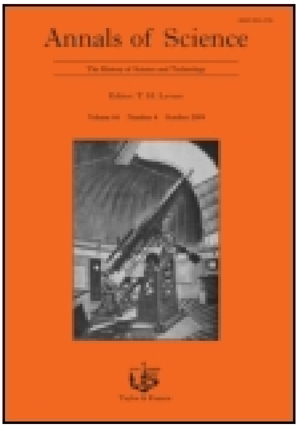

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J. J. Thomson at the cavendish laboratory: The history of an electric charge measurement

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J. J. Thomson at the Cavendish Laboratory: The History of an Electric Charge Measurement

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Summary

J. J. Thomson's discovery of the negatively charged *corpuscle* in 1897 is customarily regarded as the discovery of the electron. Thomson, however, did not immediately equate the charge of his *corpuscle* with the unitary charge, that is the 'electron', first proposed by Stoney in 1874. The aim of this paper is to clarify the means by which this identification was eventually made. To do this the work carried out by Thomson and his students at the Cavendish Laboratory between 1897 and 1899 has been examined. From this reconstruction it emerges that, following his work on the mass-to-charge ratio of the *corpuscle* in 1897, Thomson and his school initiated and developed a series of techniques for measuring the charge of the ions. These techniques could not be used directly to measure the charge of the *corpuscles* because of the conditions required to produce them. Thomson therefore sought some other phenomenon that could be interpreted in terms of *corpuscles* and which allowed exploitation of the new charge-measuring techniques. He found such a phenomenon in the photoelectric effect, which allowed the measurement of both the charge and the mass-to-charge ratio of the *corpuscle* to be made. These measurements showed the charge of the *corpuscle* to be close to that assigned to the 'electron', and the two entities gradually became equated with each other.

Contents

1. Introduction

The phenomena attending the electrical discharge through gases are so beautiful and varied that they have attracted the attention of numerous observers. The attention given to these phenomena is not due however to the beauty of the experiments, so much as to the wide-spread conviction that there is perhaps no other branch of physics which affords us so promising an opportunity of penetrating the secret of electricity; for, while the passage of this agent through a metal or an electrolyte is invisible, that through a gas is accompanied by the most brilliantly luminous effects which in many cases are so much influenced by changes in the conditions of discharge as to give us many opportunities of testing

> any view we may take of the nature of electricity, of the electric discharge, and of the relation between electricity and matter.

Thus wrote J. J. Thomson, Director of the Cavendish Laboratory in Cambridge, in his book *Notes on Recent Researches into Electricity and Magnetism.*[1] It was no coincidence that in this period the processes of electrical discharge through rarefied gases, and more generally the relationship between electricity and matter, were becoming the focal point of theoretical and experimental activity by Thomson in person and by others promoted by him at the Cavendish Laboratory. It was this type of activity, and especially research into the so-called 'cathode rays' that enabled Thomson,[2] in 1897, to capture the first signs of the existence of a sub-atomic particle: the electron or *corpuscle* as Thomson called it.

This is not the place to examine in detail the various and complex motivations that led Thomson to define cathode rays as a first atomic particle.[3] After demonstrating experimentally that the 'cathode rays' were in fact negatively charged particles, Thomson measured their mass-to-charge ratio. Irrespective of the type of gas or the cathode material, these measurements gave him results that were always the same, in order of 10^{-7} g/e.m.u. (i.e. in the range 0·5–1·0 10^{-7} g/e.m.u.). These were smaller by a factor of 10^3 than the smallest value to date, that of the hydrogen ion. At a time when the concept of the atom as a simple structure began to lose ground as new experiments were performed, Thomson's results led him to the conclusion that the particles making up cathode rays (*corpuscles*, as Thomson called them) were sub-atomic particles and, as such, were 'smaller than the hydrogen atom'. At this point Thomson was immediately faced with another question: if these hypothetical particles really did exist, how much 'smaller than the hydrogen atom' were they in fact?

This paper[4] looks at the problem and reconstructs the path followed by Thomson between 1897 and 1899, when he succeeded in giving the 'smaller than the hydrogen atom' attribute a precise numerical value based on a measurement of the charge, so providing, as J. J. Thomson wrote to Rutherford on 23 July 1899, 'direct proof of the existence of masses only 1/1000 of the hydrogen ion'.[5]

This measurement of the charge is generally neglected by historical reconstructions of the discovery of the electron. These reconstructions indeed tend to give ample space to the measurements carried out by Thomson in 1897 on the mass-to-charge ratio of

[1] J. J. Thomson, *Notes on Recent Researches into Electricity and Magnetism* (Oxford, 1893), 189.

[2] J. J. Thomson, 'Cathode Rays', *The Electrician* (21 May, 1897), 104–111; idem, 'Cathode Rays', *Philosophical Magazine*, 44 (1897), 293–316.

[3] See, for example D. L. Anderson, *The Discovery of the Electron* (Princeton, 1964); E. Whittaker, *A History of the Theories of Aether and Electricity* (New York, 1952); G. E. Owen, 'The Discovery of the Electron', *Annals of Science*, 11 (1956), 172–82; D. J. Price, 'Sir J. J. Thomson, O.M.F.R.S.', *Nuovo Cimento*, 4 (1956), Supplement, 1609–29; N. Robotti, *I primi modelli dell'atomo: dall'elettrone all'atomo di Bohr* (Turin, 1978); S. M. Feffer, 'Arthur Schuster, J. J. Thomson, and the Discovery of the Electron', *Historical Studies in the Physical and Biological Sciences*, 20, Pt. 1 (1990), 33–61; I. Falconer, 'Corpuscles, Electrons and Cathode Rays: J. J. Thomson and the "Discovery of the Electron"', *British Journal for the History of Science*, 20 (1987), 241–76; M. Chayut 'J. J. Thomson: the Discovery of the Electron and the Chemist', *Annals of Science*, 48 (1991), 527–44; H. Kragh, 'Concept and Controversy: Jean Becquerel and the Positive Electron', *Centaurus*, 32 (1989), 203–40.

[4] A preliminary study on the subject was published by N. Robotti, 'La tela del ragno: storia di una misura di carica elettrica', *Scritti di Storia della Scienza in onore di Giovanni Battista Marini Bettolo nel 75° compleanno*, a cura di A. Balio and L. Paoloni, Rendiconti della Accademia Nazionale delle Scienze detta dei XL, Serie V, 14 (1990). 378–91.

[5] J. J. Thomson to E. Rutherford, Cambridge 23 July 1899, E. Rutherford correspondence, Cambridge University Library, Cambridge.

the *corpuscle* and concerning the measurement on the charge they tend to refer to the calculations carried out much earlier in relation to electrolytic phenomena.

From this analysis, however, it appears that the measurement of the charge of the *corpuscle* was of fundamental importance in the framework of research programmes on the structure of matter carried out at the end of the nineteenth century. The *corpuscle* was a new physical entity, different from those previously introduced to interpret electrolytic phenomena and, as such, was a completely unknown object. This was the reason for Thomson's feverish search for a method to measure the charge of the *corpuscle* without reference to other physical quantities, such as atoms and molecules.

This historical reconstruction of the first measurement of the charge of the *corpuscle* has led to the re-examination of a whole series of activities promoted by Thomson at the Cavendish Laboratory from about 1890 onwards, and which eventually led to the development of new technologies (including C. T. R. Wilson's cloud chamber). These activities, suitably revised and modified, allowed Thomson to measure the physical parameters of the *corpuscle* in 1899. However, what emerged from Thomson's measurements was no longer the concept of the *corpuscle*, introduced in 1897 to explain the very specific phenomenon of cathode radiation. What was now at stake was the fundamental quantity that finally provided the key to understanding 'the secret of electricity', rewarding Thomson's many years of faith in theoretical and experimental research into the subject of 'electricity and matter'.

