J. J. Thomson — the Centenary of His Discovery of the Electron and of His Invention of Mass Spectrometry

Iwan W. Griffiths
School of Applied Sciences, University of Glamorgan, Pontypridd, CF37 1DL, UK

Joseph John Thomson (1856–1940), physicist, demonstrated the existence of the electron and, by deflection methods, measured its charge-to-mass ratio in 1897. He later applied similar methods to the study of positive ions and sorted the constituents of the beams into positive ray parabolas each corresponding to a definite ratio of charge-to-mass. As we celebrate the centenary of the measurement of *e/m*, it is apt to reflect that 'JJT' could be regarded in fact as the pioneer of mass spectrometry, the roots of which can be traced right back to that measurement.

In a remarkable career, Manchester-born Thomson discovered the electron, revealed the existence of the internal structure of the atom and laid the foundations of mass spectrometry. As well as being elected a Fellow of the Royal Society, he was awarded the Nobel Prize for Physics in 1906 for 'Investigations on passage of electricity through gases'. One hundred years after his measurement of *e/m*, it is an appropriate time to look back on his achievements and to celebrate them in the light of the immense developments which have since taken place in science and, in particular, in mass spectrometry, largely due to his pioneering efforts.

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1. THE YOUNG THOMSON

Joseph John Thomson was born in Cheetham, Manchester on 18 December 1956. His father, Joseph James Thomson, was a publisher and bookseller of Scottish extraction while his mother, Emma Swindells, came from the Manchester area.

As a small boy he was sent initially to a small school kept by some lady friends of his mother, and then to a private day school run by the Townsend brothers at Alms Hill, Cheetham. This school was traditional in its outlook and rejected the new views on education that were just coming in. He was taught Latin by memorizing the rules from the Eton Latin Grammar, and English by learning by heart chunks from Shakespeare, Byron and Scott. He did not appear to appreciate History and Geography which seemed to consist of little more than committing large numbers of facts to memory. In Mathematics, he was taught the propositions in the first book of Euclid and did a lot of arithmetic which he found an excellent intellectual exercise. At the Alms Hill school, Thomson played cricket, football, rounders, prisoner's base and shinty, which is similar to hockey. Thomson was always keen on gardening, and at this time kept a small garden in which he could do what he liked. He liked going out to look for wild flowers and reading books about them and thought at one time that he would like to be a botanist. Interestingly, the scientific names of plants irritated him a lot and he stated that if he became a botanist he would do his best to take botany out of science altogether!

It is worth bearing in mind the important role Manchester has played in the development of physical science. Two notable examples are Dalton, who discovered the law of multiple proportion in chemical combination and Joule, who established the principle of Conservation of Energy. The Manchester Literary and Philosophical Society was begun in 1781 and by 1800 John Dalton had been appointed Secretary. Dalton can be said to have proved that matter exists in the form of discrete entities called atoms (the atomic theory) and was therefore a central figure in the foundation of chemistry. Dalton was elected President of the Society in 1817 and after his death in 1844 was succeeded by James Prescott Joule. Joule had been Dalton's student and had been refused permission to go on to study chemistry until he had read mathematics. Joule had already shown that the heat produced in an electric circuit is proportional to the product of the electrical resistance of the circuit and the square of the current. In 1843 he published the first measurement of the mechanical equivalent of heat which contributed to the eventual acceptance of the principle of the Conservation of Energy. When Thomson was a boy, he was introduced to Joule by his father and this meeting clearly made an impression on him.

Thomson became a physicist rather by accident. It was intended that he would be an engineer and that he would be apprenticed to a firm of engineers. He was to go to Sharp-Stewart & Co., locomotive makers, but they had a long waiting list and it would have been some time before he could have commenced there. A family friend argued that rather than waste time waiting

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to start with this engineering firm, the young Thomson would be better off going to study at Owens College, Manchester until the firm were ready to take him on. Thomson's father took this advice and Thomson started at Owens College when he was fourteen years old. This was a critical event in Thomson's life and it determined his future career. John Owens, a merchant who died in 1846, left his estate to be devoted to the establishment of a College in Manchester free from religious tests, for instruction in the branches of knowledge taught in the English universities. Owens College started as a house in Quay Street, Deansgate, and Thomson started there in 1871. By now the number of students at the college had reached 500 and the house was really too small for this number. The Engineering Department was housed in what had once been the stables. The Chemical Department was more fortunate, as an adjacent house was used for the Laboratory whereas the Physical Laboratory was little more than a room in which the apparatus used for Lecture demonstrations was stored. This meant that the students were closedly packed, a situation in which it was easy to make friends. In 1872, the college moved to larger premises in Oxford Road and this meant that there was less overcrowding. Thomson's recollections of Owens College, however, are mainly of his time in Quay Street. It was while at Owens College that Thomson met John Henry Poynting (1852–1914) and the two men remained the greatest of friends until Poynting's death. Mention must be made here of the brilliant staff of Professors and the subsequent development of the College. The Mathematics professor was Thomas Barker; for physics, Balfour Stewart; Engineering, Osborne Reynolds; and Chemistry, H. E. Roscoe. Owens College developed into first a College of Victoria University and finally to become Manchester University.

Thomson was enrolled on the three-year Engineering Course. At the end of his second year, his father died and he had to given up the idea of becoming an engineer, as his mother did not have the money needed for him to become an apprentice. He had won some small scholarships which helped pay his fees and he decided to finish the three years' course to obtain the certificate of engineering. At the end of his three years, Professor Barker advised him to stay on at Owens for another year to study mathematics and physics and then go on to try for an entrance scholarship to Trinity College, Cambridge. Thomson liked the idea of going to Cambridge and stayed at Owens, taking the higher classes in physics and mathematics and working at the physical laboratory. In the spring of 1875 he tried an examination for the entrance scholarship to Trinity College, Cambridge. He was unsuccessful on this occasion but he succeeded at his second attempt in 1876 and he received a minor scholarship of £75 a year together with a subsizarship for certain allowances. A subsizarship is an old Cambridge term for an award made to someone with special need for pecuniary help. Thomson owed a great deal to scholarships, for without them he could not have stayed on at Owens or gone to Trinity. He also received a scholarship from the Grocers' Company while he was at Trinity. These awards clearly meant a great deal to Thomson especially since his father had died at a young age and thus was not able to provide for him.

2. CAMBRIDGE DAYS

During his time at school and Owens College, it became apparent that Thomson had no great skill in using his hands. However, from the time he arrived in Trinity College it became apparent that he had tremendous ability in interpreting and drawing correct deductions from the work done by others and this ability was to remain with him throughout his working life. It later became clear that he understood the working of complicated apparatus without actually using it himself! Thomson arrived at Trinity College, Cambridge in October 1876 and spent almost the whole of his working life there. Mrs Kemp, his landlady for four years at 16 Malcolm Street, made sure his room was comfortable and always ensured that the open fire was tended. The Master of the college was Dr W. H. Thompson and the four tutors were Joseph Prior, H. M. Taylor, Coutts Trotter and J. M. Image. Thomson's aim here was to get a good placing in the Mathematical Tripos and he was coached extensively by Dr Routh. The mathematical tripos consisted of all the branches of pure and applied mathematics known at the time. There was a competitive examination at the end of three years and a term. In order to get the highest marks, practically all of the questions had to be answered, which meant that nothing could be left out of the candidates' learning and revision. In Routh's lectures, he employed the common technique of adopting a textbook for the course and then used his lectures to point out various attributes of the contents. If the author had written satisfactorily about certain subjects, Routh just told his students to read them, but if there were parts of the book which could be improved on, Routh supplied those improvements for his students. Routh also had a set of manuscripts, on aspects of the subject that were not yet in the textbooks, which his students could refer to if they wished. A weekly problem paper kept the students on their toes and the following week they were expected to do the same paper in three hours, the time taken for the tripos exam. Thomson had a very high opinion of Routh's teaching and regarded him with the utmost respect. In 33 years teaching Routh had 27 Senior Wranglers with 24 in 24 consecutive years.

