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The Oil Drop Experiment: How Did Millikan Decide What Was an Appropriate Drop?

The oil drop experiment is considered an important contribution to the understanding of modern physics and chemistry. The objective of this investigation is to study and contrast the views and understanding with respect to the experiment of physicists or philosophers of science with those of authors of physics or chemistry textbooks and laboratory manuals. Results obtained show that physicists and philosophers of science do understand that the experiment is difficult to perform even today, primarily because of the difficulty associated with the selection of the appropriate drops and that consensus was achieved in the scientific community after a bitter dispute between R.A. Millikan and F. Ehrenhaft. In contrast, authors of physics and chemistry textbooks and laboratory manuals ignore the controversy (especially with respect to the selection of the drops) and present an inductivist interpretation in which empirical data were crucial in the quantization of the charge of the electron. By highlighting the difference between the methodologies of Millikan and Ehrenhaft, textbooks can facilitate students' conceptual understanding of the experiment and thus stimulate interest. It is concluded that although experimental data are important, epistemologically their interpretation through conflicts and controversies is even more important.

L'on considère que l'expérience de la gouttelette d'huile apporte beaucoup à la physique et la chimie modernes. L'objectif de cette recherche est de comparer les avis et les connaissances des physiciens ou des philosophes des sciences quant à cette expérience à ceux des auteurs de manuels et de cahiers de laboratoire de physique ou de chimie. Les résultats indiquent que les physiciens et les philosophes des sciences comprennent que, même aujourd'hui, l'expérience est difficile à réaliser, principalement à cause de la difficulté de choisir les gouttelettes appropriées, question sur laquelle la communauté scientifique n'est arrivée au consensus qu'après une amère dispute entre R.A. Millikan et F. Ehrenhaft. Par contre, les auteurs de manuels et de cahiers de laboratoire de physique ou de chimie font abstraction de la controverse (surtout en ce qui concerne la sélection des gouttelettes) et présentent une interprétation inductive selon laquelle des données empiriques étaient d'importance cruciale dans la quantification de la charge de l'électron. En faisant ressortir les différences entre les méthodologies de Millikan et Ehrenhaft, les manuels peuvent aider les élèves à conceptualiser l'expérience, stimulant ainsi l'intérêt que ceux-ci portent au domaine. Bien que les données expérimentales soient importantes, on conclut que, sur le plan épistémologique, l'interprétation de celles-ci par le biais des conflits et des controverses est encore plus importante.

Introduction

Most science educators would agree that the oil drop experiment[1] was an important contribution to our understanding of modern physics and chemistry. Authors of textbooks (in both physics and chemistry) even consider it as a classic experiment characterized by its simplicity and precise results. The objective of this investigation is to study and contrast the views and understanding with respect to the experiment of physicists and philosophers of

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science with those of authors of physics and chemistry textbooks and laboratory manuals. A review of the relevant literature (Holton, 1978) shows that the acceptance of the quantization of the elementary electrical charge was preceded by a bitter dispute between R.A. Millikan and F. Ehrenhaft that lasted for many years (1910-1925). Both Millikan and Ehrenhaft obtained similar experimental results, and yet Millikan was led to formulate the elementary electrical charge (electron) and Ehrenhaft to fractional charges (sub-electrons). Holton (1978) has presented a detailed reconstruction of the research methodologies of Millikan and Ehrenhaft. Millikan was guided by the presuppositions (Holton) or hard core (Lakatos, 1970) of his theoretical framework. Presuppositions constitute the theoretical rationale (heuristic principles) of a research program that a scientist does not abandon in the face of anomalous data. Ehrenhaft, on the other hand, is said to have followed the traditional scientific method (as presented in most textbooks) by allowing his theory to be dictated by experimental data. Holton's examination of Millikan's handwritten notebooks revealed that in the preparation of the crucial article (Millikan, 1913) data from about 59% of the oil drops were discarded as they did not provide empirical support for Millikan's hypothesis of the elementary electrical charge.

