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# History of physics research and physics education: The case of the first electron charge measurement

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**Summary.** — The historical case-study of Thomson's discovery of electron (1897), of the first Thomson's ion charge measurements (1897–1899) and of Millikan experiments of the elementary charge (1907–1911) is here discussed with the goal of stressing its possible physics education significance.

## 1. – Introduction

The role of history in physics education is widely recognized in scientific literature as a fruitful approach to promote understanding of the *Nature of Science*, including its non-dogmatic character and its creative and human dimension, to introduce and contextualize most relevant topics, to clarify fundamental concepts and overcome conceptual difficulties, to develop critical thinking, and to inspire didactic experiments [1-6].

Nonetheless, as a matter of fact, history as outlined in textbooks, lecture notes, websites and encyclopedias, ranging from biographies of celebrated scientists to the analysis of scientific discoveries and experiments, and only very rarely addressing the evolution of scientific concepts and its relevance to the development of a scientific literacy in school, is rarely satisfying [7-9]. It is a well-known fact that the standard physics textbooks usually outline a *quasi-history*, that is a type of material which looks historical, but in which there is no attempt to convey history truthfully [10]. Typically, historical references are introduced as mere sequences of names and dates; the description of the historical development is oversimplified; references to the historical contexts and to specific scientific

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(*) Corresponding author. E-mail: `francesca.monti@univr.it` environments are missing. This involves the risk of viewing the evolution of science as a linear path, losing a correct vision and comprehension of the modalities with which science develops, and may result in missing the rationale behind a scientific discovery, in compromising a full understanding of the related concepts and in hindering critical thinking development. On the contrary, a suitable choice of historical case studies might promote students learning and provide both students and teachers with an invaluable source of cultural enrichment.

As a matter of fact, physics education research has traditionally highlighted the need of activating scientific reasoning modalities and the personal mental involvement/engagement of students [11-13]. Most recent trends also show the need to help students face the society of acceleration and educate them to the future [14] and recognize a certain standardization and stiffening in the construction of physics curricula and the need for upgrading [15]. We believe that history of physics represents a unique way for addressing all these issues. That is why we propose an approach based on an accurate reconstruction of scientific discoveries in a didactic perspective, grounded on the original documents, and, as such, strictly related to the research in the history of physics [16-18].

An emblematic case of all the above discussed issues, that is also well suited for illustrating our approach, is the discovery of the electron. In fact, also a mere cursory perusal of secondary school and university physics textbooks reveals that two experiments are usually addressed: Sir J.J. Thomson's measurement of the $e/m$ ratio in 1897 in the case of cathode rays (traditionally labelled as the discovery of electron experiment) and, with a 14 years' jump, Robert Millikan's measurement of the charge of the electron in 1911. The same attitude can be found in many websites and encyclopedic entries (*e.g.*, in the *Encyclopaedia Britannica* entry "Electronics" we find the assertion that "the history of electronics began to evolve separately from that of electricity late in the 19th century with the identification of the electron by the English physicist [...] Thomson and the measurement of its electric charge by the American physicist [...] Millikan in 1909" as if nothing had happened in between). Thomson's discovery of the electron experiment usually appears at the beginning of modern physics courses and in introductory courses on electronics, where the measurement of the charge of the electron is proposed in hands-on or virtual laboratories based on shot-noise from the thermionic effect (*e.g.*, [19]). Millikan's oil-drop experiment is often cited as the first measurement of the charge of the electron besides being proposed at the beginning of electrostatics in hands-on or virtual experiments for measuring the "elementary charge" in the context of charge quantization [20, 21].

As it is well known, J.J. Thomson's and R. Millikan's accomplishments were soon acknowledged by the Nobel Foundation, who awarded the Nobel Prize in Physics to Thomson, in 1906, "in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases" and to Millikan, in 1923, "for his work on the elementary charge of electricity and on the photoelectric effect". Yet, even in one edition of the authoritative *Fundamentals of Physics* textbook (by Halliday, Resnick and Walker), it is asserted that, not only "[Millikan's] first great success was the accurate determination of the charge of the electron", but that by this he managed "*to prove the existence of electrons empirically*" ([22] p. 26), as if this had not already been sufficiently demonstrated by Thomson in 1897.

Actually, the paternity of electron discovery is not in dispute and Thomson is the father of the first elementary particle, despite Millikan's ambitions as outlined in his 1917 book *The electron*, where we find words like these: "[here], then, is direct, unimpeachable proof that the electron is not a "statistical mean", but that rather the electrical charges found on ions all have either exactly the same value or else small exact multiples of that value"([23], p. 70). In spite of Thomson's paternity, Millikan's role in the history of the research on the electron properties cannot be underestimated and this case-study has therefore all the ingredients to become an important educational tool to promote among teachers (in-service and pre-service) and students a better understanding about the *nature of science* and its complexity as derived from an analysis of the actual history of science reconstructed through original documents.