Thomson also attended lectures in Trinity College by W. D. Niven on mathematical physics, based mainly on Maxwell's treatise on Electricity and Magnetism. Thomson gives Niven the credit for kindling his interest in Maxwell's work, which at that time was very new. J. W. L. Glaisher lectured to Thomson on Pure Mathematics and Thomson found these lectures the most interesting he ever attended on the subject. Glaisher's lectures covered a great deal of material, where never dull and were very human. Glaisher revelled in scientific societies, for example, the Cambridge Philosophical, Astronomical and Mathematical Clubs. Also, since he owned a 'penny-farthing' he was a member of the Cambridge University Bicycle Club.

As well as lectures by Professors Cayley and Adams, Thomson attended lectures by Sir George Stokes on Light. He had only simple apparatus at his disposal and no light other than that of the Sun. This meant that on bright days, he took full advantage by performing many demonstrations, and lectures tended to overrun the stipulated one hour. Like his predecessor in the Lucasian Chair, Sir Isaac Newton, he made remarkable discoveries in optics in his rooms in College, with very simple apparatus. Lord Kelvin looked upon Stokes as his teacher and often consulted Stokes on mathematical or physical problems he was having trouble with. Stokes was one of the Secretaries of The Royal Society for 31 years and contributed a great deal to the development of physics.

The undergraduate period was punctuated by the results of the annual College Examinations and the migration for the Long Vacation term from the lodgings in Malcolm Street to rooms in Great Court. Serious contenders for honours came up for the 'Long' usually at the beginning of July and stayed up to nearly the end of August. During the Long, as well as reflecting on what they had been taught, undergraduates took part in the cricket match between 'Fellows and Scholars' and 'The Rest'.

The Mathematical Tripos examination in January 1880 was 'an arduous, anxious and very uncomfortable experience'. (Quotation from Thomson's autobiographical '*Recollections and Reflections*'). It was held in Senate House in mid-winter without any heating of any kind. The examination was divided into two periods the first of which lasted four days. In the first three days, the students were examined on geometry, conic sections, algebra and plane trigonometry, statics and dynamics, hydrostatics and optics, Newton and astronomy. There were five papers on these subjects with each paper consisting of about twelve questions, each question being a piece of book-work and a rider which was a question whose solution was closely connected with the piece of book-work. There was also a sixth paper which contained questions to be answered without being asked for the associated book-work. During the first three days, the students were not allowed to use the differential calculus or analytical geometry. The fourth day consisted of two papers. There were easy questions on the higher parts of pure and applied mathematics and also on the physical subjects, heat, electricity and magnetism. A new external examiner had been appointed to deal with the physics section, and the first one was James Clerk Maxwell, a man who had a huge influence on Thomson. On the fourth day, differential calculus and analytical geometry were allowed. At the end of the fourth day, the examiners drew up a list of candidates who could proceed to mathematical honours by taking the second part of the tripos in about ten days' time. This second stint, lasting five days, counted for six times the number of marks allotted to the first four days. The first two days of this session covered material which had been in the Mathematical tripos right from its inception and the examinations were governed by a rule which stated that they should not contain more questions than could be answered by a well-prepared candidate in the time available. To achieve high marks in these examinations required a thorough knowledge of the subject to answer the book-work parts of the questions and a tremendous facility at doing problems to attempt the riders. Concentration on the question at hand was vital as was the ability to quickly begin tackling another question as soon as the previous one had been completed. Mistakes in manipulation had to be kept to an absolute minimum and this ability usually came by endless practice in doing similar questions. In the final three days of the Tripos, it was acknowledged that it was impossible to answer all the questions in the time allotted even by a well-prepared student. Although there were fewer questions set, the book-work sections were far longer and the riders were more difficult.

Sometimes the papers were so absurdly difficult that not one candidate succeeded in completing a single question from a long paper. It is clear that the old Mathematical Tripos was a good examination for candidates having exceptional ability in mathematics but was a very poor one for people with more moderate ability. Thomson himself mused on the merits of the examination system and noted that the questions set in mathematical physics often stopped where the real interest began. Usually the question asked for a relationship between a number of mathematical symbols representing various physical quantities based on some initial conditions and a few physical laws. Often the physical consequences resulting from this were not asked for or even considered but this was the very thing which interested Thomson the physicist. Thomson reflects that the great amount of time which he and his fellow students spent on memorizing a lot of detail for the Tripos examinations would, perhaps have been better spent doing a piece of original research. In the Tripos examination of 1880, Joseph Larmor was Senior Wrangler and Thomson was Second Wrangler.

3. THE CAVENDISH LABORATORY

Thomson began working at the Cavendish Laboratory in Cambridge immediately after taking his degree in 1880. He began to prepare a dissertation to satisfy the requirements of the Fellowship Examination, based on an idea that he had had before arriving at Trinity. At that time, the view was held that there were many different forms of energy, kinetic energy, potential energy, thermal energy, energy in electric and magnetic fields and chemical energy. Energy of kind A could be converted into energy of type B but always at a fixed rate of exchange, i.e. 'X' A-units could be converted into 'Y' B-units. If all kinds of energy were reckoned on a 'gold' standard the principle of the conservation of energy stated that the total amount of energy could not be altered by any physical process. Energy was then pictured as transforming itself from one form into another but Thomson thought this was confusing and conceptually difficult. In his dissertation he proposed that energy was all of one kind and that transformation of energy could be more appropriately described as a transference of energy from one system into another, with different physical effects resulting from the different physical systems in which the energy resided. Thomson stated that all energy was in fact kinetic energy and his dissertation used the Hamiltonian and Lagrangian equations to look at various questions in physics and chemistry. His results indicated that there were interesting relationships between various physical effects which must be true whatever might be the kind of mechanism producing the effects. For example, if the stiffness of a spring depends on temperature, extending the spring will change its temperature and the temperature change will be such as to make spring extension more difficult. There is a general principle here, namely that the alteration in temperature produced by any change in a system is that which will increase the resistance to that change. This principle was published independently and almost simultaneously by Le Chatelier. Thomson's dissertation was published in expanded form in two papers in the *Transactions of The Royal Society* and was the basis for his book *Applications of Dynamics to Physics and Chemistry*. Thomson was elected to a University Fellowship at his first attempt in 1880 and also to an Assistant Lectureship in Mathematics at Trinity College in 1882.

The Adams Prize, established to commemorate the discovery of Neptune by Professor Adams, provided Thomson with an opportunity to study the section of two vortex rings on each other. Sir William Thomson [otherwise Lord Kelvin (1824-1907), no relation] had suggested that all matter might be composed of vortex rings and this prospect intrigued the younger Thomson. His essay was awarded the Adams Prize in 1883. He also worked on the problem of finding the electrical oscillations which can occur on the surface of a conducting sphere and published this work in the *Proceedings of the London Mathematical Society*.

Thomson then began the research which was to occupy him, in one form or another, for the next forty years. He began by making mathematical investigations on moving electric charges. Crookes had performed some beautiful experiments on cathode rays and these inspired Thomson to investigate the behaviour of moving charges using Maxwell's new theory. In Crookes's experiments a discharge was set up through a gas contained in a glass tube with cathode and anode electrodes. The gas was usually at a fairly low pressure and it was possible from observing the discharge to infer the motion of negative charges coming from the cathode. These experiments will be referred to again in Section 5.

