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Electron - a Main Actor in Scientific Controversies

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ELECTRON – A MAIN ACTOR IN SCIENTIFIC CONTROVERSIES*

1. Introduction

The story of the electron can contribute to the study of the continuity–discontinuity of the scientific thinking in modern age as well as to discussions of models and metaphors in the history of science. Actually, the electron played a central role in several scientific controversies: the nature of electricity and cathode rays, structure and properties of matter.

The idea of an atom of electricity was introduced by Michael Faraday (1791–1867) and adopted by Hermann von Helmholtz (1821–1894). In 1874, Johnstone Stoney (1826–1911) estimated its charge and named it electron. However, James Clerk Maxwell (1831–1879) had stated that a complete knowledge of electricity would eliminate the necessity of such particles.

The controversy about the nature of electricity lied dormant for years until it was brought to light by the study of discharges in gases. The nature of cathode rays divided physicists and chemists, with the electron playing the major role in the dispute. The experiences of Jean Baptiste Perrin (1870–1942) in 1895 and Joseph John Thomson (1856–1940) in 1897 seemed to confirm the existence of the electron, but did not convince all scientists. The electron became the main protagonist of a controversial image of matter: the atomistic view.

In 1913 Niels Bohr's (1885–1962) atomic theory was received with enthusiasm by some physicists but with criticism by others. Nevertheless, the atomic structure of matter gradually wins acceptance by reason of its extraordinary power in predicting spectral lines. Eventually, electrons were accepted as particles, coherent with facts and theories. Some years later, however, with Louis De Broglie's (1892–1987) and Erwin Schrodinger's (1887–1961) works, the electron, ceases to be a new paradigm and becomes an old concept. The complete formulation of quantum mechanics, given by Paul Dirac (1902–1984) in 1925, and its interpretation by Bohr, justified that the electron was not a particle anymore. Remarkably, some of the founders of the quantum mechanics remained sceptical of this interpretation. Today the controversy goes on; with the electron again the protagonist.

2. *Atoms of electricity*: from Faraday to Helmholtz

The *History of the Electron* starts in 1832 with the discovery of Faraday's laws of electrolysis. Faraday found that the amount of a substance that would be decomposed by an electric current depended only on the quantity of electricity which passed through the respective solution of that substance. This implies that electricity, like matter, consists of discrete units or *atoms of electricity*. Presumably each molecule was held together by such an atom of electricity, which was released when the molecule was broken up. Although Faraday must have felt the need of this assumption concerning the atomic nature of electricity, he said very little about it. Later, Maxwell stated that a complete knowledge of electricity would probably eliminate the necessity of assuming the existence of molecules of electricity[1]. The continuous medium in which lines of force existed and the electromagnetic waves travelled was of utmost interest for physics at the time of Maxwell.

One can say that these two approaches of electricity – the discontinuous and the continuous – are still present today in several domains of theoretical as well as experimental science. The two points of view have coexisted in the 19th century and were a source of some controversy.

Existence, nature and properties of the electron belong to the old debate involving physics, chemistry and philosophy, concerning our image of the universe. In some historical episodes, the concept of electron played an even more central role in the evolution of thinking about matter and energy. For that reason it seemed to be important to tell the history of that evolution, but this time under the point of view of the electron. The historical overview will cover the main facts as well as the scientists who contributed the most to it.

Wilhelm Eduard Weber (1804–1891) was Carl Friedrich Gauss's (1777–1855) assistant and leading collaborator when he started working on the experimental validation of the André–Marie Ampère (1775–1836) force. To do it, Weber devised a new apparatus, the electrodynamometer (see Fig. 1–a & 1–b), which could directly measure, to within fractions of a second of arc, the angular displacement caused in a multiply wound electric coil by another electrical coil perpendicular to it. Weber's results led him, in 1846, to state his Fundamental Electrical Law achieving the unification of all known electrical phenomena under a single conception. Instead of the mathematical entities, described as current elements by Ampère, Weber hypothesized the existence within the conductor of positive and negative electrical particles. Weber's law is based on the Newtonian force of attraction or repulsion between the two kinds of charges.

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[1] G. Holton, *The scientific imagination: case studies*, Cambridge University Press, Cambridge 1978, p. 41.