Also, Millikan's attempt to downplay the importance of previous research carried out by Thomson is useful at the educational level to improve students' views and concerning scientific *argumentation* and modelling. Neglect of scientific argumentation in the school science curriculum gives indeed "the impression that science is the unproblematic accumulation of data and theory". In consequence, "students are often puzzled and may even be alarmed by reports of disagreements among scientists on matters of contemporary importance" ([24], p. 926). Millikan's experiments had been studied in the past as a case in point of an alleged cherry-picking of data on his part [25, 26] and as a glaring example of harsh disagreement among scientists due to the dispute, occurred around 1910, between Millikan himself and Austrian physicist Felix Ehrenhaft over the existence of the elementary electric charge [27,28]. In this paper, we will instead focus on the more fundamental disagreement concerning the status of the respective research of Thomson and Millikan as evidence of the existence of the electron.

In order to make order out of the electron case study, with the goal of stressing its possible physics education significance, we will fill the 14 years-gap between Thomson's 1897 experiment and Millikan's 1911 experiment with a threefold look: a) briefly reconstructing Thomson's 1897 discovery of the "corpuscle", which later became the *electron* as it is understood today, through his $e/m$ measurements; b) reconstructing the ion charge measurements performed by Thomson in the years 1897–1899, eventually leading in 1899 to the first measurement ever of the *electron charge*, as understood today; and, finally, c) reconstructing Millikan's experiments from 1907 to 1911, leading to the most accurate possible value of the *elementary charge*, of which all charges are integer multiples, and consequently of the electron charge as understood today(1).

## 2. – Thomson's "corpuscle"

In his classic 1897 paper [29,30], J.J. Thomson (1856–1940) succeeded in demonstrating that *cathode rays* —that is the radiation originating in the cathode and responsible for the effects occurring in low-pressure discharge tubes (fig. 1)— were deflected by a magnetic and by an electric field and carried a negative charge, hence driving the conclusion that they are "negatively electrified particles" ([30], p. 294).

At this point, a new question arose: "What are these particles? Are they atoms, or molecules, or matter in a still finer state of subdivision?" ([30], p. 302) To answer this question Thomson route was to measure their mass to charge ratio $m/e$. He made use of two different experimental methods, respectively based on a) cathode rays' deflection

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(1) Some of the topics discussed in this paper had been previously addressed in the following seminars for teachers: "Una prospettiva storica all'insegnamento della Fisica: dalla nascita dell'elettrone a quella del nucleo atomico", held by F. Monti and N. Robotti in Verona, Italy, in 2019 (organized within the context of the Italian Scientific Degree Plan); "La misura della carica elettrica: il caso dell'elettrone", held by N. Robotti in 2021 during an AIF (Italian Association for Physics Teaching) online training course.

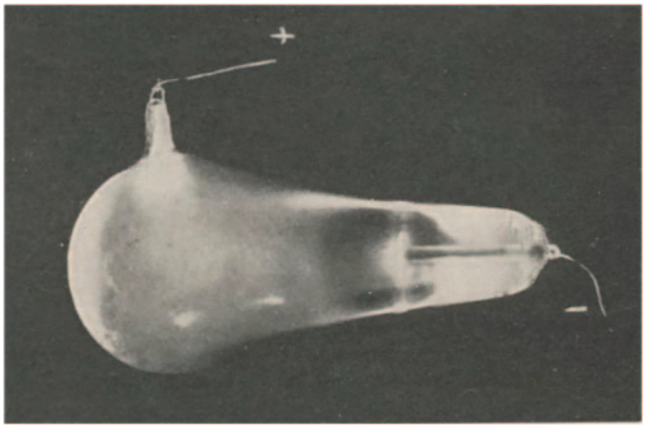

Fig. 1. – “General nature of the [cathode rays] phenomenon” (J.J. Thomson, Cathode Rays, Harper’s Monthly Magazine, Sept 1901, p. 565).

in both an electric and a magnetic field and on b) cathode rays’ deflection in a magnetic field supposing that when under measurement their kinetic energy was entirely converted into heat when hitting a thermocouple (under this hypothesis, by measuring the increase in temperature of a body when cathode rays strike against it, velocity of the particles and $m/e$ could be derived). By these methods, Thomson obtained a value for $m/e$ of the order of $10^{-7}$ g/emu (the electromagnetic unit of charge —*emu*— was a unit of charge in the cgs system and corresponded to 10 *coulombs*; to convert emu into the other cgs unit of charge usually used at the time, the *esu*, electrostatic unit of charge, you need to multiply emu by the speed of light expressed in cm/s, that is $3 \times 10^{10}$) irrespective of the type and pressure of the gas and of the cathode material. Moreover, as Thomson himself emphasized, the value $10^{-7}$ “is very small compared with the value $10^{-4}$, which is the smallest value of this quantity previously known, and which is the value for the hydrogen ion in electrolysis” ([30], p. 310).

But this result, taken alone without a separate determination of its mass or its charge, didn’t give enough information, and allowed for various explanations: the mass of these new particles could be much smaller than the hydrogen ion, or their charge could be much higher, or both.