It seemed to Thomson that a good way of testing the theory would be to look at the behaviour of a moving charged particle and he proceeded to work out what would be the magnetic field produced by the moving particle and also what the magnetic force would be on such a particle if it were subjected to an external magnetic field. His results were published in the *Philosophical Magazine* of April 1891. One result, which is perhaps worthy of mention and which would not be presented in the same way in modern textbooks, concerns the mass of charged bodies. The magnetic field in Maxwell's theory is proportional to the rate of change of the electric field. If e is the charge and v the velocity of the charge, the electric field at a given point will be proportional to e, and its rate of change to ev. This implies that the magnetic field at any point is proportional to ev and, furthermore, this magnetic field carries with it a magnetic energy, the density of which is proportional to the square of the magnetic field. Hence the energy in the space around the moving charge will be equal to a quantity Ae^2v^2 where A is a positive quantity depending on the shape and size of the charged body. In the absence of charge, the kinetic energy would be $mv^2/2$ where m is the mass of the particle. The total kinetic energy now is $[(m/2) + Ae^2]\,v^2$ i.e. its kinetic energy under the action of forces is the same as if its mass had been increased from m to $(m + 2Ae^2)$. By the arguments presented, the mass increase is in the space around the charged body not in the body itself. It is then perhaps inevitable to formulate an electrical theory of matter, where all mass is electrical in origin and is situated not in atoms or molecules themselves but in the surrounding spaces.

The Cavendish Laboratory played an enormously important part in Thomson's life. It was 1869 before it was decided to open a Physical Laboratory at Cambridge and to appoint a Professor of Experimental Physics. The University was so poor at that time that they had to look to a benefactor, the Chancellor of The University, the 7th Duke of Devonshire, to provide money to build the laboratory and stock it with equipment. Clerk Maxwell was appointed the first Professor of Experimental Physics in 1871. The Laboratory was officially opened by the Chancellor in October 1874. One of the first undergraduates working at the Cavendish was H. F. Newall who later became Professor of Astro-Physics at Cambridge. Between 1874 and 1879 important research was done at the Cavendish on the following: the accuracy of Ohm's law, a proof that the attraction of a point charge is inversely proportional to the square of the distance, the wave surface in a biaxial crystal, spectroscopy and the measurement of resistance. Maxwell himself did not do any substantial research work during his time at the Cavendish, instead devoting a lot of his time to editing the works of Henry Cavendish (1731–1810). Cavendish had left twenty packages of manuscripts on mathematical and experimental electricity with much of it unpublished. One experiment described Cavendish using his own body as a galvanometer by estimating the shock he received when a current was passed through his body. Visitors to the laboratory were tested with electricity to see if they made good galvanometers. Cavendish's papers were eventually published in 1879 under the title *The Electrical Researches of the Honourable Henry Cavendish*. The papers showed that Cavendish was an exceptional experimenter and had anticipated Faraday (1791–1867) with his work on induction, had already come up with the idea of capacitance, had anticipated Ohm's Law, and had proved experimentally that the field produced by a single point charge of electricity fell off as the inverse-square of the distance. Later on, Cavendish discovered the composition of water and measured the density of the Earth using his torsion balance. Cavendish has been elected to the Royal Society in 1760 and attending meetings and dinners in connection with this society was his main social outlet. Otherwise he was a misogynist and a recluse.

Maxwell died in November 1879 and John William Strutt [who became Lord Rayleigh (1842–1919)], took his place in 1880. Lord Rayleigh rapidly introduced a scheme for teaching undergraduates in experimental physics, something for which there had been no provision previously. He also began the work of determining the absolute measure of various electrical quantities beginning with the ohm. In three different experiments spread over three years he improved the accuracy of the determination of the ohm and showed that a previous standard ohm was in fact 1.3% too low. Lord Rayleigh, in conjunction with collaborators, also made absolute determinations of the Ampère and the Volt and, in this way, revolutionized electrical measurement. Rayleigh had said that he only wished to stay as Professor for five years and it was some considerable surprise to J. J. Thomson to find himself elected as Rayleigh's successor in December 1884.

The number of science students at Cambridge increased greatly after 1885 and there was considerable pressure on space at the Cavendish Laboratory. This pressure was eased in 1896 when a new wing was added to the Laboratory, to the south. In 1895, the University opened its doors to graduates of other universities. The

Cavendish Physical Society was founded in 1893 and provided a forum where recently published papers in physics could be discussed. During Thomson's first two years as Professor, foreign students such as Olearski, Natanson, P. Langevin and H. F. Reid were beginning to arrive at the Cavendish. H. L. Callendar came in as a classics student but followed his classics degree with another one in mathematics in the following year, 1895. Thomson noticed he had a good feel for taking physical measurements and put him to work on the accurate measurement of electrical resistance. The resistance of a platinum wire depends on its temperature so that, if the resistance of the wire at different temperatures is known, one can determine temperature by measuring the resistance. Siemens had made a platinum thermometer, but it had a number of defects in use, which made accurate determinations impossible. Callendar took up the problem with enthusiasm and eventually concluded that if the wire were kept free from strain and contamination from vapours, it made a very reliable thermometer.

W. C. Dampier Whetham (Sir William Dampier) did research on the velocity of ions in liquid electrolytes and the slipping of liquid when moving in contact with solid surfaces. J. B. Peace measured the potential differences between parallel electrodes required to produce sparks of different lengths and through different gases. C. T. R. Wilson worked at the Laboratory looking at the formation of clouds, this work leading eventually to the Wilson Cloud Chamber which was of vital importance to the development of modern physics.

Thomson made a long series of experiments on the passage of electricity through gases when the electric field producing the discharge was obtained by electromotive induction. This was achieved by discharging a capacitor through a coil of wire setting up large alternating currents. When a glass tube containing the low-pressure gas was placed inside the coil, the electric field inside the tube caused a discharge through the gas. He also made investigations on the passage of electricity through hot gases and these results, taken together, indicated that some kind of dissociation was associated with the conductivity of the gas and that the current was carried by charged particles.

The new research regulations that had come into force in 1895, meant that students from universities other than Cambridge could obtain Master of Arts degrees and, later, Doctor of Philosophy degrees. This heralded a period of rapid expansion in the numbers of research students and October 1895 saw the arrival of two notable scientists to the ranks of the Cavendish Laboratory from outside the hallowed halls of Cambridge — Ernest Rutherford and John Sealy Edward Townsend. Ernest Rutherford (1871–1937) was a New Zealander and came to Cambridge from Canterbury College. Lord Rutherford O.M., F.R.S., as he later became, went on to establish the existence and nature of radioactive transformations, the electrical nature of matter, the nuclear structure of the atom and the transmutation of one element into another. J. S. E. Townsend (1868–1957) was an Irish physicist who came to Cambridge from Trinity College, Dublin and became well known for his work on ionization and conduction in gases. Here is a list of some of the workers in the Laboratory during the period 1896–1900: L. Blaikie, G. B. Bryan, J. B. B. Burke, W. Craig Henderson, J. Erskine Murray, J. Henry, P. Langevin, J. G. Leathem, R. G. B. Lempfort, Theodore Lyman, J. A. McLelland, J. C. McLennan, C. F. Mott, I. Nabb, H. F. Newall, Vladimir Novak, R. B. Owens, J. Patterson, J. B. Peace, O. W. Richardson, A. A. Robb, W. A. D. Rudge, E. Rutherford, G. F. C. Searle, G. A. Shakespeare, W. N. Shaw, S. Skinner, S. W. J. Smith, Hon. R. J. Strutt, J. Talbot, J. S. E. Townsend, J. H. Vincent, E. B. H. Wade, G. W. Walker, W. C. Dampier Whetham, R. L. Wills, C. T. R. Wilson, H. A. Wilson, J. Zeleny. Trinity College elected Rutherford to the Coutts Trotter Scholarship in 1898 and Townsend to a Fellowship in 1902. Also in 1902, a portrait of J. J. Thomson by Arthur Hacker R.A. was presented to the Laboratory by students past and present.