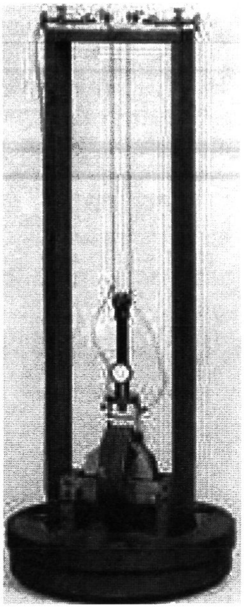

Fig. 1–a
Electrodynamometer constructed in 1841 by Wilhelm Weber and used in the final determination of the validity of Ampere's electrodynamics.

http://www.21stcenturysciencetech.com/.html

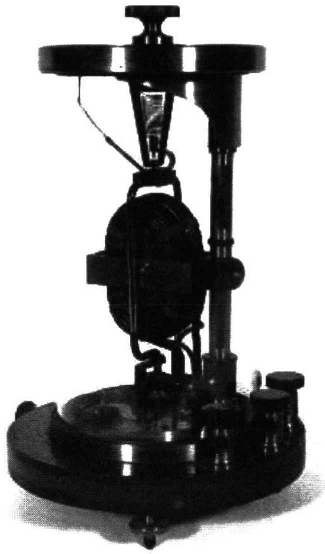

Fig. 1–b
One of the best preserved Electrodynamometers (Depauw University) (Imported by Queen & Co. of Philadelphia, 1880).

http://physics.kenyon.edu/EarlyApparatus/Electrical_Measurements/Electrodynamometer/.html

Weber's discovery brought about a revolution in physics, the full implications of which are still unrealized. Worse, today the underlying discovery itself is all but forgotten. Even though, recently there has been a renewed interest in Weber's electrodynamics[1], which is discussed and interpreted in the light of modern physics. Furthermore, Weber's approach retained preference among most Continental physicists for a long time, before the justification of Maxwell's theory in the experiments of Heinrich Rudolf Hertz (1857–1894), perhaps because, as Woodruff says, *whether or not Maxwell's ideas were fundamentally consistent, there is no doubt that they confused his contemporaries*[2]. In the 1890's most Continental physicists sought to meld the more

[1] See J. J. Caluzi & A. K. T. Assis, *A Critical Analysis of Helmholtz's Argument against Weber's Electrodynamics* in: *Foundations of Physics* 27, 10/1997, pp. 1445–1452.

[2] A. E. Woodruff, *The Contributions of Hermann von Helmholtz to Electrodynamics* in: *Isis* 59, 3/1968, pp. 300–311.

concrete Weberian notion of charged particle with the Maxwellian treatment of the field. In spite of that and following Maxwell's electromagnetic theory, atomistic theories were finally abandoned in favor of the view of electricity as a continuous substance. In fact, around 1890, Hertz's waves were in the forefront of electrodynamics[1]. However, the deeper nature of electric current, or the precise relation between ether and matter, did not to be known [was not explored ?].

In retrospect, the significance of the work of Helmholtz in electrodynamics was that it made Maxwell's theory intelligible to the German physicists and inspired the experimental research of Hertz which confirmed it.

To decide the existence or not of *atoms of electricity* was not a priority to most scientists in the middle of the 19^{th} century. However, another problem, related with that *existence*, caught the interest of the British Association for the Advancement of Science: the problem of finding the appropriate unit of electrical resistance. The relationship between electromagnetic current and electrostatic charge by a given length had been studied since Weber's time. Measurements achieved in order to establish the ratio had indicated that the velocity of the charge looked remarkably like the speed of light. This apparently mysterious fact could lead to think that the fundamental units of electricity would be one of the basic constants of the universe. In 1874, Johnstone Stoney, an Irish physicist and member of the British Association for the Advancement of Science, proposed a system of electrical units based on Faraday's law of electrolysis[2]. Stoney's idea of a unity or *atom of electricity* had little impact[3] at the moment but, in 1891, he proposed it again and this time in connection with his theory of the atomic origin of spectra. Then, he called his atom *electron*. He was the first to relate an orbiting electron as the generator of electromagnetic radiation.

Meanwhile, in 1881, in the Faraday lecture at the Royal Institution, Helmholtz (1821–1894) talked about the chemical aspect of electricity. Going back to Faraday, he stated that *if the elements are made up of atoms, then electricity in electrolyte are [is ?] made up of definite elementary portions, which behave like atoms of electricity*[4]. Chemical affinities could be explained by electrical properties. The lecture was received with great applause.