2. Unitary charge and the divisible atom: preamble

In 1891, Stoney[6] introduced a new scientific term, 'electron', by which he meant the 'defined quantity of electricity' or multiples of it, by means of which atoms seemed to combine chemically and which was evident in electrolytic processes, when the molecules of the electrolyte broke down into 'positive ions' and 'negative ions' under the action of the electric field.

Stoney first looked at this 'defined quantity of electricity' in 1874[7] when he interpreted Faraday's electrolysis laws in the light of Kekulé's recently proposed atomic valence theory. In 1881 Helmholtz independently arrived at a similar concept using Faraday's work as a basis.[8] In a paper sent to the Chemical Society in London, significantly titled 'On the modern development of Faraday's conception of electricity', Helmholtz stated that:

> Faraday's law tells us that through each section of an electrolytic conductor we have always equivalent electrical and chemical motion. The same definite quantity of either positive or negative electricity moves always with each univalent ion or with every unity of affinity of a multivalent ion and accompanies it during all its motions through the interior of the electrolytic fluid. This quantity we may call the electric charge of the atom.[9]

[6] G. J. Stoney, 'On the cause of the double lines and the equidistant satellites in the spectra of gases', *Scientific Transactions of the Royal Dublin Society*, 4 (1891), 518–29.

[7] G. J. Stoney, 'On the Physical Units of Nature', *Report of the British Association, Forty-fourth Meeting, Belfast, 1874*, published with the same title in *Philosophical Magazine*, 11 (1881), 381–90; *Proceedings of the Royal Dublin Society*, 3 (1883).

[8] N. Robotti, 'L'elettrone di Stoney', *Physis*, 21 (1979), 103–24.

[9] H. Helmholtz, 'On the modern development of Faraday's conception of electricity' (The Faraday Lecture, delivered before the Fellows of the Chemical Society, in the Theatre of the Royal Institution, on Tuesday, April 5, 1881), *Journal of The Chemical Society* (1881), 277–304.

Unlike Helmholtz, Stoney had already estimated the value of the 'unitary charge' in 1874.[10] Basing his ideas on kinetic theory (which made it possible to calculate Avogadro's number and thus the mass of the hydrogen atom) and using tables of electrochemical equivalents relating to the electrolysis of water, Stoney arrived at the figure of 3×10^{-11} e.s.u. ($1{\cdot}03 \times 10^{-21}$ e.m.u.). Other estimates were made after this, all with values between $1{\cdot}40 \times 10^{-10}$ e.s.u. ($4{\cdot}71 \times 10^{-21}$ e.m.u.) and $1{\cdot}29 \times 10^{-10}$ e.s.u. ($4{\cdot}31 \times 10^{-21}$ e.m.u.). In the last decade of the nineteenth century therefore, the concepts of 'unitary charge' or 'electron', and with it the concept of 'ion' understood as the 'atom of matter with its charge' took their place in common scientific discourse.

This said, one immediately asks why Thomson, when in 1897 he identified the *corpuscle* as the first subatomic particle and measured its mass-to-charge ratio, did not give it a charge value equal to the 'charge unit' that had emerged from research into electrolytic processes? This would immediately have led to an initial estimate of the mass of the *corpuscles* without waiting for a separate measurement of the charge.

The answer may be sought in the significance that Thomson attributed to the term *corpuscle* and in the innovative role it played in the concept of the atom at that time. In fact, it was one thing to think, as scientists did, that atoms or molecules contained one or more unitary charges and that these, as Stoney was first to suggest, were the basis of chemical bonds, electrolytic phenomena, etc. In this light the atom was certainly a complex structure, but still indivisible. It was another thing, however, to suppose, as Thomson put forward in 1897, that the atom was formed not only by charged particles of matter—the *corpuscles*—but that it could be broken down into the *corpuscles*. In this case the indivisibility of the atom, which until then had never been questioned, was automatically sacrificed and, as Fitzgerald[11] pointed out, the possibility of 'transmutation of matter' would have had to be considered. To sum up, Thomson's idea of the divisibility of the atom was a truly revolutionary and remarkable idea in the framework of physics in the 1890s. Indeed its acceptance was not immediate and total.[12]

This is how Thomson presented the new atom in 1897:

> The explanation which seems to me to account in the most simple and straightforward manner for the facts is founded on a view of the constitution of the chemical elements which has been favourably entertained by many chemists: this view is that the atoms of the different chemical elements are different aggregations of atoms of the same kind. In the form in which this hypothesis was announced by Prout, the atoms of the different elements were hydrogen atoms; in this precise form the hypothesis is not tenable, but if we substitute for hydrogen some unknown primordial substance X, there is nothing known which is inconsistent with this hypothesis ... If in the very intense electric field in the neighbourhood of the cathode, the molecules of the gas are dissociated and are split up, not into the ordinary chemical atoms, but into these primordial atoms, which we shall for brevity call corpuscles; and if these corpuscles are charged with electricity and projected from the cathode by the electric field, they would behave exactly like the cathode rays.[13]

[10] Stoney (footnote 7), 389.
[11] G. F. Fitzgerald, 'Dissociation of atoms', *The Electrician* (21 May, 1897), 102.
[12] This subject is covered excellently in paragraph 5 of Falconer (footnote 3).
[13] Thomson, *Phil. Mag.* (footnote 2), 311.

Thomson thus concluded:

> Thus on this view we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state: a state in which all matter—that is, matter derived from different sources such as hydrogen, oxygen, etc.—is of one and the same kind; this matter being the substances from which all the chemical elements are built up.[14]

With this idea of the *corpuscle*, it is clear that in 1897 there was no a priori reason for seeing the *corpuscle* and the 'electron' as one. In other words 'electron' on the one hand and *corpuscle* on the other started out and continued to seem to be two entities not necessarily connected and had to be treated as such. This was the basic reason why Thomson, faced with the problem of physically defining the *corpuscle*, had to devise a research programme (1897–99) to measure its specific charge. Only at the end of this programme was he able to see that the charge of the *corpuscle* and the 'electron' were one and the same thing, thereby uniting two aspects of reality that until then had seemed to be two distinct entities.[15]

Thomson's research programme involved studying other sectors because of the difficulties he immediately encountered in designing a charge measurement for cathode rays. It was made possible by the dense network of activities focused on the 'passage of electricity through gases' that he had started to develop at the Cavendish Laboratory in the 1890s.

3. A new technique

On 8 November 1893, C. T. R. Wilson wrote to Professor J. J. Thomson in order to apply for the Clerk Maxwell scholarship:[16]

> The subject I would propose to investigate is the way in which a dissolved body distributes itself in its solvent when the top and bottom of the solution are kept at different constant temperature ... I would determine the concentration of different parts of the solution optically.

Less than two years later the journal *Proceedings of the Cambridge Philosophical Society* carried a brief note by Wilson entitled 'On the formation of cloud in absence of dust'.[17]

This note, which was only marginally related to the programme of studies Wilson had originally proposed,[18] marked the beginning of a new phase of experimental activity at the Cavendish Laboratory, focusing on the processes of condensation of saturated and supersaturated vapours and their connection with the presence of charge. Interest

[14] Ibid., 312.

[15] Kelvin's 1902 proposal (Lord Kelvin, 'Aepinus atomized', *Philosophical Magazine*, 3 (1902), 257–83) to use the term 'electron' in place of *corpuscle* is highly significant. It reflected the need to include the two historically different concepts of electron and ion in a single term. The first concept was unitary charge and the second meant more generally an atom of matter associated to a charge.

[16] C. T. R. Wilson, Sidney Sussex College 8 November 1893, correspondence of J. J. Thomson, Cambridge University Library, Cambridge.