4. THE DISCHARGE OF ELECTRICITY THROUGH GASES

The burgeoning numbers of research students at the Cavendish Laboratory coincided with the announcement by Röntgen of his discovery of X-rays. Thomson copied his apparatus and started producing the new rays at the Cavendish; his first priority was to see what effect the rays would have on a gas and whether they would change the electrical properties of gases. He found that X-rays did indeed induce gases to become electrically conducting, even when the applied electric fields were very low. Thomson was delighted by this discovery because up until then, the only way to get a gas to conduct was to apply very high electric fields to it or to use very high temperatures such as in a flame. X-rays were much more easily controlled and enabled accurate measurements on gaseous conduction to be made for the first time. 'The X-rays seemed to turn the gas into a gaseous electrolyte'. (Quotation from Thomson's autobiographical *Recollections and Reflections*)

In 1895 Thomson began experimenting with electrical conduction in gases exposed to X-rays. He found that the conductivity produced by the X-rays did not reach its full value immediately when the rays were turned on and neither did the conductivity disappear immediately when the rays were turned off. There was a period when the gas was conducting even though the rays were off. On studying the gas in this state, Thomson found that the conductivity was destroyed by passing the gas through a filter of glass wool. The conductivity could also be filtered out without using a mechanical filter, for example, by exposing the gas to electrical fields. Thomson had already deduced three important conclusions about the gas in this state:

1. the conductivity is due to particles present in the gas
2. these particles are charged
3. the X-rays are producing these particles in the gas.

In experiments designed to investigate the relationship between the potential difference and the current in the gas, he found:

(a) for small voltages, the current produced was directly proportional to the potential difference
(b) for larger voltages, this proportionality did not persist and eventually, as the potential difference was increased further, the current reached a plateau
(c) no further increases in current were possible

unless the potential difference were increased to far higher values, values so large that they would have produced a large current even in the absence of the X-rays.

This is precisely what would have been expected if the X-rays were producing charged particles in the gas. When the current flows the charged particles move and eventually come into contact with the electrodes; there, they lose their charges and can no longer carry the current in the gas. The current passing through the gas is proportional to the number of charged particles which strike the electrodes in one second and, since the charged particles are produced by the rays, this number cannot be greater than the number of charged particles produced by the rays in that time. Thus, when X-rays are being used, the current has a limiting value controlled by the intensity of the rays and this effect can be used as a measure of the ray intensity.

The disappearance of the conductivity in the gas after the X-rays were stopped was due to the combination of the positive and negative ions to form neutral particles which could not carry electricity. This work led to many publications during the ensuing years; many of these papers were concerned with measuring some of the properties of the positive and negative ions, especially, perhaps, their mobilities and their rate of recombination. Rutherford made his own measurements of the coefficient of recombination and the ion mobilities. Zeleny also made important measurements of the ion mobilities by finding the electric force which would just move an ion against a known current of neutral gas and succeeded in showing that the mobility of the negative ion was often greater than that of the positive ion. He found that this difference was greater in carefully dried and pure gases than in damp or impure gases. Some considerable time later, Franck showed that the mobility of the negative ion could, in some cases, be reduced greatly by the addition of a trace of impurity. In pure helium, for example, the mobility of the negative ion was 100 times that of the positive ion, but adding a trace of oxygen reduced this ratio to 1.2. In retrospect, it can be understood that the high negative-charge mobility in pure helium is due to electrons which, when ejected from the helium by X-rays, can then move rapidly and conduct electricity. When oxygen is present, the liberated electrons are captured by oxygen molecules which can only move slowly under the action of an applied electric field.

5. THE DISCOVERY OF THE ELECTRON

Cathode rays had been known since 1859 when Plücker investigated the green phosphorescence on the glass near the negative electrode in his discharge tube. A pupil of Plücker, Hittorf, went on to observe that a solid body placed between a pointed cathode and the walls of the tube cast a well defined shadow. Goldstein made further observations along these lines and obtained shadows caused by a small object placed near a cathode of considerable area, showing that the rays casting the shadow came in a definite direction from the cathode. Goldstein advanced the theory that the rays were, in fact, transverse vibrations in the ether.

William Crookes (1832–1919) had performed experiments in which he had investigated the conduction of electricity through gases at various pressures.

When the discharge tube containing air was evacuated and a potential difference of about 10kV applied between cathode and anode, it was observed that pink streamers occurred between the electrodes. As the pressure was reduced, these streamers merged into a continuous band filling the tube. At a pressure of about 1mm of mercury, it became possible to distinguish several characteristic regions in the discharge such as the cathode glow and the Crookes and Faraday dark spaces as shown in Fig. 1. As the pressure fell further, the striations spread further apart and moved along the tube, eventually disappearing at the anode. At a pressure of about 1 micron of mercury the Crookes dark space extended the whole length of the tube, leaving only a slight glow on the cathode. Cathode rays were shown to be moving from cathode to anode. It is possible, of course, to interpret these results in terms of modern atomic structure, but all in due course. Before the discovery of the electron the properties of these cathode rays were investigated further in elegant demonstrations by Crookes and Lenard. They showed that many minerals and glass fluoresce with a characteristic colour when placed in a beam of cathode rays and that the rays can cast a shadow, for example, of a Maltese cross. The cathode rays were also demonstrated to carry energy and were shown to cause a piece of platinum foil placed in the path of the rays to become red- or even white-hot.

Jean Baptiste Perrin (1870–1942) had shown that the cathode rays carried with them a negative charge. In his experiments, a beam of cathode rays was allowed to pass inside a metal cylinder through a small hole. The cylinder, in this way, picked up a negative charge which could be measured with an electrometer. If the beam was deflected by a magnetic field, the cathode rays missed the hole and the cylinder did not charge up. This did not rule out the possibility that the cathode rays were waves in the ether and that the negative charges coming from the cathode were merely accompanying the cathode rays and were not the rays themselves. Thomson tried a refinement of Perrin's experiment involving two coaxial cylinders with the inner cylinder connected to an electrometer. In this case, the cathode rays could not fall on the cylinders unless deflected by a magnet. When the rays were so deflected, they passed through a slit in the outer cylinder and charged up the inner cylinder. In the absence of the deflecting magnet, the cylinder remained uncharged and the experiment proved that a stream of negatively-charged particles always accompanied the cathode rays.

Phillipp Lenard (1862–1947) was able to measure the range of cathode rays in various substances and drew important conclusions. He made a discharge tube containing a window composed of thin aluminium foil which was able to transmit the cathode rays from the inside of the tube to the outside. Lenard found that the

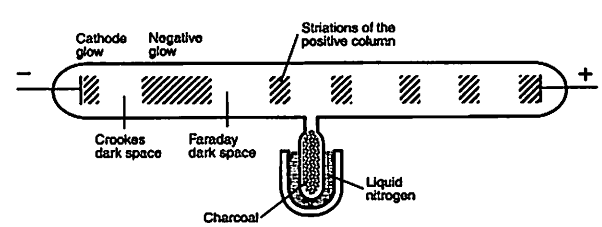

Figure 1. A low-pressure gas discharge tube. The pressure of the gas in the tube is typically a few mm of mercury. The charcoal, cooled by liquid nitrogen, acts as a pump to evacuate the tube to low pressures.

magnetic deflection of the rays outside the tube was independent of the density and chemical composition of the gas outside the tube although it did vary with the pressure of the gas inside the tube. These observations were consistent with the view that the cathode rays were started by acceleration through a given potential difference in the tube and their energies would depend entirely on what was going on inside the tube. Lenard proceeded to measure the absorption of the rays in various media by obtaining a value for the distance the rays could travel before the intensity fell to one-half of the original value. Although the results varied enormously for different substances, he was able to show that there was a straighforward link between the absorption coefficients and the densities of the substances he used. He was able to conclude that the distance the rays could travel in these substances depended on the density of the substance and not on the nature of the matter. Thomson was able to deduce from these results something about the size of the cathode ray particles. Lenard had shown that a cathode ray could travel a distance of about half a centimetre in air at atmospheric pressure before the accompanying phosphorescence fell to one half of the original value. The mean free path of air molecules at this pressure is about 10^{-5}cm, so that if a cathode ray particle were anything like an air molecule in size, it would have lost one half of its momentum in a distance comparable with this mean free path. This means that the size of the cathode ray charge carriers must be small compared with that of atoms or molecules. This in turn implied that the charge carrier was a state of matter more finely subdivided than the atom, a result which would prove to be correct and to have profound implications for atomic theory.