In spite of the polemic about priority[5] of the idea of *atoms of electricity*, the revival of the particle atomistic theories was usually attributed to Helmholtz. With him, atoms of electricity became a prominent topic of interest. It was a plausible idea, even though not a very useful speculation.

[1] See O. Darrigol, *Electrodynamics from Ampère to Einstein*, Oxford University Press, Oxford 2000, p. 265.

[2] G. J. Stoney, *On the Physical Units of Nature* in: *Belfast meeting of the British Association for the Advanced of Science* 1874, publ. in: *Philosophical Magazine* 11, 1881, pp. 381–391.

[3] J. G. O'Hara, *George Johnstone Stoney, F.R.S., and the Concept of the Electron* in: *Notes and Records of the Royal Society of London* 29, 2/1975, p. 272.

[4] H. Helmholtz, *The Modern Development of Faraday's Conception of Electricity*, The Faraday Lecture, delivered before the Fellows of the Chemical Society in London 1881, publ. in: *Journal of the Chemical Society* 39, 1881, pp. 277–304.

[5] G. J. Stoney, *Of the 'Electron' or Atom of Electricity* in: *Philosophical Magazine Series* 38, 5/1894, pp. 418–420.

3. Electron: from light to cathode rays

In 1894, Pieter Zeeman (1865–1943) made a substantial discovery: by the operation of magnetic field a spectral line was split into several lines. Hendrik Antoon Lorentz (1853–1928) gave an explanation of the observations based on the idea that light was emitted by charge particles moving in the atom:

> *This idea of small charged particles was otherwise by no means new; as long as 25 years ago the phenomena of electrolysis were being explained by ascribing positive charges to the metallic atoms in a solution of a salt, and negative charges to the other components of the salt molecule. This laid the foundation of modern electrochemistry, which was to develop so rapidly once Prof. Arrhenius had expressed the bold idea of progressive dissociation of the electrolyte with increasing dilution. We will return to the propagation of light in ponderable matter. The covibrating particles must, we concluded, be electrically charged; so we can conveniently call them* electrons, *the name that was introduced later by Johnstone Stoney*[1].

Since 1892, the theory that matter contains a great number of charges moving freely within conductors but bounded in dielectrics had been developed by Lorentz. In his theory, electric currents were simply flows of charges and macroscopic charges were simply local accumulations of positive or negative microscopic charges. By 1899 Lorentz came to refer to these charged particles as *electrons*. He believed that it was through the effects of these electrons that many phenomena in science could be explained. But the most spectacular success of Lorentz's electron theory was the explanation of Zeeman's effect. A full–fledged treatment of the theory was published in 1909[2].

Whereas the atomistic view of electricity became a useful speculation only in the 1890's, the existence of atoms was debated from John Dalton (1766–1844) throughout the 19th century. Some argued that such talk was but a name to cover our ignorance. Wilhelm Ostwald (1853–1932), one of the most eminent German chemists, did not accept the atomic idea. In 1901 he still thought that all phenomena could be explained through the interplay of energy without the need of atoms. Ernest Mach (1838–1916) did not believe in the atomic hypothesis either. Even Max Planck (1858–1947) was *not only indifferent, but to a certain extent even hostile to the atomic theory*[3], as he recalled in his scientific autobiography.

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[1] H. A. Lorentz, *On the theory of electrons and the propagation of light. Nobel Lecture (1902)* in: *Nobel Lectures, Physics 1901–1921*, Elsevier Publish. Comp., Amsterdam 1967, p. 16.

[2] H. A. Lorentz, *The theory of electrons and its applications to the phenomena of light and radiation heat*, Columbia University Press, New York 1909.

[3] M. Planck, *Scientific autobiography and other papers*, Philosophical Library, New York 1949, p. 32.

Meanwhile, throughout the 19th century, some new phenomena as well as new theories and approaches, like the kinetic theory of gases or the study of differences in spectra of chemical elements, should prove the relevance of the atomic hypothesis. Yet the two visions, continuous and discontinuous, kept going on into the 20th century. The importance of truth of the atomic theory was still being argued in 1904[1].