[17] C. T. R. Wilson, 'On the formation of cloud in absence of dust', *Proceedings of the Cambridge Philosophical Society*, 8 (1895), 306.

[18] For further information on this subject and more generally on Wilson's attitude to study condensation processes, see P. Galison and A. Assmus, 'Artificial clouds, real particles', in *The Uses of Experiment*, edited by D. Gooding, T. Pinch and S. Schaffer (Cambridge, 1989).

in this type of study by those working at the Cavendish Laboratory, and particularly by J. J. Thomson, was not completely new. In 1893, Thomson had studied the strange phenomena[19] noticed by Helmholtz,[20] Helmholtz and Richarz,[21] Bidwell,[22] and Aitken,[23] regarding the condensation of a jet of vapour through air in the presence of 'electrification and chemical action'. Thomson had linked the phenomena with the presence of ions, to show that free ions favour condensation by virtue of the electrical charge they carry, i.e. behave like condensation nuclei. Consequently, according to Thomson, the use of a jet of vapour seemed a promising method for detecting the presence of electrification. Thomson's contribution was theoretical only. The occasion to experiment came with the arrival at the Cavendish Laboratory of C. T. R. Wilson, a young man, whom Thomson declared to be very able and promising on the experimental side.[24]

Wilson's first step at the Cavendish Laboratory was to shift the emphasis from condensation of a vapour jet to condensation of saturated gases. In 1895 he succeeded in building an experimental apparatus capable of causing the condensation of a certain quantity of air saturated with water vapour by sudden expansion cooling, even in the absence of dust.[25]

Henceforth, Wilson's experimental activity kept pace with new information regarding the various types of radiation emitted by bodies. In 1896 Roentgen[26] discovered the so-called 'X-rays' and a few months after this Wilson[27] analysed the action of this radiation on the condensation of saturated air. Becquerel[28] discovered 'Uranium rays' in the same year and in 1897 Wilson studied their effect on condensation.[29]

This type of research showed Wilson that the conditions for condensation in the case of exposure to both X-rays and Uranium rays were the same as those defined earlier in the case of ordinary air. The only difference was that even though all impurities were eliminated, far more droplets were formed in the condensation process with X-rays and Uranium rays. For Wilson this meant that both X-rays and Uranium rays passing through damp air increased the number of 'nuclei' able to act as condensation points and that these nuclei were 'identical with one another, as well as with those existing

[19] J. J. Thomson, 'On the effect of electrification and chemical action on a steam-jet, and of water vapour on the discharge of electricity through gases', *Philosophical Magazine*, 36 (1893), 313–27.

[20] R. Helmholtz, 'Versuche mit einem Dampfstrahl', *Annalen der Physik*, 32 (1887), 1–15.

[21] R. Helmholtz and F. Richarz, 'Ueber die Einwirkung chemischer und electrischer Processe auf den Dampfstrahl und uber die Dissociation der Gase, insbesondere des Sauerstoffs', *Annalen der Physik*, 40 (1890), 161–202.

[22] S. Bidwell, 'On the electrification of a steam-jet', *Philosophical Magazine*, 29 (1890), 158–62.

[23] J. Aitken, 'On some phenomena connected with cloudy condensation', *Proceedings of the Royal Society*, 51 (1892), 408–39.

[24] J. J. Thomson, letter to E. Rutherford, Cambridge, 22 November 1898, E. Rutherford correspondence, Cambridge University Library, Cambridge.

[25] C. T. R. Wilson, 'Condensation of water vapour in the presence of dust-free air and other gases', *Philosophical Transactions*, 189 (1897), 265–307.

[26] W. K. Roentgen, 'Sur une nouvelle espèce de Rayons', *Journal de Physique teorique et appliquée*, 5 (1896), 101–8, translated from *Sitzungsberichte der Wurzburger physik. medic. Gesell* (December 1895).

[27] C. T. R. Wilson, 'On the effect of Roentgen Rays on cloudy condensation', *Proceedings of the Royal Society*, 59 (1896), 338–9.

[28] H. Becquerel, 'Sur quelques propriétés nouvelles des radiations invisibles émis par divers corps phosphorescentes', *Comptes Rendus*, 122 (1896), 559–60.

[29] C. T. R. Wilson, 'On the action of Uranium rays on the condensation of water vapour', *Proceedings of the Cambridge Philosophical Society*, 9 (28 October 1895–16 May 1898), 333–8.

in very small numbers in ordinary moist, dust-free air'.[30] What was the nature of these 'nuclei' that became manifest in condensation phenomena? The answer was immediately provided by referring to the other research project being carried out at the Cavendish Laboratory.

While Wilson was studying the effects of X-rays and Uranium rays on the condensation of saturated vapours, Thomson and Rutherford[31] were looking at the effects of the same types of radiation on the conductivity of gases, and demonstrated that the rays ionized the gases they passed through, including saturated gases. At this point it was clear that the condensation nuclei in Wilson's experiments were ions. It was enough to think back to what Thomson had shown in 1893 (that the ions facilitated the process of condensation, i.e. behave like 'nuclei') to equate the 'nuclei' around which condensation formed with the ions in the gas. C. T. R. Wilson's conclusion that by a process of expansion of saturated gas the ions could be isolated in the form of water droplets closed the first phase of a process that was shortly to lead to the measurement of the charge of the *corpuscle*.

4. The charge of gaseous ions

At first sight, the research that Thomson carried out or promoted at the Cavendish Laboratory between 1897 (after identifying the cathode rays as the first atomic particle and measuring the mass-to-charge ratio) and 1899 may seem a little odd. It no longer focused on such promising themes as cathode rays but ranged over analysis of the nature of X-rays and the measurement of the speed of propagation of gaseous ions in rarefied environments.

There was, however, a subtle common denominator in all this work. It became apparent in Thomson's report to the British Association Congress in 1899,[32] when he observed:

> In a former paper (*Philosophical Magazine* 1897) I gave a determination of the value of the ratio of the mass, 'm', of the ion to its charge, 'e', in the case of the stream of the negative electrification which constitutes the cathode rays. Though there were reasons for thinking that the charge 'e' was not greatly different from the electrolytic one, and that we had here to deal with masses smaller than the atom, yet, as these reasons were somewhat indirect, I desired if possible to get a direct measurement of either m or e as well as of m/e. In the case of cathode rays I did not see my way to do this; but another case, where negative electricity is carried by charged particles ... seemed more hopeful.[33]

This then is the key to Thomson's activities in these two years. Following the failure with the cathode rays, Thomson was locking for new phenomena involving the

[30] Wilson (footnote 29), 338; idem, 'On the condensation nuclei produced in gases by the action of Röntgen rays, Uranium rays, ultra-violet light, and other agents', *Philosophical Transactions*, 192 (1899), 403–53.

[31] J. J. Thomson and E. Rutherford, 'On the passage of electricity through gases exposed to Roentgen rays', *Philosophical Magazine*, 42 (1896), 392–407.

[32] J. J. Thomson, 'Uber die Masse der trager der negativen elektrisierung in gasen von niederen Drucken', *Physikalische Zeitschrift*, 1 (1899–1900), 20–2; idem, 'On the existence of masses smaller than the atoms', Report of the Sixty-ninth meeting of the British Association for the Advancement of Science, Dover, September 1899, *Philosophical Magazine*, 48 (1899), 547–67.

[33] Thomson (footnote 32), 547–8.

corpuscles and which would allow their charge or mass to be measured as well as the mass-to-charge ratio.