Thomson was puzzled by the fact that cathode rays were deflected by a magnetic field but were apparently not deflected by an electric field. The deflection in a magnetic field was explicable in terms of the cathode rays having a negative charge, but in that case why were they not also deflected by an electric field? Hertz had found that the cathode rays were not deflected at all by electric fields but they should have been if they carried a negative charge. Thomson tried deflecting a beam of cathode rays with an electric field using the apparatus shown in Fig. 2.

The beam of cathode rays streaming from the cathode C fell upon the anode A. The small hole in A

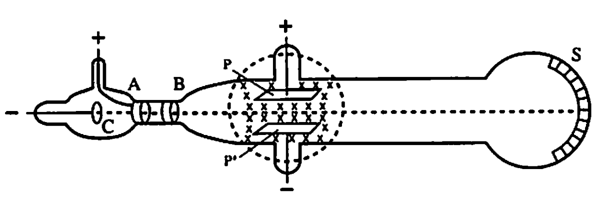

Figure 2. Thomson's method for measuring *e/m* for the cathode rays. Electrode C was the cathode and electrode A the anode, maintained at a high positive potential relative to C so that a discharge of cathode rays passed to it. Most of the rays hit A but there was a small hole through which some cathode rays passed. The rays were further restricted by electrode B thus forming a beam that fell on the fluorescent screen S. The electric field was applied between parallel plates P and P[1] in the vertical direction. The magnetic field, the use of which became standard in later experiments, was applied in the horizontal direction, shown in the diagram by small crosses indicating a field into the plane of the page. The magnetic field was switched off for the electrostatic deflection experiments.

allowed a portion of the cathode rays to proceed through to B containing a similar small hole. The narrow pencil of cathode rays so produced then passed through the space between two parallel plates across which a potential difference could be applied. Thomson failed to produce any lasting deflection of the cathode rays by this method. With his typical eye for detail, however, he noticed a slight flicker in the beam when the electric field was first switched on. He was able to deduce from this, rather cleverly, that there were likely to be some gas molecules in the space between the parallel plates. This gas could be ionized by the cathode rays when they passed through, this producing 'positively and negatively electrified particles'. The plate with a positive charge on it attracted the negatively-charged particles and the negatively-charged plate attracted the positively-charged particles. This neutralized the charge on the plates and so there was no lasting deflection of the beam of cathode rays. The flicker Thomson had seen, he reasoned, was due to the neutralizing of the plates not being instantaneous. In Thomson's view, the electric deflection experiment had failed because the pressure in the tube was too high and the next step would be to repeat the experiment with a better vacuum. This was eventually achieved, not without some problems, and Thomson was then able to get quite a marked deflection of the cathode ray beam using electric fields. This removed the discrepancy between the effects of magnetic and electric fields on the cathode rays or particles as Thomson began to call them. It also provided a method for measuring the velocity v of these particles and also m/e where m is the mass of a particle and e its electric charge.

Consider now the use of Thomson's apparatus with both a magnetic and an electric field applied. The force exerted by the electric field E on the particle is Ee and is in the same direction as E. The force exerted by the magnetic field B on the moving particle is Bev and acts in a direction at right angles both to the velocity of the particle and the field B. If the applied electric field E is at right angles both to the velocity and to the magnetic field B, the two forces act along the same straight line, and by altering B and E can be made to cancel each other out leaving the beam of particles undeflected.

In this case,

$$Ee = Bev$$

so that

$$v = E/B$$

This gave a simple method of finding v. Finding m/e for the particles could then be achieved by switching the electric field off and measuring the deflection produced by a known magnetic field acting alone, or by switching the magnetic field off and measuring the deflection produced by a known electric field acting alone. Using magnetic deflection, the cathode rays follow a circular path whose radius is

$$R = mv/Be$$

This radius could be measured and hence a value for mv/e was determined. This measurement of mv/e had been done by Schuster ten years earlier. Schuster however, had not measured v, arguing instead that the cathode particles had collided many times with gas molecules before reaching the place where the deflection was measured. On this basis, Schuster assumed that the cathode particles had the same energy as molecules of the gas at the temperature of the discharge tube. He came to the conclusion that the masses of the cathode particles were of the same order as the masses of the molecules of the gas through which they were passing. Thomson was not happy with this argument and, in particular, did not see how a beam of charged molecules which had collided many times with other molecules could maintain a sharp well-defined beam. Thomson decided to measure the energy of the cathode rays directly using a thermopile. The temperature to which the thermopile was raised in a given time was measured, and, since the heat capacity of the cylinder and its contents was known, the energy transferred in one second could be determined. If n is the number of cathode particles hitting the thermopile per second, m the mass, e the electric charge and v the velocity of the particle, the energy E given to the thermopile per second is

$$E = nmv^2/2$$

Q the charge given to the electrometer was

$$Q = ne$$

From the magnetic deflection, the value of $T = e/mv$ was obtained.
From these equations the charge-to mass-ratio was

$$e/m = 2ET^2/Q$$

giving the value of e/m in terms of quantities which could be measured.

Alternatively, by balancing the magnetic and electric deflections, the value of E/B for the case of zero deflection was obtained and then

$$e/m = TE/B$$

Thomson was able to find e/m for different gas fillings of the tube, such as air, hydrogen and 'carbonic acid gas' but found that the value of e/m was always the same. The mean value of e/m from 26 experiments was 2.3×10^7. The values of the velocity v varied from 2.3×10^9 to 1.2×10^{10} cm/s. The experiments described so far were exploratory and were not designed to given very accurate results. However, the results proved that e/m for the cathode particles was of the order of 10^7 whereas the smallest value found up to this point had been 10^4 for the hydrogen atom in electrolysis*. This meant that if e was the same charge as carried by the hydrogen atom, m had to be approximately one thousandth the mass of the hydrogen atom. The results obtained did not depend on the type of gas in the tube and Thomson found the results so surprising that he double-checked his results by trying electrodes made from other metals and discharge tubes made from different glasses. Finding no difference in his e/m result, he then tested negative particles generated by the photoelectric effect on a metal surface and from incandescent filaments. He found the same value for e/m for these particles. To make the argument for the new particle completely watertight, the charge e on the particles had to be measured directly to confirm that it was the same as the charge on a hydrogen atom in electrolysis. To do this, Thomson measured the charge by a method attributable to C. T. R. Wilson and J. S. E. Townsend. By inducing the charged particles to attach themselves to water droplets, and measuring their rate of movement in various electric fields, the charge could be inferred. This confirmed that the charge on the particles was in fact as Thomson expected, namely the same value as found in electrolysis experiments. Thomson drew the following conclusions after lengthy consideration:

1. 'That atoms are not indivisible, for negatively electrified particles can be torn from them by the action of electrical forces, impact of rapidly moving atoms, ultra-violet light or heat.'
2. 'That these particles are all of the same mass, and carry the same charge of negative electricity from whatever kind of atom they may be derived, and are a constituent of all atoms.'
3. 'That the mass of these particles is less than one-thousandth part of the mass of an atom of hydrogen.'

(Quotations from *Recollections and Reflections.*)

Thomson called the particles 'corpuscles' initially but they quickly became known as electrons, a name proposed by an Irishman, G. Johnstone Stoney. Thomson made the first announcement of the existence of the corpuscles in a Friday Evening Discourse at the Royal Institution on 30 April 1897.