Besides the consequences for atomic theory, the study of spectra should resurrect the problem of the nature of light and Maxwell himself had been concerned with the question. He had reason to believe that, if electromagnetic disturbances travel at the speed of light, light must be such a disturbance. Maxwell's idea was embraced enthusiastically by Helmholtz who, in 1879, persuaded the Berlin Academy of Sciences to offer a prize for an experimental proof of Maxwell's theory and encouraged Hertz (1857–1894) to take up the problem. In 1887/1888, Hertz detected the transmission of an oscillating charge in the *ether* and found the speed of the waves transmitted. These *Hertzian waves* had wavelengths greater than those of light. Maxwell theories concerning the identification between electromagnetic disturbances and light were justified by Hertz's experiments. The results of those experiments seemed to prove that electromagnetic energy was of a continuous nature. At last, it was not necessary to assume the existence of atoms of electricity to explain electromagnetic phenomena.

The conception of the atomic nature of electricity was again to catch the attention of the scientific world with the study of discharge of electricity in gases. Accordingly, the study of discharges in gases can be seen as representing a breakdown in concepts of energy.

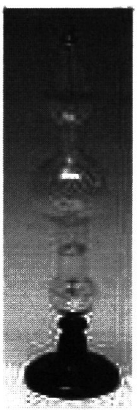
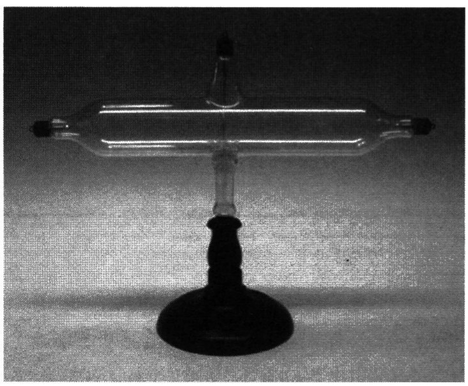


Fig. 2

A Geissler tube and a Crookes tube

http://members.chello.nl/~h.dijkstra19/page6.html



Discharges were an old instrument from the 17th century. With the improvements made in the 1850's by Johann Heinrich Geissler (1814–1879), a master glassblower, and by Heinrich Daniel Ruhmkorff (1803–1877),

[1] See G. Holton, *The scientific imagination: case studies*, p. 33.

another German craftsman, the old instrument became a modern device (Fig. 2). With it Julius Plucker (1801–1868) carried out experiments which allowed him to detect a bright green light that followed the curvature of the glass. Several years later, Johann Wilhelm Hittorf (1824–1914), his former student, could evacuate his tubes a little better than Plücker with the first mercury pumps that had come into use and then he saw *a beam of parallel rays spread out from the cathode*[1]. He also saw a shadow cast by an object placed in front of the cathode. Cathode rays were discovered. The name was coined in 1876 by Eugen Goldstein (1859–1930).

In the last decades of the 19th century, the nature of cathode rays divided physicists and chemists, with the electron or atoms of electricity playing a major role in the dispute. Germans claimed that cathode rays were waves. In England, William Crookes (1832–1919) insisted that they were electrically charged particles.

Crookes carried out systematic investigations on cathode rays in tubes where he produced very good vacuums. He developed a modification of the Geissler tube into what is known as the Crookes tube (Fig. 2). Using Sprengel's pump he could push the boundary of emptiness further and further. Gradually, in the experience, a greenish spot on the glass grew larger and brighter. This light could transmit energy too. When the stream fell upon a little wheel of vanes it turned. Once focused against some point on the tube with a magnet, the spot became burning hot. The results displayed to the Royal Institution in April 1879, as well as Crookes's theory to explain his experiences, was greeted with great applause and caused great controversy too.

Crookes believed that cathode rays were *little particles which constituted the physical basis of universe*, a *fourth state of matter*[2]. In Germany, Goldstein was convinced that the rays were not matter but ether. He argued, in spite of the deflection of the rays by a magnet, that all their characteristics could be explained by thinking of them as light. In 1891, in his last big experiments, Hertz with his student Philipp Lenard (1862–1947) found that cathode rays get through a foil of aluminium. It was inconceivable than particles could do this. Only waves of very short wavelength could do so.

In England, Arthur Schuster (1851–1934), assuming that cathode rays were particles, found the ratio of the charge to the mass of such particles. Actually, measuring the deflection of the rays by a magnet, it is possible to estimate this ratio. Schuster's results let him decide, in 1890, that cathode rays were particles.