The first phenomenon that Thomson considered was the ionization of a gas under the action of X-rays. This had been the focus of the various activities promoted at the Cavendish Laboratory in the 1890s. Between 1896 and 1897 these activities included a series of both experimental and theoretical studies,[34] carried out particularly by Thomson and Rutherford. These studies soon revealed certain differences in the behaviour of the positive and negative ions (e.g. the negative ions were much faster than the positive ones) and led Thomson to interpret ionization in terms of 'dissociation of molecules'.[35] In 1898, however, Thomson was not in a position to equate the negative ions with *corpuscles*. His aim at this stage[36] was therefore to develop a method 'in order to determine the magnitude of the charge of electricity carried by the ions which are produced when Roentgen rays pass through a gas'.[37]

Performing a measurement of this type was by no means a simple proposition, and was made possible thanks to the range of activities that J. J. Thomson, as Director of the Cavendish Laboratory, had focused on electrical discharge in gases. In this regard it must be remembered that after 1895 graduate students from outside the University were admitted for the first time to the Cavendish school giving added impetus to the renown and development of the Cavendish Laboratory. The availability of these new human resources and with it the possibility afforded by Thomson to create his own research group were without doubt decisive in setting up these activities.[38]

The knowledge and results that Thomson used in measuring the charge of the ion and in later variants were as follows:

1. Knowledge of the processes of condensation of saturated and super-saturated vapours and how they are linked with the presence of electrical charge. Research in this field (begun by J. J. Thomson) was developed by C. T. R. Wilson from 1895 and culminated in 1910 with the cloud chamber.[39]

[34] Thomson and Rutherford (footnote 31). E. Rutherford, 'On the electrification of gases exosed to Roentgen rays and the absorption of Roentgen radiation by gases and vapours', *Philosophical Magazine*, 43 (1897), 241–55. J. S. Townsend, 'Applications of diffusion to conducting gases', *Philosophical Magazine*, 45 (1898), 469–80; idem, 'The diffusion of ions into gases', *Philosophical Transactions*, 193 (1900), 129–58; idem, 'The diffusion of ions produced in air by the action of a radio-active substance, ultra-violet light and point discharges', *Philosophical Transactions*, 195 (1901), 259–78. J. Zeleny, 'On the ratio of the velocities of the two ions produced in gases by Roentgen radiation and some related effects', *Philosophical Magazine*, 46 (1899), 120–54; idem, 'On the velocity of the ions produced in gas by Roentgen Rays', *Philosophical Transactions*, 195 (1900), 193–234. C. T. R. Wilson, 'On the comparative efficiency as condensation nuclei of positively and negatively charged ions', *Philosophical Transactions*, 193 (1900), 289–308.

[35] J. J. Thomson, 'On the theory of the conduction of electricity through gases by charged ions', *Philosophical Magazine*, 47 (1899), 253–68.

[36] J. J. Thomson, 'On the charge of electricity carried by the ions produced by Roentgen rays', *Philosophical Magazine*, 46 (1898), 528–45.

[37] Thomson (footnote 36), 528.

[38] On this argument see, for example, J. G. Crowther, *The Cavendish Laboratory, 1874–1974* (New York, 1974); R. T. Glazebrook, 'The Cavendish Laboratory 1876–1900', *Nature*, 110 (1926), Supplement 52–8.

[39] C. T. R. Wilson, 'On a method of making visible the paths of ionising particles through a gas', *Proceedings of the Royal Society*, 85 (1911), 285–8; *idem*, On an expansion apparatus for making visible the tracks of ionizing particles in gases and some results obtained by its use', *Proceedings of the Royal Society*, 87 (1912), 277–90. On this subject see Gooding, Pinch and Schaffer (footnote 18).

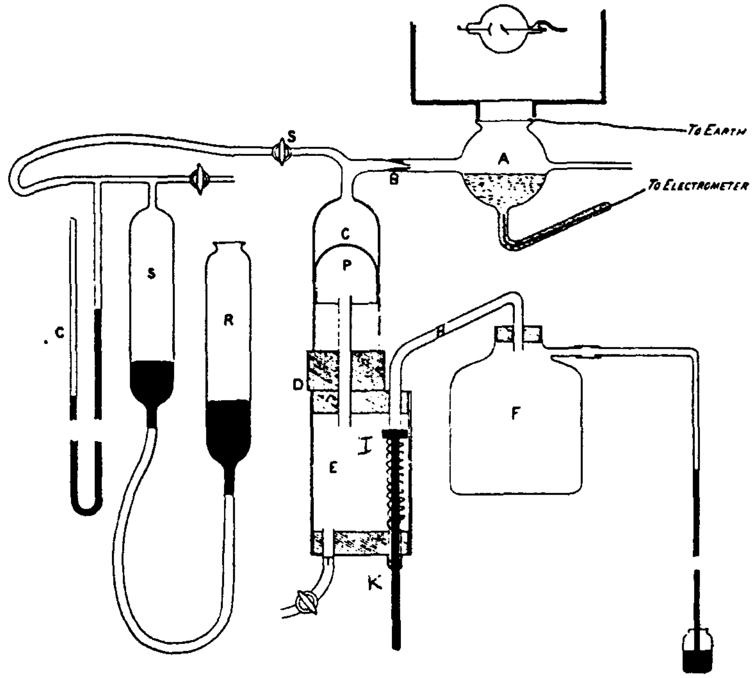

Figure 1. Thomson's apparatus for measuring the charge of the gaseous ions produced by X-rays.

2. Development of techniques for measuring the mobility of ions. This activity was carried out mainly by Rutherford,[40] and Zeleny.[41]
3. Development of techniques for measuring the diffusion of gaseous ions. This activity was conducted by Townsend.[42]

Thomson's measurement of ion charge (1898) can be looked at in two stages. Given a quantity of air or other gas saturated with water vapour and ionized by X-rays, the first operation (phase 1) was to determine the total charge Q associated with all the ions present in a unit of volume (e.g. 1 cm^3). The second operation (phase 2) was to determine the number n of ions present in the same unit volume. Having made these measurements, and assuming that each ion carries the same charge, e could be determined immediately, since if $Q = ne$, then one needed only to divide Q by n. The apparatus Thomson designed to do this is illustrated in Figure 1.

The gas being studied was introduced into vessel A and ionized by X-ray source. To measure quantity Q between the upper wall of A (aluminium foil) and the surface of the water contained in A, a weak electromotive force E was applied and the corresponding current I through A was measured. The mobility of the positive and negative ions (i.e. their velocity in the presence of a unit electromotive force) are u and v respectively and the current I per unit surface could be expressed as:

$$I = ne(u + v)E. \tag{1}$$

[40] E. Rutherford, 'The velocity and rate of recombination of the ions of gases exposed to Roentgen radiation', *Philosophical Magazine*, 44 (1897), 422–40.

[41] J. Zeleny, 'Air electrified by the discharging action of ultraviolet light', *Philosophical Magazine*, 45 (1898), 272–3.

[42] J. S. Townsend, 'The diffusion of ions into gases', *Proceedings of the Royal Society*, 65 (1899), 192–6.

Since u and v had already been measured at the Cavendish Laboratory (Rutherford did this for a number of gases) and I and E were easy to measure, equation 1 allowed Thomson to determine ne, or the quantity of charge Q contained in a cubic centimetre of gas.