Around the same time, Wiechert and Kauffmann independently obtained their own value for e/m and obtained a value reasonably close to Thomson's value. These investigators, however, did not make direct measurements of the velocity v or energy $mv^2/2$ of the cathode rays; they merely measured the magnetic deflection of the rays. Like Schuster, they estimated the energy by making assumptions about the relationship between the energy of the particle where its magnetic deflection was measured and the energy which it would have if it had been accelerated by the full potential difference between the electrodes in the discharge tube. At the one extreme, Schuster had assumed that the cathode particles lost almost all their energy by colliding with gas molecules in the tube but Wiechaert and Kauffmann assumed, at the other extreme, that they had lost none of this energy. Thomson argued that it was impossible to be sure of the energy of the cathode particules at any point in their passage through the discharge tube because the mechanism of the discharge in the gas was not understood, and placed great emphasis on measuring the velocity v directly. Kauffmann interpreted his results in a different manner to Thomson, arguing that the fact that the calculated value of e/m did not vary by using dfferent gases, or metals for the electrodes, proved that the cathode rays did not originate from the gases or the metals. Thomson interpreted these results correctly as meaning that these small corpuscles, 'bodies smaller than atoms', were contained in all atoms and that they could be extracted by various means, for example, heat, electrical discharge or by the action of X-rays. Using the

*In SI units, the currently accepted ratio of charge to mass is 1.758 × 10" C.kg^{-1}

fact that the value obtained for the charge was equal to the charge carried by the hydrogen atom in electrolysis, Thomson was able to deduce that the mass of the corpuscle was in fact about 1800 times smaller than that of a hydrogen atom. A natural extension of this investigation was to find out how many electrons were present in atoms. This was done for the first time in the Cavendish Laboratory in 1904 by measuring the scattering of X-rays passing through a gas. Barkla did this for several gases and showed that for most gases the number of electrons in the atom was about one half the atomic weight. The hydrogen atom contained just one electron. Many years later, in 1927, Davisson and Germer directed a beam of electrons at the face of a nickel crystal and measured the number of electrons coming off in different directions. They found that there were several directions in which the scattered electrons showed maxima of intensity and that these corresponded to the direction of diffracted X-rays of a particular wavelength. This wavelength λ was in good agreement with the de Broglie equation $\lambda = h/mv$ where h is Planck's constant.

Shortly after this, G. P. Thomson, J. J. Thomson's son, published results showing that a homogeneous beam of electrons could be diffracted when passing through a thin foil. The photographs he obtained showed a bright central spot surrounded by some fainter rings, the diameters of which were in agreement with the de Broglie equation.

6. THE STUDY OF POSITIVE RAYS

Positive rays, or 'Kanalstrahlen' were discovered by Goldstein in 1886 as rays moving towards the cathode and colliding with it. He observed them as fine pencils streaming through holes he had made in one of his cathodes. They were not appreciably deflected by magnetic fields, but Wien eventually proved that they were, in fact, deflected though to a lesser extent than cathode rays and in the opposite direction. Wien had proved, therefore, that the rays carried positive charges and he succeeded in measuring their e/m value as being a maximum of 10^4. Thomson investigated these carriers of positive charge and wanted to know if they were all of the same type.

The method he used to investigate this was to send a narrow beam of rays between two parallel brass plates and to apply an electric and a magnetic field, both in a direction at right angles to the plates (see Fig. 3). As the beam passed between the plates, the positive ray particles experienced two forces; a force along the y direction (see Fig. 3(b)), due to the electric field and one along the z direction due to the magnetic field. A spot was produced on the photographic plate at the end of the tube where the particles struck it. One can show that, if the ions are considered to be moving initially in the x direction and the fields are applied in the y direction, then ions of charge Q and mass M will be deflected in the apparatus to form a parabola in the yz plane on the screen or photographic plate according to the equation

$$z^2 = k\frac{Q}{m}y$$

where k is a constant depending on the field strengths and the distances L and D. The discharge tube bore a strong similarity to the earlier one used for the determination of e/m for the electron. There was a wide range of velocities to be catered for and Thomson was compelled to use the parallel electric and magnetic

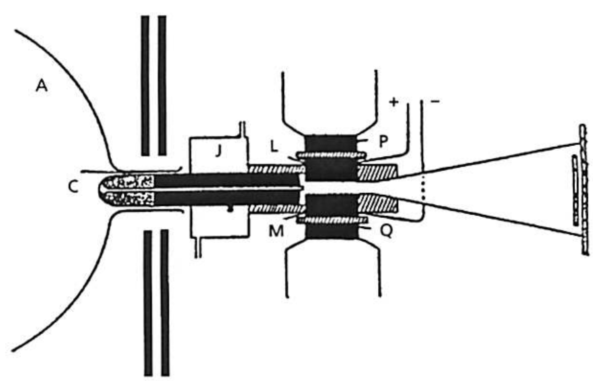

Figure 3. (a) Thomson's positive ray apparatus built in 1897, reproduced from his book, *Positive Rays and Their Application to Chemical Analysis* (1913). A is a vessel containing gas at low pressure. The cathode C is long and of narrow bore. The pencil of positive rays is acted upon by an electric field as it passes between the plates L and M. A magnetic field is applied between the poles of an electromagnet P and Q.

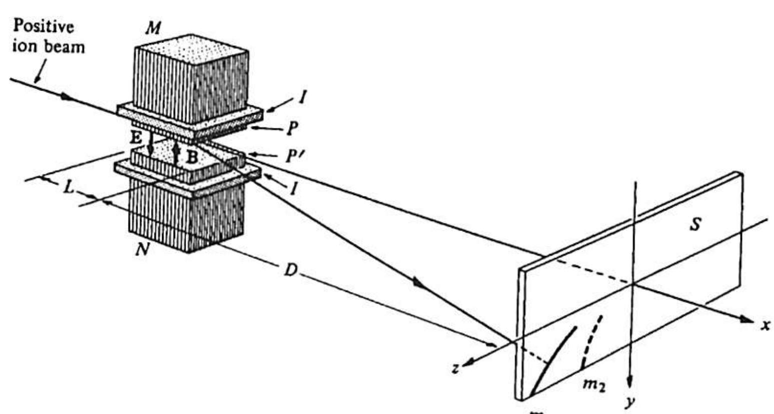

Figure 3. (b) Formation of positive ray parabolas. The electric and magnetic fields are applied in opposing directions along the y axis. The x axis corresponds to the original direction of motion of the positive-ray beam. The z axis is at right angles to x and y. In this diagram, the poles of the electromagnet are shown as M and N and the electrical deflection is produced by plates P and P^1. A layer of insulating material is shown as I.

fields for this reason. The extent of the arc of the parabolas obtained depended on the spread of energies in the beam, those particles with the highest energies coming closest to the origin.