Three years later, in 1893, J. J. Thomson took up the subject at the point Schuster had reached. In the first years he could not advance much more and, meanwhile, in 1895, the French physicist Jean Perrin found substantial proof that cathode rays were negatively charged particles. He sent the rays into a Faraday cage and showed that they carried a negative charge. Perrin's experiment opened the way for further research.

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[1] A. Keller, *The infancy of atomic physics*, Clarendon Press, Oxford, 1983, p. 38.

[2] R. K. DeKosky, *William Crookes and the Fourth State of Matter* in: *Isis* 67, 1/1976, p. 36.

A few weeks after Perrin published his results, Wilhelm Conrad Röntgen (1845–1923), working at a cathode ray tube, discovered a new kind of rays, the X–rays, as he called them. He also discovered that objects were transparent to these new rays. On 1st January 1896, he sent out the preprints of his discovery containing one of the most famous scientific photographs ever published – an image showing the bones of a hand.

In the same year, Henri Becquerel (1852–1908) thought of a possible relation between X–rays and fluorescence and began testing whether fluorescent substances emitted X–rays. His experiments led to the discovery of radioactivity. This discovery, even though it had not been performed in the cathode ray tube, was a consequence of research work performed on that device. Experiments in cathode ray tube also gave birth to the next discovery which marked the birth of microphysics – the electron. One could then say that cathode ray tube is the birth place of a new era in physics.

4. A turning–point in the history of the electron: from Thomson to Millikan

In 1897, J. J. Thomson published the results of his crucial experiments confirming the corpuscular nature of cathode rays. He was the first to observe the electric deflection of the rays and from his measurements he could determine the ratio of charge to mass of the particles. He also observed that this value is independent of the experimental conditions:

> *The results of the determinations of the values of* e/m *made by this method are very interesting, for it is found that, however the cathode rays are produced, we always get the same value of* e/m *for all the particles in the rays. We may, for example, by altering the shape of the discharge tube and the pressure of the gas in the tube, produce great changes in the velocity of the particles, but unless the velocity of the particles becomes so great that they are moving nearly as fast as light, when other considerations have to be taken into account, the value of* e/m *is constant. The value of* e/m *is not merely independent of the velocity. What is even more remarkable is that it is independent of the kind of electrodes we use and also of the kind of gas in the tube. The particles which form the cathode rays must come either from the gas in the tube or from the electrodes; we may, however, use any kind of substance we please for the electrodes and fill the tube with gas of any kind and yet the value of* e/m *will remain unaltered.*[1]

In spite of those results *several contemporary scientists who were involved in the development of the theory of electrons did not think that the*

[1] J. J. Thomson, *Carriers of negative electricity. Nobel Lecture (1906)* in: *Nobel Lectures, Physics 1901–1921*, p. 148.

electron had been discovered by J. J. Thomson, or any other scientist for that matter[1]. Actually, after twenty years or more of experiments and controversy over the cathode, *a sudden discovery episode is too simplistic*[2]. However, even though it did not mean *the discovery of the electron*, Thomson's results represented a turning point in the way of thinking about matter and energy.

At the time of Thomson's *discovery* the conviction in the existence of atoms was not yet definitely established. In the beginning of the 20th century *there really was little direct evidence from phenomena for the reality of atoms and molecules, that is, for the necessity of discreteness itself*[3]. Although the opponents of the atomic hypothesis were, probably, *unfavourably disposed toward the electron*[4], as the basic equipment to repeat Thomson's experiences was available to most physical laboratories, the charged particles could be *seen* and *measured* in any physics department. In that way, Thomson's experiences were decisive in order to establish a *belief* in the existence of electrons. Furthermore, Thomson's hypothesis that *the charged corpuscles are constituents of the atom* represents the first, even incipient, idea of atomic structure.

After 1897 several scientists spoke of *seeing* electrons[5]. One of them was Robert Andrews Millikan (1868–1953), who studied under Michael Pupin (1858–1935). Pupin was an anti–atomist but Millikan, in spite of admiring and respecting him, did not absorb his epistemology. He found in Benjamin Franklin (1706–1790) and in J. J. Thomson his theoretical and philosophical basis for the work on measuring electric charge of the electron[6].