Indeed, Thomson argued that a choice among these possibilities could have been made based on Philipp Lenard’s 1894 experiments on cathode rays’ absorption [31]. In fact, these experiments showed that the mean free path of cathode rays in air at atm pressure was equal to 0.5 cm, while, under the same conditions, the mean free path of air molecules resulting from the kinetic theory of gases, was $2\ 10^{-5}$, *i.e.*, it was of a completely different order of magnitude. Therefore, according to Thomson, it could be recognized that particles that constitute cathode rays “must be small compared with ordinary molecules” ([30], p. 310).

Given that their $m/e$ ratio was the same independently from utilized materials and pressure, Thomson drew the conclusion that atoms were complex and divisible structures, and that they were made not only of “aggregations of atoms of the same kind” ([30], p. 311) (a hypothesis that had been already favorably entertained in chemistry by Prout, Dumas, de Marignac and other scientists who considered atoms as composed by the hydrogen atom) but, more specifically, of "primordial atoms" that were electrically charged, and that cathode rays represented one of these charged parts that were "projected from the cathode by the electric field". To this atomic constituent of negative charge (that would become our "electron") Thomson gave the name of "corpuscle" ([30], p. 311).

## 3. – The "corpuscle" *versus* the "electron"

Why did Thomson name "corpuscle" this new sub-atomic particle, that we now name "electron"?

Actually, in 1897, the term "electron" already existed. It had been coined by George Johnstone Stoney (1826–1911) in 1891 for the "definite 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" [32]. In fact, Stoney had first looked at this "definite quantity of electricity" in 1874 (at the Belfast meeting of the British Association in a paper "on the Physical Units of Nature"), when he interpreted Faraday's electrolysis laws in the light of Kekulé's recently proposed atomic valence theory [33]. Basing his ideas on the kinetic theory (which made it possible to calculate the Avogadro's number and thus the mass of the hydrogen atom) and using tables of electrochemical equivalents related to water electrolysis, Stoney obtained a value of $1.03 \times 10^{-21}$ emu. After him, other estimates of the unitary charge were made by different scholars, all giving values between $4.71 \times 10^{-21}$ emu and $4.31 \times 10^{-21}$ emu.

Therefore, in the last decade of the nineteenth century, the concepts of "unitary charge" or "atom of electricity" [34] or "electron" and, with it, the concept of "ion" understood as the "atom of matter with one or more unitary charges", had found their place in the common scientific discourse.

Anyway, one thing was to think, as scientists did, that atoms or molecules contained one or more unitary charges and that these, as Stoney first suggested, were the basis of chemical bonds, electrolytic phenomena, and so on: in this light, the atom was certainly a complex structure, but still indivisible. Another thing was, instead, to suppose, as Thomson put forward in 1897, that the atom was not only formed by charged particles of matter, but that it could be broken down into these sub-atomic particles —the *corpuscles*. In this case, the indivisibility of the atom, which until then had never been questioned, was automatically sacrificed.

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. It is therefore clear that in 1897 there was no *a priori* reason for seeing the "corpuscle" and the "electron" as necessarily linked to each other. In other words, the "electron" on one hand and the corpuscle on the other hand started out and continued to seem two separate entities and they had to be treated as such. This was the basic reason why Thomson, facing with the problem of physically characterizing the corpuscle, *i.e.*, to establish how much smaller it was than the hydrogen atom, did not give it a charge value equal to the "electron" —that would immediately have led him to an initial estimate of the mass of the corpuscles without waiting for a separate measurement of the charge. Instead, between 1897 and 1899, he devised a research program to directly measure the specific charge of the corpuscle.

## 4. – Thomson's measurement of the charge of the ions in 1898

Fulfilling the corpuscle's charge measurement was not a straightforward job. Thomson did not see the way to reach this goal in the case of cathode rays and looked for new phenomena involving the corpuscles that would allow their charge (or mass) as well as their mass-to-charge ratio to be measured.

The first phenomenology chosen by Thomson was the ionization of a gas under the action of X-rays. This had been the focus of various activities promoted at the Cavendish Laboratory in the 1890s. Between 1896 and 1897, these activities had included a series of both experimental and theoretical studies, carried out especially by Thomson and Ernest Rutherford. These studies had soon revealed some differences in the behavior of positive and negative ions (*e.g.*, negative ions were much faster than positive ones) and led Thomson to explain ionization in terms of "dissociation of molecules". In 1898, however, Thomson was not able to identify the negative ions with the corpuscles. His aim at this stage 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" ([35], p. 528).

Performing a measurement of this type was by no means a simple proposition, and it was made possible thanks to a range of competences about gas discharges gained at the Cavendish Laboratory since 1890, in particular:

1) Knowledge of the processes of condensation of saturated and super-saturated vapors and how they are linked with the presence of electrical charge. Research in this field (begun by Thomson himself) was developed by C. T. R. Wilson (1869–1959) from 1895 and culminated in 1911–12 with the development of the so-called *cloud chamber* [36].

2) Development of techniques for measuring the mobility of ions. This activity was carried out mainly by Rutherford and Zeleny [37, 38].

Thomson's apparatus for measuring the charge of the gaseous ions produced by X-rays is illustrated in fig. 2. Vessel A contains air, or another gas, saturated with water vapor and ionized by an X-ray source (on the right top side in the figure). The adiabatic expansion was obtained by means of a piston, P: when volume increases, the temperature in A lowers and water vapor condenses on the ions in the form of water droplets.