To obtain n (phase 2) Thomson used the property brought to light by C. T. R. Wilson, i.e. that ions present in a gas saturated with water vapour and subjected to sudden expansion behave as nuclei for condensation. The method employed to produce the cloud and measure the expansion, as Thomson himself indicated, was the same as that used by Wilson. Vessel A (Figure 1), which contains water and is covered by an earthed aluminium plate, is connected to vessel C through tube B. Inside C is a thin-walled test-tube P, which serves as a piston. D is an indiarubber stopper closing the end of tube C: the lower part of tube C ought to be filled with water to such a height that the mouth of the piston is always below the surface. A glass tube connects the inside of test-tube P with space E. Space E may be connected with exhausted space F through tube H. The end of tube H inside the space is ground flat and closed by indiarubber stopper I, which is kept pressed against tube H by means of a spiral spring. Stopper I is fixed to rod K. Pulling the rod down sharply lowers the pressure inside the test-tube, and piston P falls rapidly until it strikes indiarubber stopper D. The falling of the piston causes the gas in A to expand. Tubes R and S are used to vary the amount of the expansion (in this experiment the condition required[43] for condensation to occur was a ratio of final-to-initial volume $\geqslant 1{\cdot}31$). Before an expansion piston P is raised by admitting air through T, which is then closed. Then, when everything is ready, K is pulled. In this way, by increasing the total volume, the temperature in A is reduced and water vapour condenses on the ions in the form of water droplets.

Supposing there is one ion per droplet of water, n (the number of ions per unit volume of gas) was obtained by calculating the number of droplets deposited per unit volume. The total mass M of water deposited per unit volume of gas was easy to measure and could be expressed in terms of n as

$$M = na^3 4/3, \tag{2}$$

where a is the radius of each water droplet. At this point it was necessary to determine a in order to obtain n. In turn, a was linked to the velocity v' of the water droplet falling in gravitational field g as established by Stokes' law[44]

$$v' = 2ga^2/g\mu, \tag{3}$$

where μ is the coefficient of viscosity of the medium. By measuring v' it was therefore possible to obtain a value for a and hence n. As they were the same size, the droplets all fell together. Observation of the time the top layer of the cloud (illuminated by an arc light) took to fall a given distance allowed the determination of v'.

The year before a similar type of measurement had been performed by Townsend,[45] who graduated in Dublin and who became a Fellow at Trinity College in Cambridge after 1899. He had determined the charge carried by gaseous ions produced in

[43] This condition required for condensation was established experimentally by Wilson (footnote 25).

[44] G. Stokes, 'On the alleged necessity for a new general equation in hydrodynamics', *Philosophical Magazine*, new series 1 (1851), 157–60.

[45] J. S. Townsend, 'On electricity in gases and the formation of clouds in charged gases', *Proceeding of the Cambridge Philosophical Society*, 9 (28 October 1895–16 May 1898), 244–59; *idem*, 'On the electrical properties of newly prepared gases', *Philosophical Magazine*, 45 (1898), 125–51.

the electrolysis of acids. This measurement was reported in a paper published in the *Proceedings of the Cambridge Philosophical Society*, where J. J. Thomson was acknowledged 'for the advantages that have been derived from his very valuable suggestions'. Stokes' law was used by Townsend (in the same manner as Thomson was to do at a later date) to determine the radius and therefore the mass of the droplets of water that condensed around the gaseous ions to measure the charge of them.[46]

Thomson, however, made no mention of this measurement by Townsend (3×10^{-10} e.s.u. or 1×10^{-20} e.m.u, i.e. of the same order as the result he obtained in 1898) until 1903[47] when in his *Conduction of Electricity through Gases*, he included it among the various measurements of the electrical charge of the monovalent ion.

Going back to Thomson's 1898 measurement it should be noted that, though conceptually sound, it was based on four hypotheses of which only one (the second) was verified much later.[48]

1. The number of ions per cubic centimetre was made to coincide with the number of water droplets per cubic centimetre, whereas, as H. A. Wilson[49] was to show in 1900, a droplet could contain one, two, three, etc. charges and not necessarily only one.
2. It was assumed that Stokes' law was valid even though it still had not yet been verified experimentally; moreover, this validity was also extended to very small droplets.
3. All droplets were taken to be identical, falling at the same velocity and without being affected by evaporation or other factors (in actual fact, after the sudden expansion, as in Thomson's experiment, there was a lowering of the temperature and the return to the initial temperature caused evaporation).
4. It was assumed that during the measurement of the velocity of fall of the water droplets there were no convection currents.

In any case Thomson successfully used this type of measurement to establish that

> when a gas is ionised by Roentgen rays, the charges of the ions are identical whatever the nature of the gas (i.e. we obtain the same charges on the ions whether

[46] There were differences between the two measurement systems in other respects. As we have seen, in Thomson's apparatus the ions (and therefore the condensation nuclei) were produced directly in the atmosphere saturated with water vapour. In Townsend's apparatus, however, the gaseous ions were produced by a process of electrolysis outside the test apparatus and then passed through a chamber containing water vapour (not necessarily close to saturation point) where, as Townsend discovered, they became condensation nuclei even without lowering the temperature and water droplets formed around them. Another different between Townsend and Thomson lay in the method of measuring the total mass (M) of the droplets of water and the total charge conveyed by the ions. In order to measure M, Townsend passed the water droplets through a series of absorbent tubes containing sulphuric acid which was weighed before and after the water droplets passed through. He obtained the mass M by subtracting the two results. The total charge per cubic centimetre transported by the droplets was determined directly by measuring the charge acquired by the sulphuric acid during absorption of the water droplets using a quadrant electrometer. As far as the rate of fall v' of the droplets was concerned, Townsend photographed the cloud twice at an interval of 20 and 30 s. He used the photographs to measure by how much the top layer of the cloud had shifted in the interval of time selected, and so to calculate the speed.

[47] J. J. Thomson, *Conduction of Electricity through Gases* (Cambridge, 1903), French translation: *Passage de l'électricité a travers les gaz* (Paris, 1912).

[48] For a general discussion of the experimental difficulties connected with the measurement of the charge of the electron see R. A. Millikan, *The Electron* (Chicago, 1917).

[49] H. A. Wilson, 'Variation of the electric intensity and conductivity along the electric discharge in rarefied gases', *Philosophical Magazine*, 49 (1900), 505–16.

> we ionise hydrogen or oxygen) and these charges are equal or at least of the same order as the charge of the hydrogen atom in electrolysis, i.e. in the order of 10^{-10} e.s.u.[50]

Thomson's measurements seemed to be pointing to a single charge underlying different phenomena, but what conclusions were to be drawn about the link between this charge and that of the *corpuscle*? Apparently none, since on the one hand the measured charge represented the mean value of the charge carried by each ion (whether positive or negative) and on the other hand there were not sufficient grounds for seeing negative ions and *corpuscles* as one and the same. With these measurements, however, Thomson achieved an improved goal: he had found a way of measuring charge that, unlike the other methods that had been developed for electrolytic phenomena, was not based on knowledge of any atomic or molecular parameter and was thus ideal for measuring charge independently of its carrier, be it a molecule, atom or *corpuscle*.

As Thomson had already realized, this method did not lend itself to measuring charge in the case of 'cathode rays' on account of the experimental conditions required to produce the rays. Therefore Thomson had to look for another phenomenon that could be interpreted in terms of *corpuscles*, that would provide a measurement of charge of the type he had just developed and that would also allow the mass-to-charge ratio to be measured as in the case of 'cathode rays'. As Thomson observed, this new phenomenology necessarily occurred at very low pressures, as only in these conditions there was a probability of finding *corpuscles* separated from atoms. Here too, Thomson was able to conduct research along these lines thanks to the knowledge base that he had developed in the field of electrical discharge in rarefied gases, one of the very areas of study that he had established at the Cavendish Laboratory.

5. The charge of the *corpuscle*

In his *Notes on Recent Researches into Electricity and Magnetism* (1893), the various phenomena that Thomson associated with the 'passage of electricity through a gas' included 'the effect of ultraviolet light on electrical discharge'.[51] Thomson began by retracing the steps that led from Hertz's 1887 observation[52] to the conclusion that 'a metallic surface, when exposed to the action of ultraviolet light quickly loses a negative charge, while the same surface keeps a positive charge', and concluded by recalling the following result obtained by Elster and Geitel in 1890:[53]

> When the pressure of the gas surrounding the body is less than 1 mm (Hg) the escape of the negative electricity from the illuminated surface is considerably checked by placing it in a strong magnetic field.[54]

In 1893, these properties did not arouse any particular interest for Thomson, if not from a phenomenological point of view, and were seen as one of the many manifestations that accompanied discharge processes in gas. The same phenomena became much more important for Thomson in 1898. Faced with the problem of finding

[50] Thomson, *Phil. Mag.* (footnote 32), 554.