In 1910, using the *oil–drop method*, Millikan proved that the charge carried by an electron was constant for all electrons. Millikan's convincing demonstration of the discreteness of charge helped considerably to establish finally the atomic theory of matter. To him, *who has seen that experiment, and hundreds of investigators have observed it, has literally* seen *the electron*[7]. Actually, in Millikan's experiments, the *discontinuity* in the observable phenomena – new at the time – fitted splendidly with the hypothesized discontinuity in the concept of quantized charge.

The power of visualisation was important at the time when there was no direct evidence of atomic events like particle tracks in Wilson chambers or flashes or tricks in Geiger counters.

Millikan's results could be seen as the epilogue of a long history of controversial theories and interpretations. Discontinuity in concepts of energy seemed to be getting more and more coherent with Thomson's ideas, the

[1] T. Arabatzis, *Representing Electrons*, University of Chicago Press, Chicago 2006, p. 63.

[2] T. Arabatzis, *Representing Electrons*, p. 63.

[3] G. Holton, *The scientific imagination: case studies*, p. 33.

[4] T. Arabatzis, *Representing Electrons*, p. 67.

[5] G. Holton, *The scientific imagination: case studies*, pp. 36–38.

[6] G. Holton, *The scientific imagination: case studies*, p. 54.

[7] R. Millikan, *The Electron and the Light–Quant from the Experimental Point of View. Nobel Lecture (1924)* in: *Nobel Lectures, Physics 1922–1941*, Elsevier Publishing Company, Amsterdam 1965, p. 58.

electron becoming the main protagonist of that controversial image of nature: the atomistic view.

5. Electron: from unity to duality

Meanwhile, in the first decade of the century, new discoveries and new theories changed the way of thinking about matter and energy. In 1900, Max Planck (1858–1947) established his law describing the spectral radiance from a black body. To do it, Planck would have to consider that energy is not continuous but composed of a number of finite parts or *quanta*. As Planck himself wrote, if a quantum of action must play a fundamental role in physics, *here was something entirely new, never before heard of, which seemed called upon to basically revise all our physical thinking*[1]. Planck's view failed to win international recognition, until Lorentz's *conversion* to the quanta theory in 1908. However, three years before, a young and yet unknown scientist – Albert Einstein (1879–1955) – expressed ideas which showed how Planck's theory could explain matter and ether–radiation interaction. Assuming Planck's formulae, it made sense to say that radiation is composed of unities or quanta. Einstein's idea was the base of the mathematical description of how the photoelectric effect was caused by absorption of a quantum of light. For Einstein (1879–1955), light, that is, the electromagnetic field itself, is quantized. After the *atoms of electricity*, it was the *atoms of light*.

In 1913, Bohr's theory of atom *brought together the new theory of discontinuous radiation and the new theory of atom's structure*[2]. Bohr's model of the atom, which demonstrated extraordinary power in predicting spectral lines, was, in 1916, enhanced by the Sommerfeld–Wilson quantization condition. In 1921, Stern and Gerlach's experiment demonstrated space quantization. Atom and radiation became reconciled, in discontinuity, and the world seemed to be discontinuous, at last.

Nevertheless, the electron, once a time [?], changed that apparently perfect view over matter and energy. In 1924, in his doctoral thesis, *Research on Quantum Theory*, De Broglie introduced the theory of electron waves which included the wave–particle duality theory of matter. This research culminated in the hypothesis stating that *a wave must be associated with each corpuscle*[3]. De Broglie's idea was thus to extend the duality to material particles, especially to electrons, as he said in his Nobel Lecture:

> *The determination of stable motion of the electrons in the atom involves whole numbers, and so far the only phenomena which whole numbers were involved in physics were those of interference and of eigenvibrations. That suggests the idea to me that electrons themselves could not represented as simple*

[1] M. Planck, *The Genesis and Present State of Development of the Quantum Theory* in: *Nobel Lectures, Physics 1901–1921*, p. 416.

[2] A. Keller, *The infancy of atomic physics*, p. 169.

[3] L. De Broglie, *The wave nature of the electron. Nobel Lectures (1929)* in: *Nobel Lectures, Physics 1922–1941*, p. 252.

> *corpuscles either but that a periodicity had also to be assigned to them too.* [...] *I thus arrived at the following overall concept which guided my studies: for both matter and radiations, light in particular, it is necessary to introduce the corpuscle concept and the wave concept at the same time. In other words the existence of corpuscles accompanied by waves has to be assumed in all cases.*[1]

Then, two seemingly incompatible concepts can each represent an aspect of the truth. They may serve, each in its turn, to represent the facts without ever entering into direct conflict. Finally, the electron was a corpuscle, but it was continuous, too. Clear cut experimental proof of interference phenomena produced by electron waves was obtained by Clinton Davisson (1881–1958), and Lester Germer (1896–1971)[2] and by George Paget Thomson (1892–1975)[3] (Fig. 3).