Thomson's experiment can be looked at in two stages.
Phase 1): determining the total charge $Q$ associated with the number $n$ of ions present in a unit of volume (*e.g.*, $1\,\mathrm{cm}^3$).
Phase 2): determining the number $n$ of ions present in that unit volume.
Having made these measurements, if each ion carries the same charge $e$, the latter can be determined immediately from $Q = ne$ dividing $Q$ by $n$.

Concerning phase 1, the total charge $Q = ne$ associated with the droplets was determined by applying a weak electromotive force $E$ between the upper wall of A (aluminum foil) and the water surface, measuring the corresponding current $I$ in A.

Given the average mobility $v$ of positive and negative ions (*i.e.*, their velocity in the presence of a unit electromotive force), the current $I$ per unit surface can in fact be expressed as

$$I = ne\ v\ E. \tag{1}$$

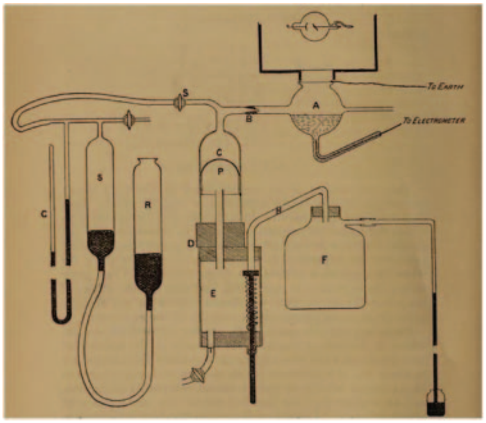

Fig. 2. – Thomson's apparatus for measuring the charge of the gaseous ions produced by X-rays ([35], p. 534).

Since $v$ had already been measured at the Cavendish Laboratory by Rutherford [37], and $I$ and $E$ were easy to measure, eq. (1) allowed Thomson to determine $ne$, *i.e.*, the quantity of charge $Q$ contained in a cubic centimeter of gas.

Concerning phase 2, to obtain $n$, Thomson used the property that ions behave like nuclei for condensation. Then, assuming that there is one ion in each water droplet, $n$ can be obtained by calculating the number of droplets in the falling cloud deposited per unit volume. To this aim, the total mass $M$ of water deposited per unit volume of the gas could be easily determined by the method given by C.T.R. Wilson in his paper on the formation of clouds in dust-free air, that is by the equation connecting the temperature reached at any moment with the quantity of water which has condensed $M$ and the latent heat of vaporization through the mass of unit volume of gas and the gas specific heat at constant volume, given the lowest temperature reached ([36], p. 299). Such a mass $M$ could be expressed in terms of $n$ and of the mass $m$ of a single droplet ([35], p. 538) as

$$M = nm, \tag{2}$$

where the mass of each single droplet depends on its radius $a$ (given the value of water density equal to 1):

$$m = 4/3\pi a^3. \tag{3}$$

The mass of a droplet, hence the number of droplets in the falling cloud, can be determined from the knowledge of $a$ which is linked to the velocity $v'$ of the water droplet falling in the gravitational field $g$ by Stokes' law. If we neglect the density of the gas in comparison with that of the drop and if there is no slip between the sphere and the gas:

$$v' = 2ga^2/9\mu, \tag{4}$$

where $\mu$ is the coefficient of kinematic viscosity $[l^2t^{-1}]$ of the medium. By measuring $v'$ it was therefore possible to obtain a value for $a$, hence $n$ ([35], p. 541).

Thomson successfully used this type of measurement to establish that when a gas is ionized 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 we ionize hydrogen or oxygen) and these charges are equal or at least of the same order of the charge of the hydrogen atom in electrolysis, *i.e.*, in the order of $10^{-10}$ esu (the cgs electrostatic unit of charge —esu— corresponds to $3.3 \times 10^{-10}$ C). In the final section of his paper ([33], p. 543) he reports a value for the charge of an ion

$$e = 6.5 \times 10^{-10}\,\text{esu(that is } 2.1 \times 10^{-19}\,\text{C)}.$$

## 5. – The first ever measurement of the charge of the corpuscle by Thomson in 1899

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 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.

Therefore, Thomson had to look for another phenomenon that could be explained in terms of corpuscles, that would provide a measurement of charge with the method he had just developed for the ions and that would also allow for the mass-to-charge ratio to be measured as in the case of "cathode rays".

The first phenomenology addressed by Thomson was "photoelectric emission" [39], for which since the 1880s it was known that negatively charged as well as a neutral Zn or Al plates exposed to the action of ultraviolet light emit negative charge [40]. Moreover, it was known by Elster and Geitel's research [41] that at low pressures "the rate of escape of the negative electrification [...] is much diminished by magnetic force if the lines of magnetic force are at right angles to the lines of electric force" ([39], p. 548).

Based on these properties, Thomson proposed identifying "the escape of negative electricity" that characterized the photoelectric effect with "an escape of corpuscles". This explanation 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.