Thomson experienced great difficulties due to the fact that the penetrating power of the positive rays is far less than that of cathode rays, resulting in the positive rays failing to reach the screen unless the pressure was very low. If he made the pressure low enough for the positive rays to reach the screen, then he could not obtain a gas discharge. If, on the other hand, he made the pressure in the discharge tube higher than on the other side of the cathode, gas flowed through the holes and raised the pressure there also. To overcome this difficulty, Thomson introduced a fine-bore capillary so that gas in the discharge tube had to pass through this before reaching the other side of the cathode. This acted as a small leak and continuous pumping ensured that the pressure in the remainder of the tube was low enough to enable the positive ray particles to reach the screen. The first result he obtained on his screen was a straight line passing through the origin giving an *e/m* value of 10^4. This line was always present no matter what gas was being used in the discharge tube and it looked as though the carriers of positive electricity were all the same; charged hydrogen atoms. By using a large vessel as the discharge tube and using a lower pressure for the discharge, Thomson then got two lines on the plate, the first one the same as before with $e/m = 10^4$ and the second one with $e/m = 0.5 \times 10^4$ the value to be expected for a molecule of hydrogen. These two lines were the only ones he saw until be inserted helium, and he then got a third line with $e/m = 0.25 \times 10^4$, the value corresponding to an atom of helium. A new liquid air plant at the Cavendish Laboratory then meant that lower pressures could be achieved and soon the experimenters had no difficulties in obtaining parabolas for atoms and molecules of oxygen and nitrogen and atoms of carbon. Hydrogen had been observed in the early experiments because hydrogen was always present on the walls of the discharge tube and was given off when the discharge was passed through the gas. The light hydrogen atoms and molecules had greater penetrating powers than the heavier elements and so were able to reach the screen easily. Helium was almost as penetrating as hydrogen and so that was detectable but detection of rays corresponding to the other gases had had to wait for improved vacuum techniques. These experiments showed that the positive charges were just atoms which had lost one electron. The improvement in vacuum made a huge difference to the applicability of the positive ray method as shown by the plate of Fig. 4.

The gas in the tube in this case was the residual gas left after it had been pumped to a very low pressure. There are parabolas due to particles for which $m/e \times 10^4$ equals 1,2,12,14,16,28,44 due to atoms of carbon and molecules of nitrogen, carbon monoxide, carbon dioxide and hydrogen, some of which may to too faint to be observed in the reproduction shown in Fig. 4. If this plate and similar ones were examined carefully, it was observed that there were a series of straight lines connecting the parabolas with the origin. Thomson was able to show that these were due to particles which had been charged during only a portion of the path through the magnetic and electric fields. In other words, positive ions could be converted to neutrals in collision processes and, in a similar way, previously neutralized particles could be converted back to positively-charged particles. Going back to the parabolas themselves, each kind of charged carrier produced its own parabola on the plate. A spectrum of the gas was produced and, by inspecting the plate, Thomson was able to infer not only the number of kinds of carriers, but also from the dimensions of the parabolas the atomic or molecular weight of each carrier. This spectrum enabled the nature of the gases inside the tube to be determined and thus provided a method of chemical analysis. Thomson quickly realised the power of the new method for analysis and contrasted it to ordinary spectrum analysis. An unknown line in the optical spectrum of a discharge tube, for example, could only be interpreted as a possible unknown substance in the tube. However, if a new parabola was observed in the positive ray spectrum, the atomic or molecular weight could be read off immediately giving an indication of what the substance was. Thomson also realized that by taking very long exposure times, he could make the method extremely sensitive and detect trace quantities of gases too small to be detected by spectroscopy. He concluded 'the amount of gas required is very small, as the pressure of the gas is exceedingly low, generally less than one-hundredth part of a millimeter of mercury.' Another advantage of the method was that it did not matter if the sample gas was impure; any impurities

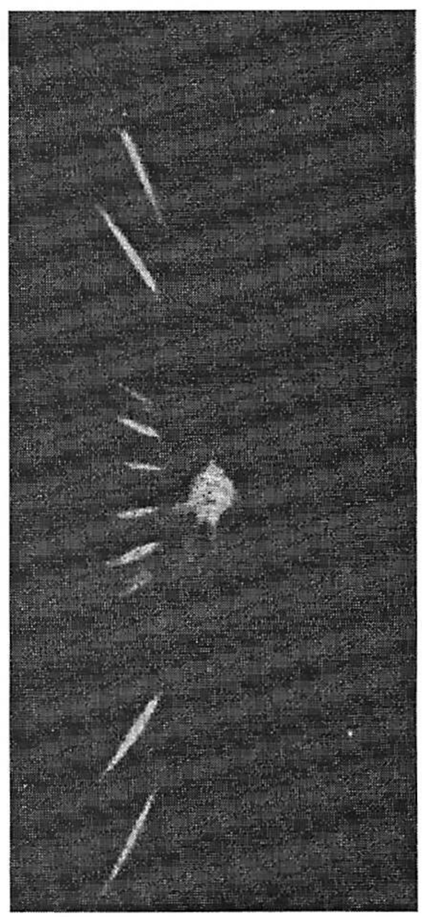

Figure 4. Positive ray parabolas. The pressure on the camera side of the apparatus was approximately 0.001 mm of mercury. The deflection due to the magnetic field is in the vertical direction and that due to the electric field is in the horizontal direction.

present would merely appear as extra parabolas in the spectrum and would not interfere in the measurement of the atomic weight of the main constituents of the sample. Thomson was also very quick to realize that intermediate forms or free radicals could be detected in the analysis since the rays were registered on the photograph approziately one microsecond after their formation and that this could give insights into the process of chemical combination. Thomson took large numbers of photographs of the parabolas from different gases, among these some samples of gases obtained from the residues of liquid air. These produced, among other parabolas, a strong parabola of neon, atomic weight 20, and another parabola nearby corresponding to mass 22. The neon 20 line was always accompanied by the 22 line and another line apparently corresponding to a particle of mass 11. It could have been argued that 22 corresponded to neon 20 as a hydride NeH_2 and that the line at 11 could have been interpreted as doubly-charged carbon dioxide. Thomson realised this was unlikely because although atoms were frequently observed in doubly-charged form, molecules almost never were. Carbon dioxide was fairly easily removed from the tube but doing this did not affect the intensity of the 22 line. This was the first observation of stable isotopes among the elements. 'Two elements A and B' (in this case neon 20 and neon 22) 'are isotopes if their chemical properties are identical but their atomic weights different.' (Quotation from *Recollections and Reflections*.)

Sometimes Thomson's parabolas showed a smaller deflection from the line of no electrostatic deflection than was usual, indicating that these positive rays had higher energy than normal. This was explained on the basis that two electrons had been removed from the atom or molecule in the discharge and it had thus picked up twice as much energy as usual from the accelerating field. If the doubly-charged particle then regained an electron after passing through the cathode and before reaching the deflecting fields, they would lie along the parabola corresponding to the normal charge but extending much nearer to the origin. If they did not regain an electron after passing through the cathode, those rays would appear along the parabola with a double value of *e/m*, and this second parabola was always observed along with the ones showing the prolongation. In fact, Thomson was able to go further than this and was able to observe multiple-charged atomic ions with any number of positive charges from 2 to 8. The gas discharge usually decomposed any gas consisting of molecules into its constituent atoms or into any combination of the atoms. It was also possible to observe association reactions as well as decomposition. For example Conrad obtained a positive ray spectrum for 'marsh gas' methane (CH_4) shown in Fig. 5. There are lines here corresponding to C,H,CH, CH_2,CH_3,CH_4; C_2,H_2,C_2H,C_2H_2,C_2H_3,C_2H_4; C_3,H_3, C_3H,C_3H_2,C_3H_3,C_4H_4

It was evident that the normal rules of valency were suspended but it was also recongized that some of these species may have had only a transient existence. It is clear from the example of methane that polyatomic ions could now be observed routinely in positive ray experiments. In subsequent experiments, ion/molecule reactions were observed for the first time producing, for example, CH_5^+ from methane gas. It also became clear, by examining the traces produced in many experiments, that negative ions could be generated. These were observed as parabolas which had been deflected in the opposite direction to the positive ray parabolas, in other words, having negative electric and magnetic deflections. Dissociation of molecular ions was observed using the parabola apparatus and Thomson pondered the mechanism by which a molecular ion could fragment in the process of collision with a neutral atom or molecule. Thomson was also able to infer the existence of strange processes such as charge-stripping and charge-exchange by collision. He did this by