[51] Thomson (footnote 1), 58.

[52] H. Hertz, 'Ueber eine Einfluss des ultravioletten Lichtes auf die electrische Entladung', *Annalen der Physik und Chemie*, 31 (1887), 983–1000.

[53] J. Elster and H. Geitel, 'Uber den hemminden Einfluss des Magnetismus auf lichtelectrische Entladungen in verdunnten Gasen', *Annalen de Physik und Chemie*, 41 (1890), 166–76.

[54] Thomson (footnote 1), 62.

a new field of study, other than cathode rays, for the measurement of the physical parameters, mass, and charge of the *corpuscle*, Thomson in fact made reference to the photoelectric effect and proposed identifying 'the escape of negative electricity' that characterized the effect with 'an escape of *corpuscles*'.[55] This interpretation of the photoelectric effect in terms of *corpuscles* (even if Thomson was not able at that time to indicate whether they came from the plate or from the gas in contact with it) was new[56] and allowed an immediate explanation of the results of Elster and Geitel.

It was enough 'to consider what effect a magnetic force would have on the motion of a negatively electrified particle' like the *corpuscle*: the effect was the deflection of the particle by an amount depending on the velocity. It was therefore possible for certain *corpuscles* to move at a sufficiently high velocity to be deflected by the 'magnetic force', in such a way as to return to the plate, so reducing the 'rate of leakage of the negative electrification at low pressures', as was reported by Elster and Geitel. From this standpoint, as Thomson wrote, the phenomena observed when a negatively charged metal plate in a gas at low pressure is illuminated by ultraviolet light becomes a promising field in which to attempt to measure both the charge value and the mass-to-charge ratio of the *corpuscle* simultaneously.

With this in mind Thomson, in the same year (1898), promoted a series of studies[57] at the Cavendish Laboratory with the aim of studying the various forms of photoelectric emission. These studies established that at low pressure, 'the majority of the electrification was conveyed by negative gaseous ions produced at the surface of the plate' and, that these 'negative electricity carriers' (the speed of which was measured in the presence of different electromotive forces) 'acted like those produced by Roentgen rays, in forming nuclei around which water will condense from dust-free air when the supersaturation exceeds a certain definite value'.[58]

At this point the feasibility of measuring the charge of 'the negative electricity carrier' for 'emission produced by the action of ultra-violet light' was guaranteed. The equipment already built by Thomson for ions produced by Roentgen rays and mentioned earlier could be used by adding a suitable metal plate illuminated by ultraviolet light in the condensation container, and then proceed, as in the case of ions produced by the Roentgen rays, to measure the charge.

The apparatus used is shown in Figure 2.

AB is a glass tube, 3·6 cm in diameter, in which the expansion takes place, and is connected through the smaller tube L with the expansion apparatus (Figure 1). K is a

[55] Thomson, *Phil. Mag.* (footnote 32), 548.

[56] In 1898, the problem of interpreting the photoelectric effect was still completely open. The phenomenology gathered was vast, and because there was no distinction made between low and high pressures, it appeared to be extremely complicated. After Lenard and Wolf's hypothesis (P. Lenard and M. Wolf, 'Zerstauben der Korper durch das ultraviolette Licht', *Annalen der Physik und Chemie.*, 2 (1889), 443–56) that 'metallic dust' was responsible for the discharge was abandoned, the photoelectric effect was generically interpreted in terms of the molecules of the surrounding gas which, when they came into contact with the illuminated plates, became charged and acted as carriers for the electricity. See B. R. Wheaton, 'Philipp Lenard and the photoelectric effect: 1889–1911', *Historical Studies in the Physical Sciences*, 9 (1978), 299–322; S. Galdabini, G. Giuliani and N. Robotti, 'Photoelectricity within classical Physics: from the photocurrents of E. Becquerel to the first measurement of the electron charge', *Proceedings of the European Physical Society* (Como, 1992) (in press).

[57] C. T. R. Wilson, 'On the production of a cloud by the action of ultra-violet light on moist air', *Proceedings of the Cambridge Philosophical Society*, 9 (28 October 1895–16 May 1898), 392–3; E. Rutherford, 'The discharge of electrification by ultra-violet light', *Proceedings of the Cambridge Philosophical Society*, 9 (28 October 1895–16 May 1898), 401–16.

[58] Thomson, *Phil. Mag.* (footnote 32), 557.

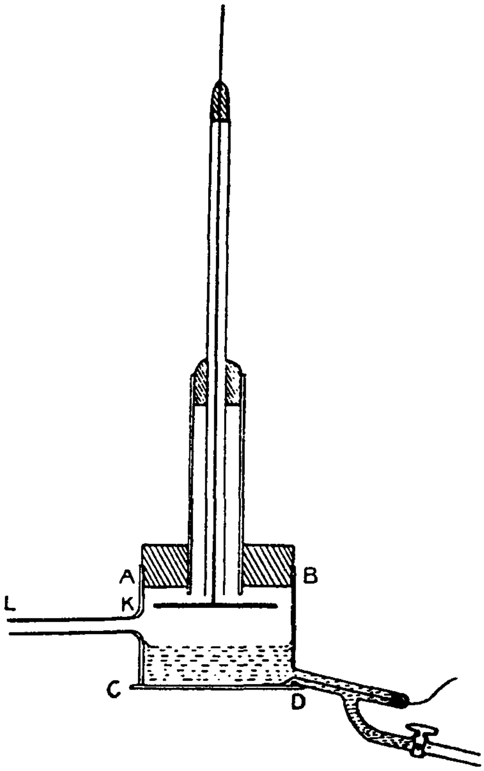

Figure 2. Thomson's apparatus for measuring the charge of the *corpuscles* produced by ultraviolet light.

clean zinc plate, 3·2 cm in diameter while CD is a quartz plate, on the top of which there is a layer of water. CD ensures that the resulting vessel is airtight and yet allows ultraviolet light to pass and illuminate the zinc plate. The ultraviolet light is produced by an arc between zinc terminals connected with an induction coil and located about 40 cm below the lower face of the quartz plate. When the zinc plate is illuminated by ultraviolet light and expansion takes place, a cloud is formed in vessel ABCD. The space between the zinc plate and the water surface is illuminated by an arc-light to allow the rate of the drops to be accurately measured. In this respect a great many precautions must be taken. Indeed there were some features in the condensation of clouds by ultraviolet light that were not present in the clouds formed by Roentgen rays. In the first place the cloud due to the ultraviolet light was only formed in an electric field. When there was no field the ions remained close to the surface of the illuminated plate and were not diffused through the region in which the cloud had to be formed. The plate was therefore negatively electrified. The ions then diffused and the expansion produced the cloud.