With this idea in mind, Thomson promoted a series of studies on photoelectric emission at the Cavendish Laboratory. These studies established that the "negative electricity carriers" that escaped from the illuminated surface "act 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" ([39], p. 557).

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 the ions produced by Roentgen rays and described in sect. 4 could be utilized by adding a suitable metallic plate illuminated by ultraviolet light inside the condensation vessel, and then proceeding, as in the case of the ions produced by Roentgen rays, to measure the charge of the emitted corpuscles.

Thomson's apparatus is shown in fig. 3(a). ABCD is a glass vessel (3.6 cm in diameter) —in place of the vessel A in fig. 2— in which the expansion takes place and is connected through the smaller tube L to the expansion apparatus. K is a clean zinc plate, 3.2 cm in diameter, while CD is a quartz plate which allows ultraviolet light (produced by an arc lamp located below the lower surface of the quartz plate) to pass and illuminate the zinc plate. When the zinc plate is illuminated by ultraviolet light and expansion

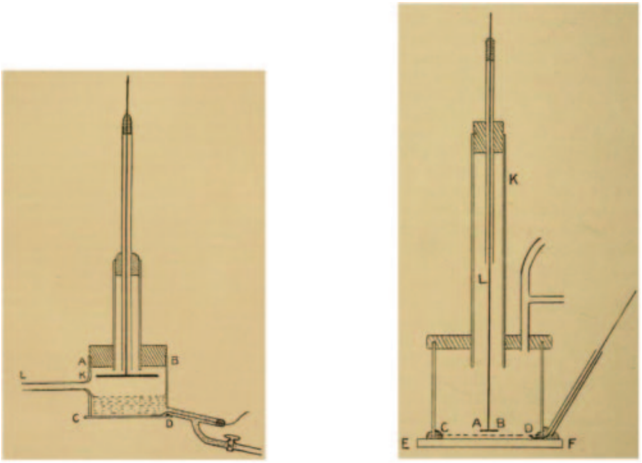

Fig. 3. – (a) Thomson's apparatus for measuring the charge of the corpuscles produced by photoelectric emission ([39], p. 559); (b) Thomson's apparatus for measuring the mass to charge ratio of corpuscles produced by photoelectric emission ([39], p. 550).

takes place, a cloud is formed in vessel ABCD. At this point, with the same method as that applied in 1898, Thomson measured the charge of the corpuscles produced by photoelectric emission.

In this way, in 1899 Thomson arrived at a value for the charge of the corpuscle ([39], p. 562)

$$e = 6.8 \times 10^{-10}\,\text{esu (that is } 2.2 \times 10^{-19}\,\text{C)},$$

*i.e.*, the same as $e$ for the ions produced by Roentgen rays, and the same as that commonly attributed to the hydrogen ion in ordinary electrolysis.

This is the first ever measurement of the charge of the corpuscle in history, and it should be remembered and valued as such.

## 6. – Thomson's 1899 measurement of the $m/e$ ratio for the photoelectric effect corpuscles

To characterize the mass of the corpuscle, in the same 1899 paper, Thomson measured the mass to charge ratio also in the case of photoelectric emission.

The apparatus designed by Thomson is shown in fig. 3(b). 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. The importance of creating vacuum for measuring the mass-to-charge ratio of the corpuscle was clear to Thomson thanks to his 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 round an electrified body" and therefore would have lost its identity ([39], p. 564).

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 negative charges that start from AB, when it was illuminated, moved toward 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, the path of the negative charges that started from AB were cycloids whose generating circle rolled perpendicularly to the zinc plate and had a diameter $d$ given by

$$d = 2Xm/eH^2, \tag{5}$$

where $e$ and $m$ are, respectively, the charge and the mass of the particle. If the distance between the zinc plate and the gauze is greater than the diameter of the cycloid, the particles cannot reach the gauze. If, however, the distance between the plates is less than the diameter (eq. (5)), the particles can reach the gauze and convey current to the electrometer.

In his experiment, Thomson began placing the plates at a very close distance that was gradually increased. In the initial phase until the distance between the plates was less than the diameter of the cycloid (eq. (5)), the rate at which CD received a negative charge was constant, but as soon as the distance was equal to eq. (5), 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 eq. (5) to calculate the $m/e$ ratio of the corpuscle.

Thomson obtained a mass-to-charge ratio for the "carriers of negative charge produced by ultraviolet light" of $1.3 \times 10^{-7}$ g/emu, that was of the same order of magnitude as the value measured in 1897 for the cathode rays.

Furthermore, an almost identical value was also obtained by Thomson for another phenomenon, also linked to gas discharges, and reported in the same paper: the "negative charge emission by an incandescent carbon filament in an atmosphere of hydrogen at low pressure".

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 $3 \times 10^{-26}$ g or approximately 1/1000 of the mass of the hydrogen ion.

As Thomson wrote, leading to the final characterization of the corpuscle: "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" ([39], p. 548).

## 7. – Subsequent measurements of the charge of the ions at the Cavendish Laboratory

From that time on, measurements of the ions' charge continued at the Cavendish Laboratory, but for different purposes. Indeed, the aim was now to improve the measurement of ions' charge value to estimate other universal constants, particularly Avogadro's number.