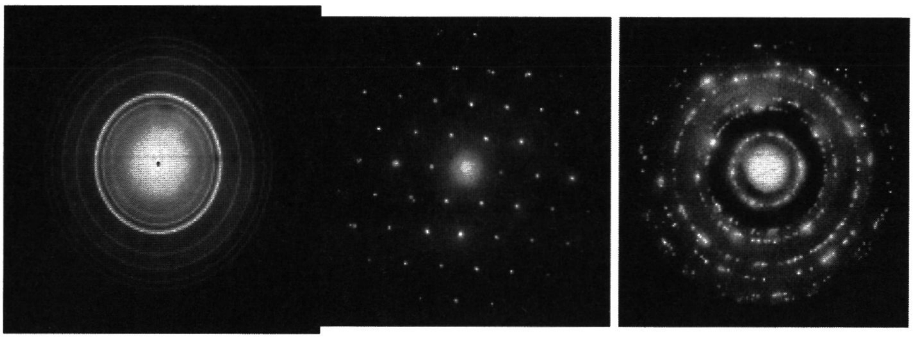

Fig. 3
Electron diffraction patterns
http://www.physics.brown.edu/physics/demopages/Demo/modern/demo/7a6010.htm

De Broglie's theory was used by Dirac in 1925 and by Schrödinger in 1926 to develop wave mechanics. De Broglie's method of quantization was primitive, but it helped Schrödinger in the discovery of the real wave equation of the electron. Heisenberg (1901–1976) found another formulation of quantum mechanics which avoided the representation of electronic orbits (1925) but which was equivalent to Dirac's and Schrödinger's theories. Heisenberg showed, in 1927, that classical concepts such as that of the orbit of a particle failed when applied to microscopic objects such as an electron. Because of its double nature it is impossible to achieve the measurement of its

[1] L. Broglie, *The wave nature of the electron*, p. 247.

[2] C. J. Davisson & L. H. Germer, *Diffraction of Electrons by a Cristal of Nickel* in: *Physical Review* 30, 1927, p. 707.

[3] G. P. Thomson, *Experiments on Diffraction of Cathode Rays* in: *Proceedings of Royal Society* 117, 1928, p. 600.

position and momentum. Heisenberg's theory banished the picture of electron with definite orbits and periods of rotation. In the following years Bohr deepened the ideas of quantum mechanics and established the idea of complementarity, which was adopted by the Copenhagen School. Quantum mechanics explained some phenomena that had been known for a long time.

However, the new formulation of the electron problem given by quantum mechanics was not the epilogue of the story over continuity and discontinuity of matter and energy. To many physicists and philosophers of science, as well as to several schools of thought, the subject is still open a matter of study and of controversy.

6. Concluding remarks

The history of the electron calls up great names as well as important topics and great discoveries, in theoretical and experimental chemistry and physics of the last two centuries. One can say that the electron is always present and always controversial an *entity* in the history of modern science from the 19^{th} to the 21^{th} centuries. This history can actually be recounted as the story of evolution of the concept of *electron*.

In addition, the electron is also relevant for the philosophy of science. Some episodes of its history bear evidence of discontinuity at work in the history of sciences, justifying the use of concepts as Kuhn's paradigm or Bachelard's *epistemological break*. The evolution of theories concerning the electron can also be viewed as an illustration of Popper's criteria of *verification* and *falsifiability*.

The concept of electron gave rise to several philosophical questions some of which remain relevant to modern philosophy of physics, like the interpretation of quantum mechanics. Other questions can be asked about the concept, for instance questions concerning its operational character: *facts about electric charges are nothing but facts about the electric field!*[1]

Furthermore, the electron is still a good example of the *need for an interaction between the history and philosophy of science*[2]. In conclusion, there is a lot of theoretical and experimental research to be done on the history of the electron and related topics.

[1] M. Lange, *An Introduction to the Philosophy of Physics*, Blackwell Publishing, Oxford 2002, p. 165.

[2] T. Arabatzis, *Representing Electrons*, p. 1.