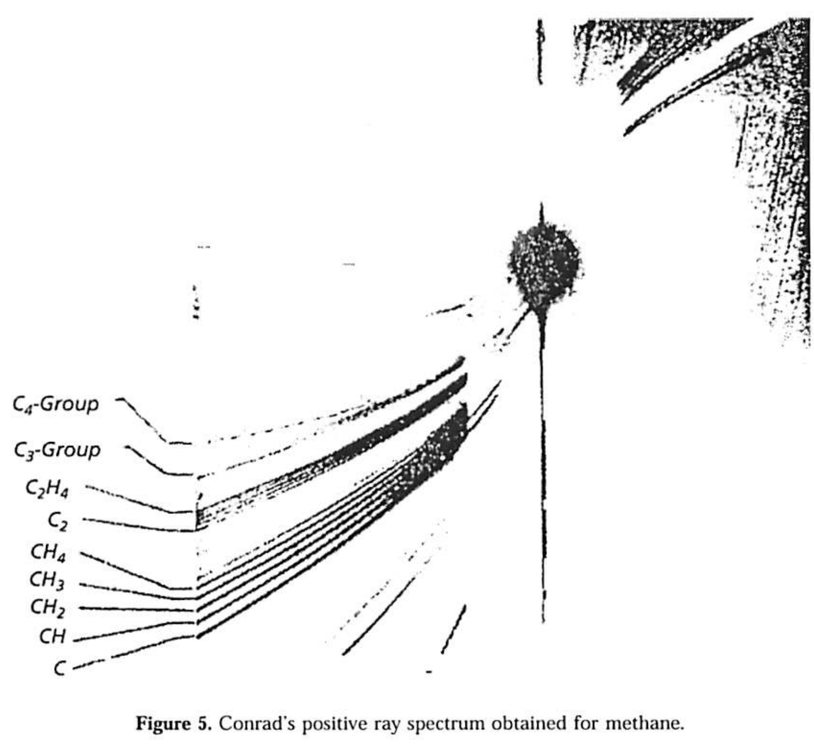

Figure 5. Conrad's positive ray spectrum obtained for methane.

producing positive rays in a tube modified so as to allow room for two electromagnets along the flight path. By undertaking experiments with this tube he was able to deduce that positive ions could be converted to neutral particles in a collision process. Furthermore, in subsequent collisions these neutrals could convert to negative ions. All three entities could be detected on the screen of Thomson's modified apparatus. All of these discoveries were to become of immense importance in the field of mass spectrometry, but the commercial exploitation of mass spectrometry was still a long way off when Thomson reported all these discoveries in his book *Positive Rays and Their Application To Chemical Analysis* in 1913. Thomson's closing words in this book were 'The positive rays thus seem to promise to furnish a method of investigating the structure of the molecule, a subject certainly of no less importance than that of the structure of the atom.' It is a tribute to Thomson that all the important discoveries had been made and mass spectrometry, as a field of study, really took off from the 1930s onwards after Aston, Bainbridge, Dempster and Nier had made a full and thorough study of the isotopes of heavier elements.

Francis William Aston (1877–1945), one of Thomson's students, made many valuable accurate mass measurements on isotopes and discovered isotopes for most of the elements using a new design of positive ray instrument. This instrument (Fig. 6) built upon the work which Thomson had undertaken with positive ray parabolas and was the forerunner of all double focusing sector machines. In this instrument the electric and magnetic fields were placed in series with the positive rays passing through the electric field first and the magnetic field second.

The positive ray is deflected first downwards by the electric field between the plates P_1 and P_2 and then upwards in a magnetic field indicated by a coil M. By suitable construction of the instrument it was possible to ensure that positive rays with the same *e/m* but with arbitrary velocity were focused at one and the same point P on the photographic plate. A mass spectrum would then be obtained on the photographic splate. A selection of Aston's results is shown in Fig. 7.

Aston investigated the atomic weights of most of the elements and found that, for example, chlorine was composed of isotopes of masses 35 and 37. Previously, chlorine had only been known to have an atomic weight of 35.4 and this elucidation of the isotope patterns for the elements continued in a thorough examination of the Periodic Table involving Aston and other workers. Thomson was awarded the Nobel Prize for Physics in 1906. Aston was awarded the Nobel Prize for Chemistry in 1922, this being only one of at least seven Nobel prizes which have been won by Thomson's students.

Thomson retired from the Cavendish Laboratory in 1919, but never stopped work. He died on 30 August 1940.

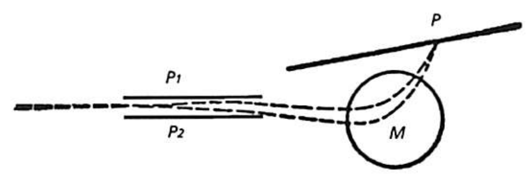

Figure 6. Aston's mass spectrograph. The parallel plates P_1 and P_2 produce electric deflection of the ion beam. The electromagnet M produces a magnetic field in the space between the pole pieces.

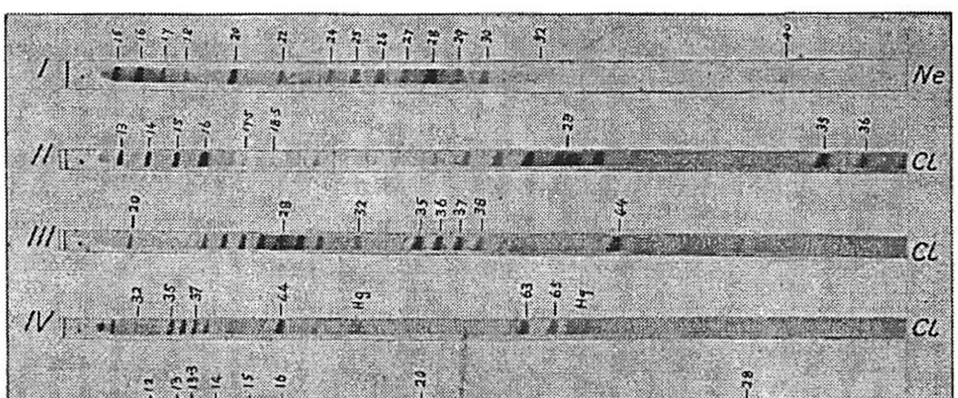

Figure 7. Mass spectra produced by Aston using the 'focus method' for neon, chlorine, argon, krypton and xenon.

7. ACKNOWLEDGEMENTS

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In a life as full as that of J. J. Thomson's, it is impossible in an article of this length to cover all the aspects that one might wish to, and the author apologizes if anything important has been left out. Hopefully, any missing details can be obtained by referring to the publications listed in the bibliography in Section 8, although this is by no means exhaustive. The author would like to thank the University of Glamorgan for its support.

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18. J. J. Thomson in *Phil.Mag.*, **VI**, xviii, p.824 (1910), on positively-charged particles becoming first neutral and then negatively-charged as a result of collisions.

SOME IMPORTANT DATES IN THE LIFE OF J. J. THOMSON

1856 Born at Cheetham, Manchester, UK.
1871 Started at Owens College.
1876 Arrived at Trinity College, Cambridge.
1880 Graduated via the Cambridge Mathematical Tripos.
1882 Appointed lecturer in mathematics at Trinity College.
1883 Appointed University Lecturer.
1884 Elected Fellow of The Royal Society.
1884 Cavendish Professor of Experimental Physics.
1887 Bakerian Lecturer (again in 1913).
1890 Married Rose Elizabeth Paget.
1892 His son, George Paget Thomson, was born.
1897 Announced the measurement of *e/m* for cathode ray particles.
1905 Appointed Professor of Natural Philosophy at the Royal Institution.
1906 Awarded Nobel Prize in Physics.
1908 Knighted.
1909 Was made President of The British Association.
1912 Admitted to Order of Merit.
1914 Awarded Copley Medal of Royal Society.
1916 Elected President of the Royal Society.
1919 Resigned chair at Cavendish Laboratory.
1920 Resigned chair at Royal Institution.
1940 Died. Ashes were buried in the nave of Westminster Abbey, London, near those of Newton, Darwin, Herschel, Kelvin and Rutherford.