In 1903, Thomson repeated the 1898 measurement of "*e*" taking into account the new finding by C.T.R. Wilson that in the case of the volume expansion used by Thomson ($V_f/V_i = 1.3$) the droplets form only on the negative ions, giving for the negative ion an average value of $3.4 \times 10^{-10}$ esu ($1.1 \times 10^{-19}$ C), that is only about half the value [...] I found in the earlier experiments" ([42], p. 354).

In the same year, at the Cavendish Laboratory, Harold A. Wilson performed a new measurement of "*e*" [43]. H. A. Wilson's method, like Thomson's 1898 one, was again based on the property discovered by C. T. R. Wilson that all kinds of ions produced in air act as condensation nuclei of supersaturated water vapor and form a cloud after a sudden adiabatic expansion. H. A. Wilson added an electric field and measured two velocities of sedimentation of the vapor cloud, with and without the applied electric field: this represented a fundamental turning point in these types of investigations. The advantage is that it does not require calculating the number of drops in the cloud (fig. 4).

H. A. Wilson considered a droplet containing one ion, and consequently having a charge $e$. The mass of the droplet can be determined by measuring its rate of fall in air, $v_1$ (under gravity alone), according to Thomson's equations (3) and (4). If a vertical electric field $X$ is applied to this droplet, there will be a vertical force on the droplet $Xe$ due to the field, so that the total force on the droplet will be $Xe + mg$. Then, if $v_2$ is rate of fall in the viscous fluid under the total force, we have

$$mg/(mg + Xe) = v_1/v_2. \tag{6}$$

As obtained by Thomson in 1899 by Stokes' law ([39], p. 561), the relation between $m$ and $v_1$ is given by

$$m = 3.1 \times 10^{-9} (v_1)^{3/2}. \tag{7}$$

Hence using eqs. (6) and (7), "if X is known measurements of $v_1$ and $v_2$ are sufficient to determine $e$ absolutely" ([43], p. 430). By this method, the electric charge could be

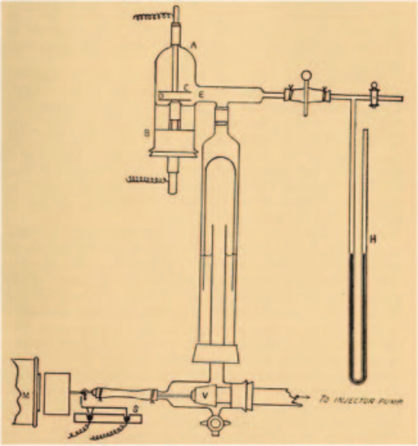

Fig. 4. – H. A. Wilson's apparatus for measuring "*e*" ([43], p. 431).

calculated giving an average value of

$$e = 3.1 \times 10^{-10}\,\mathrm{esu}(1.0 \times 10^{-19}\,\mathrm{C}).$$

In a footnote to the paper, H. A. Wilson reported that "since this paper was written Prof. Thomson has informed me that he has lately made a fresh determination of $e$ by its original method but with an improved apparatus, and he has very kindly consented to my mentioning the result he has obtained, here. It is $e = 3.8 \times 10^{-10}$ [esu, that is $1.3 \times 10^{-19}$ C], and so agrees very well with the mean result of my experiments [...]. It appears that in the earlier experiments the cloud was formed mainly on the negative ions and not on both positive and negative ions as was supposed at the time, consequently the result obtained was nearly twice too big" ([43], p. 429).

It is worth noting that in the presence of an electric field Wilson observed two or three separated layers in the cloud falling at different velocities and recognized that different sets corresponded to droplets carrying a different number of electric charges: indeed, he gave an estimation of the charge carried by the droplets in each set but did not go further in taking the minimum value ($e = 2.04 \times 10^{-10}$ esu, that is $0.68 \times 10^{-19}$ C) as the unitary electric charge ([43], p. 440).

This procedure was in fact the one later followed by Millikan starting from 1907.

## 8. – Millikan's route to the elementary charge measurement

In his first major paper devoted to the determination of the elementary charge, a couple of years after having started working on his so-called *oil-drop experiment*, Millikan began with the following words:

> Among all physical constants there are two which will be universally admitted to be of predominant importance; the one is the velocity of light, which now appears in many of the fundamental equations of theoretical physics, and the other is the ultimate, or elementary, electrical charge, a knowledge of which makes possible a determination of the absolute values of all atomic and molecular weights, the absolute number of molecules in a given weight of any substance, the kinetic energy of agitation of any molecule at a given temperature, and a considerable number of other important physical quantities.
>
> While the velocity of light is now known with a precision of one part in twenty thousand [thanks largely to the contribution of R. A. Millikan's patron and colleague at Chicago, Albert A. Michelson], the value of the elementary electrical charge has until very recently been exceedingly uncertain ([44], p. 209).

The fact that Millikan was interested in the elementary charge and in its accurate determination also emerges from his above mentioned 1917 book *The electron* [23] where he did not mention Thomson's 1899 experiments on the "corpuscle", but only cited the ones that represent the first measurement of the value of the elementary charge, *i.e.*, the measurements by Townsend and Thomson in 1898 and by H. A. Wilson in 1903.