Furthermore, as Thomson indicated, it was necessary to use low intensity ultraviolet light as too strong a light produced 'nuclei not only from the illuminated plate but also in the gas through which it passed'. These nuclei had not therefore to be counted in estimating the number of 'negative electricity carriers'. Finally, differential observation was required in order to avoid including undesired condensation nuclei in the

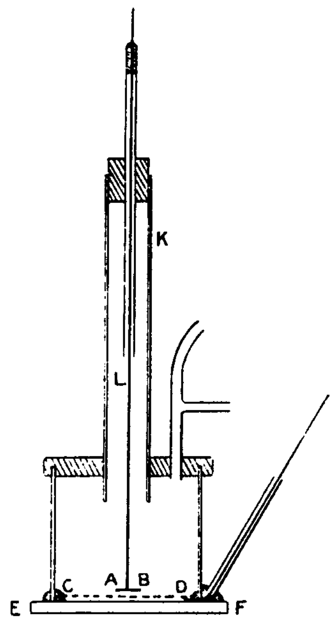

Figure 3. Thomson's apparatus for measuring the mass-to-charge ratio of the *corpuscles* produced by ultraviolet light.

count—one observation without illuminating the zinc plate and a second one by illuminating it with ultraviolet light.

The total charge Q associated with the droplets was determined in the same way as in the 1898 experiment on the charge of ions produced by Roentgen rays, i.e. by applying a weak electromotive force E between the zinc plate and the surface of the water. In the case of ultraviolet light it was nevertheless necessary to consider in equation 1 only the mobility of the negative ions (this value had already been measured by Rutherford).

In this way, in 1899 Thomson[59] arrived at a value for the charge of the *corpuscle* in the case of ultraviolet light of $e = 6{\cdot}8 \times 10^{-10}$ e.s.u. ($2{\cdot}3 \times 10^{-20}$ e.m.u.), i.e. the same as e for ions produced by Roentgen rays and the same as that commonly attributed to the hydrogen ion in ordinary electrolysis (see above). It was now a question of measuring the mass-to-charge ratio, for which purpose Thomson exploited the 1890 discovery of Elster and Geitel (recalled by Thomson in 1893), that a magnetic field, placed parallel to a plate illuminated by ultraviolet light, attenuated the emission of the negative charge. The apparatus designed by Thomson is shown in Figure 3.

AB is a carefully polished zinc plate (1 cm in diameter) that is exposed to ultraviolet light. CD is a very fine wire gauze through which light can pass, placed parallel to AB on the quartz plate EF. The ultraviolet light is provided by an arc and enters through quartz plate EF. L is a metal rod that allows the distance between AB and CD to be varied. The entire apparatus is contained in a glass tube and connected to a mercury pump provided with a McLeod gauge, so that the pressure of the gas can be reduced to 1/100 mm Hg. An electric field X of measured strength was applied between AB and CD, perpendicular to AB (the potential of CD was greater than that of AB so that the

[59] Ibid., 563.

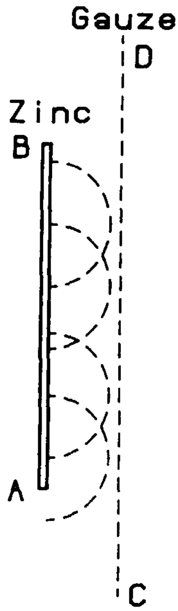

Figure 4. Diagram showing the calculated paths of the *corpuscles* produced by ultraviolet light under the influence of crossed magnetic and electric fields.

negative charges that start from AB, when it was illuminated, moved towards CD). The rate of leak of negative electricity from AB to CD when AB was illuminated by ultraviolet light was measured by a quadrant-electrometer, with one pair of quadrants connected to wire gauze CD, and the other pair to earth.

A magnetic field H of measured strength (parallel to plate AB) was applied across the region between AB and CD. In these conditions, as Thomson demonstrated,[60] the paths of the negative electrified particles that started from AB were cycloids, the generating circle of which had a diameter equal to:

$$2Xm/eH^2, \tag{4}$$

(where e and m are respectively the charge and the mass of the particles) and rolled perpendicularly to the zinc plate.

[60] Let X be a uniform electric field arranged along the x-axis and H be an electric magnetic field parallel to the z-axis. The equations of motion of a negative particle of mass m and charge e were:

$$m\,\mathrm{d}^2x/\mathrm{d}t^2 = Xe - He\,\mathrm{d}y/\mathrm{d}t$$

$$m\,\mathrm{d}^2y/\mathrm{d}t^2 = He\,\mathrm{d}x/\mathrm{d}t.$$

The solutions of these equations, under the initial condition that x, y, $\mathrm{d}x/\mathrm{d}t$, $\mathrm{d}y/\mathrm{d}t$ all vanish when $t = 0$ were, according to Thomson's figures:

$$y = Xm/eH^2 \cdot [eHt/m - \sin(eHt/m)]$$

$$x = Xm/eH^2 \cdot [1 - \cos(eHt/m)].$$

From these equations it was clear that the path of the particle was a cycloid, the generating circle of which had a diameter equal to:

$$2Xm/eH^2.$$

Figure 4 shows possible theoretical paths of the particles. Here the distance between the zinc plate and the gauze is greater than the diameter of the cycloid and the particles cannot therefore reach the gauze. If, however, the distance between the plates is less than the diameter (see equation 4), the particles reach the gauze and convey a current to the electrometer.[61]

In his experiment Thomson began with this arrangement, i.e. with the plates very close together, and gradually increased the distance between them. In the initial phase until the distance between the plates was less than the diameter to the cycloid (equation 4), the rate at which CD received a negative charge was constant, but as soon as the distance was equal to equation 4 it decreased sharply to almost zero. By measuring the critical distance between the zinc plate and the gauze at which the charge detected at CD starts to decrease, Thomson could use expression 4 to calculate *m/e* of the *corpuscle*.

It was worth nothing that the importance of creating a vacuum to measure the mass-to-charge ratio of the *corpuscle* is the result of Thomson's earlier studies: if he had worked at a higher pressure, as Thomson himself said, the *corpuscle* would have acted as a 'nucleus around which several molecules collect, just as dust collects around an electrified body' and therefore would have lost its own identity.

Using the method described above, Thomson obtained a mass-to-charge ratio for the 'carriers of negative charge produced by ultraviolet light' of $1{\cdot}3 \times 10^{-7}$ g/e.m.u, that is of the same order of magnitude as the value measured for cathode rays.[62]

Furthermore, an almost identical value was also obtained by Thomson for another phenomena, also linked to discharge in gases: 'negative charge emission by an incandescent carbon filament in an atmosphere of hydrogen at low pressure'.[63]

This phenomenon, as Thomson mentions, was discovered in 1882 by Elster and Geitel.[64] It demonstrated that an incandescent platinum, palladium or iron filament in a low pressure environment produces the same phenomena as the photoelectric effect. The action of the magnetic field on the charge at low pressure was also the same.[65] According to Thomson, this was consistent with an interpretation in terms of *corpuscles* and lent itself to a further measurement of the mass-to-charge ratio of these corpuscles.

The apparatus that Thomson used for this new measurement was of the same type as that used for the photoelectric effect, suitably modified. The wire gauze and the zinc plate were replaced by two parallel aluminium discs. Quite close to the upper disc was a small, semicircular carbon filament that was raised to red heat by the current from four storage-cells. The purpose of the upper disc was to make the electric field between the discs more uniform. The lower plate was connected with the electrometer.

[61] It must be remembered that Thomson deals with the most favourable case for the passage of charges from plate AB to CD, i.e. in which the particles are emitted perpendicularly to AB.

[62] In 1899, Lenard (P. Lenard, 'Erzeugung von Kathodenstrahlen durch ultraviolettes Licht', *Annalen der Physik*, 2 (1900), 359–75) provided an interpretation of the photoelectric effect in terms of *corpuscles*, which Lenard called 'quantums'. He measured the charge-to-mass ratio, and obtained a value similar to that proposed by Thomson. Unlike Thomson, however, Lenard did not manage to measure the charge. This was possible for Thomson as he had already perfected (as we have seen) an *ad hoc* measurement technique precisely to measure charge. The *e/m* obtained by Lenard was reported by Thomson in *Philosophical Magazine* (footnote 32) as a confirmation of his own result.

