particulate nature of the electron. In 1923, Louis de Broglie (1892-1987) first proposed that particles such as electrons could also behave as waves. At the age of fourteen, when his father died, Louis's education was directed by his older brother Maurice who was a well respected physicist. Maurice had a particular interest in the properties of X-rays and later in the photo-electric effect.

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[21] p 347-52 Pais 1986
[22] p 352 Pais 1986

It would seem only natural that when Louis showed an interest in Physics that his older brother should direct Louis into the study of X-rays and light. In 1923 and 1924 while still completing his postgraduate studies, Louis de Broglie published a series of papers in which he explored the notion that particles could also have wave properties, *"it is then possible to save both the corpuscular and the undulatory characters of light"*.[23] However, it was not until 1925 when Louis submitted his thesis that he had finally formulated the basis of wave-particle duality. In his thesis, de Broglie starts with Einstein's model for the particle nature of light waves, i.e. the energy and momentum relationships of Special Relativity holds not only for photons but also for particles such as electrons. He further, suggests that if this premise is correct then electrons should also behave as waves. Thus he suggested that electrons should exhibit diffraction patterns. De Broglie's ideas were so unusual that his thesis was shown to Einstein for a comment. Einstein in turn approved of the young man's work and de Broglie graduated in 1925.[24]

De Broglie's prediction of electron diffraction patterns were verified in 1927 by two groups working independently, C.Davisson and L.Germer, and G.Thomson (son of J.J.Thomson) and A.Reid.[25] It is of interest to note that while J.J.Thomson worked to establish the particle nature of electrons, his son George confirmed the wave properties of electrons. Both father and son won Nobel Prizes for their work.

The atomic electrons could now be regarded as standing wave patterns which only occur at predetermined positions around the central nucleus. These predetermined positions for standing wave patterns coincide with the energy levels which have already been discussed. This led to the situation that subatomic electrons could now be regarded as both waves and as particles. Once the idea of the wave-particle duality of matter was suggested, a new atomic model was required to explain both

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[23] p 457 de Broglie, L 1924
[24] p 252 Pais 1986
[25] p 60 Gribbin 1987

these two disparate set of properties for the single entity, the electron. The solution came from two individuals who approached the problem from two different perspectives.

In 1925, Werner Heisenbeg (1901-76) rejected the notion of developing a concrete model of the atom, instead he suggested that an understanding of atomic structure could be gained by using those variables or quantities which could be measured. In short, he started to develop a purely abstract mathematical model based on quantities which could be measured. With the assistance of P.Jordan (1902-1958) and his mentor Max Born (1882-1970), Heisenberg arranged all the measurable quantities in square arrays called matrices. By defining mathematical operations between these matrices, Heisenberg developed a mathematical model of the atom which could account for all the then known experimental evidence and was even able to predict phenomena which were only later discovered.[26]

Within two years Heisenberg discovered from his computations that some of these measurable quantities seemed to occur in pairs for which it was not possible to measure simultaneously both quantities in the pair accurately. This led Heisenberg to develop his Uncertainty Principal which states that for a pair of quantities such as momentum and position, only one can be measured with complete accuracy.[27]

Erwin Schrödinger (1887-1961) developed a wave equation for electrons in their stationary Bohr orbits in the atom. Schrödinger arrived at his wave mechanics solution in 1926, by developing de Broglie's ideas into a mathematical model. At the time Schrödinger's wave equation produced a series of solutions which agreed with the existing understanding of electron energy levels within the atom. [28] The solutions

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[26] p 43-4 Ne'eman and Kirsh 1986
[27] p 47-8 Ne'eman and Kirsh 1986
[28] p 45 Ne'eman and Kirsh 1986

of the Schrödinger wave equation proved to be identical to the solutions of Heisenberg's matrix equations when identical conditions were considered.[29]

The culmination of the wave-particle model occurred in 1928 when P.A.M.Dirac developed a relativistic wave equation for the electron. He utilised matrix mechanics, i.e. modern quantum mechanics and developed the earliest version of quantum electrodynamics.[30] The development of quantum electrodynamics continued with contributions by Sin-tiro Tomonaga (1906-79), J.Schwinger (b1918) and R.Feynman (1918-1987). However the story of the electron does not end with the development of quantum electrodynamics or with the discovery of the positron. The development of the modern theories of the electron are far more complex than the classical models and have developed extremely rapidly compared to classical physics.

The focus of this work has been the classical electron and this last chapter is only a very brief sketch of the voluminous history of the post classical electron. The contemporary notion of the electron is the same concept that was developed by Dirac, Heisenberg, de Broglie, Schrödinger and Bohr by 1932. They have not only provided modern physicists with an understanding of what an electron is, but have also provided an understanding of the nature of matter. It is not too great an exaggeration to say that all the physico-chemical properties of the world around us are essentially the properties of electrons (except the property of mass) and that by 1932 all the essential points had been understood by at least some physicists. This was a stupendous achievement which had its basis in the centuries long struggle to understand electrical phenomena and the classical electron.

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[29] p 253-62 Pais 1986 and p 299-307 Wheaton 1983
[30] p 288-92 Pais 1986

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