Clearly, with respect to previous measurements, Millikan's objective was to reach the most possible accurate determination of the elementary charge by carefully analyzing, identifying, and overcoming all the involved experimental drawbacks and difficulties.

The series of measurements carried out by Millikan on the elementary charge began in 1907 with a study presented in 1908 at the Chicago Meeting of the Physical Society, jointly with his student Begeman, of which there is only a very synthetic abstract [45]. This study was based on the cited 1903 work by H. A. Wilson (sect. 7). Millikan and Begeman used a radium source instead of X-rays to ionize the (not specified) gas and corrected some (not specified) errors in the previous measurement by Wilson, obtaining the following value for *e:*

$$e = 4.03 \times 10^{-10}\,\text{esu}(1.35 \times 10^{-19}\,\text{C}).$$

On 23 October 1909, at the next Princeton Meeting of the Physical Society, Millikan alone presented a new study that was published in 1910 on *Philosophical Magazine* (the above mentioned first major paper of the series). Here the most significant change was that of observing individual drops instead of a cloud layer: "it was not found possible to balance the cloud as had been originally planned, but it was found possible to do something very much better; namely, to hold individual charged drops suspended by the field for periods varying from 30 to 60 seconds" ([44], p. 216). Millikan used Wilson's equation (6), choosing shorter distances and shorter time than Wilson's, to reduce the problems related to evaporation and using new more accurate values for the viscosity of water and alcohol. He measured different values of the electric charges carried by droplets and recognized that the only possible elementary charge was the greatest common divisor:

$$e = 4.65 \times 10^{-10}\,\text{esu}(1.53 \times 10^{-19}\,\text{C}).$$

In 1911, Millikan made the great step leading to a highly precise determination of the elementary charge: he substituted the water or alcohol droplets created by the adiabatic expansion with oil drops, *i.e.*, drops of a non-volatile substance directly produced by an atomizer [46].

This *oil-drop experiment* to study the single droplet was further improved in the two final papers of the series in 1913 and in 1917 to obtain the most precise determination of the elementary charge [47, 48]:

$$e = 4.774 + / - 0.009 \times 10^{-10}\,\text{esu}(1.593 \times 10^{-19}\,\text{C}).$$

To summarize, in the final form of the experiment (fig. 5) a cloud of small oil drops is produced by a commercial atomizer inside chamber C. Many of the drops that exit the atomizer are electrically charged due to friction. The drops are let fall under gravity through a small hole $p$ in the space between two accurately machined plates 16 mm apart, $M$ and $N$, then the hole is closed. An accurately measured electric field (3000–5000 V) can be applied and removed between the two plates. By illuminating the drops against a black background, "the appearance of [a] drop is that of a brilliant star" ([46], p. 352). A single droplet can be selected for observation through a short focus telescope placed about 2 feet distant and its rate of fall under gravity is observed. Given the viscosity of the air, the size and the mass of the falling drop can be determined (eqs. (3) and (4)). When the electric field is applied to balance gravity, a new rate of fall or rise is determined (eq. (6)). If the electric field is adjusted to hold the droplet at rest, the upward force must equal the weight, and the charge is at once determined. This *balancing* method was actually adopted only in the initial phase of the research ([44], p. 216), to be later replaced by Millikan with the method of comparing the falling time, when only the action of gravity is present, with the ascent time required to travel upwards the same distance when the field is on. "This operation is repeated and the speeds checked an indefinite number of

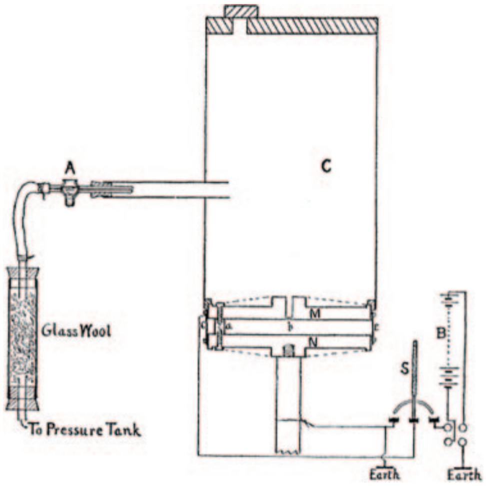

Fig. 5. – Millikan's famous oil-drop apparatus ([46], p. 352).

times, or until the droplet catches an ion from among those which exist normally in air, or which have been produced in the space between the plates by any of the usual ionizing agents like radium or X-rays" ([46], p. 353).

The charge on a drop can indeed occasionally change (between 1 and 150), and the frequency of change can be increased by irradiation with gamma rays. The change in the charge results in a change in the speed and the ratio between the previous and the new charges can be accurately determined. Millikan was thus able to establish beyond doubt that all charges and their variations were whole multiples of a minimum value, corresponding to the elementary charge. The attainment of a highly accurate value for this fundamental physical constant was not so easy and required a modification of the Stokes' law to obtain more consistent results.

It is worth noting that although this kind of measurement has been repeated by several other researchers, the accuracy of Millikan's results has never been equaled.