[63] Thomson, *Phil. Mag.* (footnote 32), 554.

[64] J. Elster and H. Geitel, 'Ueber die Electricitat der Flamme', *Annalen der Physik*, 16 (1882), 193–222; idem, "Ueber Electricitatserregung beim Contact von Gasen und gluhenden Korpern', *Annalen der Physik*, 19 (1883), 588–624; idem, 'Ueber die Electricitat der Flamme', *Annalen der Physik*, 22 (1884), 123–8.

[65] J. Elster and H. Geitel, 'Einige Demonstrationsversuche zum Nachweis einseitiger Electricitatsbewegung in verdunnten Gasen bei Anwendung gluhender Electroden', *Annalen der Physik*, 38 (1889), 27–39.

As Thomson observed, the corpuscles emitted by the carbon filament in the presence of crossed electric and magnetic fields ought to have followed helicoidal trajectories with the same radius of curvature as those previously obtained for the photoelectric effect and represented by equation 4. Therefore, as for the photoelectric effect, by varying the distance between the incandescent wire and the lower plate until the rate of leak between them started to decrease and measuring this distance, *e/m* could be obtained from equation 4.

Thomson, however, had great difficulty in obtaining consistent results with the incandescent carbon filament. As he himself admitted, sometimes the filament would discharge positive as well as negative electricity; indeed sometimes it would discharge positive and not negative electricity.[66] These irregularities were traced by Thomson 'to gas given out by the incandescent filament'. Finally, however, by keeping the filament almost white-hot for several hours, and continually pumping and refilling with hydrogen and then using the filament at a much lower temperature, Thomson succeeded in eliminating the irregularities so that 'nothing but negative electrification' was discharged from the filament.

In this way, Thomson arrived at a *m/e* of $1{\cdot}2 \times 10^{-7}$ g/e.m.u., which was in line with the values obtained for cathode rays and the photoelectric effect. At this point attempts to calculate the mass of the *corpuscle* could proceed. Thomson used *e* and *m/e* measured using the photoelectric effect to calculate *m* of the order of 3×10^{-26} g or approximately 1/1000 of the mass of the hydrogen ion.

Thomson wrote:

> The experiments just described, taken in conjunction with previous ones on the value of *m/e* for the cathode rays show that in gases at low pressures negative electrification, though it may be produced by very different means, is made up of units each having a charge of electricity of a definite size; the magnitude of this negative charge is about 6×10^{-10} electrostatic units, and is equal to the positive charge carried by the hydrogen atom in the electrolysis of solutions .... 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 $1{\cdot}4 \times 10^{-3}$ of that of the hydrogen ion, the smallest mass hitherto recognized as capable of a separate existence .... In this case, therefore, we have clear proof that the ions have very much smaller mass than ordinary atoms; so that in the convection of negative electricity at low pressures we have something smaller even than the atom, something which involves the splitting up of the atom, inasmuch as we have taken from it a part, though only a small one, of its mass.[67]

6. Epilogue

Thomson's measurements led to the *corpuscle*, the smallest negatively charged particle of the atom hypothesized in 1897, becoming a well-defined physical reality. These, for example, are Perrin's comments in 1901 on Thomson's experiments:

> Il est remarquable que l'existence de ces corpuscles, grace aux fortes charges électriques qu'ils trasportent, est démonstrée de manière plus directe que celle des atomes ou des molécules, pourtant beaucoup plus gros. Dans L'expérience de

[66] Thomson, *Phil. Mag.* (footnote 32), 548.
[67] Ibid., 565.

> condensation des gouttes d'eau, on peut dire que chaque corpuscle, pris individuellement, a été isolé et atteint. En ce sens, l'existence des corpuscles a plus de certitude que celle meme des atomes, et l'on peut dire que l'hypothèse corpuscolaire, la dernière venue parmi les hypothèse moléculaires, est la seule qui se soit trouvée accessible à une vérification directe.[68]

The hypothesis of a divisible atom also became a reality, because, as Thomson repeatedly confirmed, 'in the convection of negative electricity at low pressures we have taken from the atom a part, though only as small one, of its mass'.

The fact that the value of the charge of the *corpuscle* and the value of the 'unitary charge' or 'electron' are the same also allowed the phenomenon of ionization to be reinterpreted and the concept of the ion to be reworked in the framework of a general theory of the structure of the atom. For example, as Thomson observed, if the atom is thought of as a collection of *corpuscles* and 'something positive' that guarantees electrical neutrality, ionization is the 'detachment from the atom of the corpuscle', while the negative ion is the *corpuscle* itself and the positive ion is 'the remaining part of the atom'.[69]

To sum up, Thomson's measurement of the charge of the *corpuscle* meant that not only 'cathode rays', but all electrical phenomena would have to be re-examined. Thomson wrote:

> From what we have seen, this negative ion (*corpuscle*) must be a quantity of fundamental importance in any theory of electrical action; indeed, it seems not improbable that it is the fundamental quantity in terms of which all electrical processes can be expressed. For, as we have seen, its mass and its charge are invariable, independent both of the processes by which the electrification is produced and of the gas from which the ions are set free. It thus possesses the characteristics of being a fundamental conception in electricity.[70]

From that time on measurements of the *corpuscle*'s charge continued at the Cavendish Laboratory, but for different purposes.[71] Indeed, the aim was now to improve the measurement of the charge value, in order to estimate other universal constants, and particularly Avogadro's number. This is the path that Wilson[72] and Thomson[73] were to follow independently, and in 1903 both obtained a new estimate of the *corpuscle* charge,[74] in the range $3{\cdot}1 \div 3{\cdot}4 \times 10^{-10}$ e.s.u. ($1{\cdot}3 \div 1{\cdot}1 \times 10^{-20}$ e.m.u.).

At which point of his work did Thomson abandon the term *corpuscle* in favour of what we now know as the 'electron'? This is a difficult question to answer with certainty, but it is a fact that Thomson continued to use the term *corpuscle* for many years. As late as 1912, when the conventional term 'electron' for the negatively charged atomic

[68] J. Perin, 'Les Hypothèses moléculaires', *Revue Scientific*, 15 (1901), in *Ouvres Scientifiques de Jean Perrin* (Paris, 1950), 165.

[69] See, also J. J. Thomson, 'Indications relatives a la constitution de la matière fournies par les recherches sur le passage de l'électricité a travers les gaz', *Rapports présentés au Congrès International de Physique*, III (Paris, 1990), 138–51.

[70] Thomson, *Phil. Mag.* (footnote 32), 565.

[71] S. Weinberg, *The Discovery of Subatomic Particles* (New York and San Francisco, 1983).

[72] H. A. Wilson, 'A Determination of the Charge on the Ions Produced in Air by Roentgen Rays', *Philosophical Magazine*, 5 (1903), 429–41.

[73] J. J. Thomson, 'On the charge of electricity carried by a gaseous ion', *Philosophical Magazine*, 5 (1903), 346–55.

[74] It can be seen that this is close to the currently accepted $4{\cdot}7 \times 10^{-10}$ e.s.u. ($1{\cdot}6 \times 10^{-20}$ e.m.u.)

particle had been already accepted by the scientific community, Thomson in the twelfth edition of his famous *Conduction of Electricity through Gases*[75] used only the word *corpuscle*. Again in 1913, during the opening talk[76] of the Solvay Congress he used only the term *corpuscle* perhaps as a warning not to forget the history and to emphasise the extent to which the *corpuscle* played an innovative role, and how different the terms *corpuscle* and 'electron' were at the outset.

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[75] Thomson (footnote 47).

[76] J. J. Thomson, 'La structure de la matière', in *Rapports et discussions de Conseil de physique tenue à Bruxelles du 27 au 31 octobre 1913* (Paris, 1921), pp. 1–21.