## 9. – Conclusions and future perspectives

In conclusion, what does the analysis of this case study tell us and what does it tell us that is potentially useful for physics education of teachers and students?

Basically, it shows us how the history of physics can be a very *rich reservoir and an ideal testing ground for discussing the nature and features of science* with secondary school and university students and with teachers in training and in service. Of course, nature and features of science can also be addressed by referring to contemporary debates between scientists, science journalists and policy makers. However, isn't it more reliable, engaging and culturally enriching to derive the basic characteristics of the scientific enterprise through documented, and not necessarily "boring", accounts of events that have marked our past··· such as, for example, those that led to the discovery of the electron and the measurement of its charge? Our answer is a resounding yes!

Even a cursory glance at our historiographical account should convey the impression —which is also a salient trait of the nature of science— that *physics is not a one-man show.* And this especially applies to our case-study, where the identity of the father of the electron was one of the issues.

In this regard, about twenty years ago, philosopher and historian of science Robert Crease carried out a poll with readers of *Physics World* on what they thought were the most beautiful experiments ever done [49]. Out of three hundred candidates, he selected the ten most frequently mentioned ones. In this top ten list figured also *Millikan's oil-drop experiment*. As reported by *The New York Times* on September 24, 2002, "in 1897 (in an experiment that could easily have made this list) the British physicist J.J. Thomson had established that electricity consisted of negatively charged particles —electrons. It was left to the American scientist Robert Millikan, in 1909, to measure their charge." As outlined above, however, Millikan was neither the first to measure the electron charge, nor was the first to measure it by a method consisting in catching ions on droplets, isolating by a suitable arrangement a single one of these droplets and measuring its speed first in a vertical electrical and gravitational field combined, then in a gravitational field alone. As it was admitted by Millikan himself, "the only essential modification in [my] method consists in replacing the droplets of water or alcohol by one of oil, mercury or some other non-volatile substance and in introducing it into the observing space in a new way" ([44], p. 351). Millikan, in other words, does nothing but make some changes —of course, fundamental to obtain much more precise measurements than in the past— to methods already used, as outlined above, by physicists such as Thomson and C. T. R. Wilson. This does not mean, of course, that Millikan's role was not fundamental. The great merit of Millikan's experiment was in fact that of demonstrating that all charges are integer multiples of an elementary charge, that of the electron.

Secondly, cultural enrichment is one of the main contributions that history of physics can give to the formation of in-service and pre-service physics teachers. And, if you delve into this historical case-study with an eye to the evolution of Thomson's research program starting from the 1897 measurement of the mass to charge ratio (m/e) for the cathode rays [50] up to 1903, when he finishes dealing with this and related topics [51], and with another eye on the birth and the first developments of Millikan's research program on the determination of the "unit of charge", or as it was already called in the late nineteenth century, "electron", you realize how wrong it is —*both historically and culturally*— to consider Millikan's 1911 experiments as the completion of Thomson's 1897 experiments.

Thus, not only Millikan's experiments are not the first empirical demonstration of the existence of electron —as Millikan ambitiously argued— but they are not the completion of Thomson's 1897 experiment either. Thomson's and Millikan's are two completely different research programs and should be therefore disentangled, especially at the educational level. As outlined above, their origin and conceptual context were completely different. Notwithstanding this, the two sets of measurements converge towards a common result with Millikan's measurement also representing an accurate characterization of the charge of the electron since the value of the charge of the electron *is* the elementary charge.

Thirdly, this case-study provides a stimulating environment, historically rooted, *to potentially enhance argumentation skills* among students. The potential contributions of the history and philosophy of science to the enhancement of argumentation in science education have been frequently addressed in the near past. As it was asserted by one author, "since scientists produce and evaluate arguments all the time in order to do science, a school science that is structured around argumentation would convey important messages about the nature of science, hence the need to inform argumentation-based instruction with findings from the philosophy and history of science" ([52], p. 1446). In this regard, an investigation aimed at studying the impact of a teaching-learning sequence designed to promote students' argumentation through the question "Who discovered oxygen" found that "this historical case can be useful for promoting students' argumentation and is also appropriate for high school students" ([53], p. 1201).

We believe that our account, where a very complex historical situation is briefly summarized and stripped of many non-essential details in order to emphasize the information more relevant at the educational level, provides clues to think that also the electron case-study could promote argumentation skills among students. Of course, providing arguments to believe in a position is one thing and empirically demonstrating it is another thing altogether. It is left therefore to a future research to test this hypothesis.

Finally, as the saying goes, devils is in the details. And even Millikan's oil drop experiment, as for example the almost contemporary "Rutherford's experiment" on alpha particle scattering [16], does not escape this rule. Analysis of literature has indeed stressed in the past that textbooks often portray a caricature and oversimplification of Millikan's experiment [20]. Our analysis adds to this picture all those elements of continuity that link Millikan's experiment to the experiments conducted years earlier at the Cavendish Laboratory. Elements, as emphasized in the Introduction, almost always absent from textbooks, and which instead contribute to creating a much more reliable picture of the nature of the scientific enterprise, thus preparing today's students, or tomorrow's citizens, in the best possible way.

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