The Oil Drop Experiment as Viewed by Physicists and Philosophers of Science

It is important to observe that after almost 90 years physicists are still trying to analyze and understand the dilemma faced by Millikan with respect to the selection of the appropriate oil drops. According to Goodstein (2001),

> If a drop was too small, it was excessively affected by Brownian motion, or at least by inaccuracy in Stokes's law for the viscous force of air. If it was too large, it would fall too rapidly for accurate measurement. He [Millikan] also preferred to have a drop capture an ion a number of times in the course of observation, so that he could investigate changes as well as total charge, which had to be an integer multiple of the fundamental unit, *e*. (p. 57)

Both Ehrenhaft and Millikan found fractional charges that were $1/3e$, $2/3e$, $1/10e$, and so on. Millikan attributed the fractional charges to experimental errors, whereas Ehrenhaft used these results to question the existence of the elementary electrical charge. This raises a question as to the possibility that Ehrenhaft and Millikan might have been observing quarks. Experimental conditions in their laboratory in that period (1910-1925), however, were such that they could not have observed quarks (compare Dirac, 1977; Fairbank & Franklin, 1982). Nevertheless, the search for the isolation of elementary particles with fractional charge (quarks) has continued (Hellemans, 1999). Quarks were first proposed by Gell-Mann and Zweig in 1963 (the quaint name was taken from a James Joyce novel). Hadrons are considered to be fundamental particles composed of quarks. Although quarks have not been isolated or directly observed, several predictions of the quark model have been confirmed, and their properties explain hadron characteristics. Originally three quark types (flavors) were proposed: up (u), down (d), and strange (s). For example, the proton is composed of three quarks: uud, so that its total charge is $+ (2/3)\,q + (2/3)\,q - (1/3)\,q = q$, as expected. With the spins aligned the proton's intrinsic spin is $+ (1/2) + (1/2) - (1/2) = (1/2)$, also as expected, and the spins of the up quarks are aligned so that they would be in the same state.

Perl and Lee (1997) at the Stanford Linear Accelerator Center have been particularly active in the search for fractional charges (quarks) and have expressed their concern for the selection of the appropriate drops:

> If the drop does not contain a particle with fractional charge, then Q [charge on the drop] will have, within measurement error, one of the values ... 0, ±1q, ±2q, ... [q, being the elementary electrical charge]; depending on whether the drop contains an equal number of protons and electrons, or there is an excess of protons or electrons. If, to our great pleasure, the drop contained say a free quark of charge $1/3q$, then Q would have one of the values $+1/3q$, $+4/3q$, $+7/3q$, ..., or $-2/3q$, $-5/3q$, ... depending on the proton-electron balance in the drop... This was Millikan's method and this is our method eighty years later. Millikan studied a few hundred drops, we have studied almost 10^7 drops. (p. 700)

It is important to note that Millikan excluded drops not only for experimental or calculational difficulties, but also those that did not give the expected value of the elementary electrical charge, based on his presuppositions/theoretical framework. Millikan's procedure seems to have consisted of making a rough calculation for the value of e as soon as the data for the times of descent or ascent of the oil drops started coming in. Holton (1978) reproduced the data in Millikan's handwriting from one of the 140 experiments that are included in the notebooks (Archives, California Institute of Technology, Pasadena). Apparently this was an experiment that did not give the value of e that Millikan was expecting, and he noted frankly, "*Error high* will not use ... can work this up & probably is ok but point is [?] not important" (Holton, p. 207). In a reevaluation of Millikan's notebooks, Franklin (1997) goes beyond this by suggesting that Millikan may have excluded data in order to gain the upper hand in the controversy with Ehrenhaft:

> Despite his claim to the contrary, Millikan did not publish *all* of his oil-drop results. Many drops he excluded because he was not sure that the apparatus was working properly ... and a few seem to have been excluded solely because they increased the experimental uncertainty. One drop, which gave a value of e that was 40% low, was also excluded. For that one, Millikan wrote "won't work" in his notebook. I speculate that this exclusion was simply to avoid giving Felix Ehrenhaft ammunition in the charge-quantization controversy. Later analysis has shown that the data for this drop were indeed unreliable. (p. 26)

Interestingly, Millikan not only excluded some of the drops, but also excluded some of the measurements (time of fall/ascent of the oil drop) on the same drop.

This section shows that physicists and philosophers have been fully aware of the difficulties faced by Millikan, his controversy with Ehrenhaft, and his publishing of a selected group of drops (despite claims to the contrary) that provided support for the postulation of the elementary electrical charge e.

The Oil Drop Experiment as Viewed by Laboratory Instructors

Based on results obtained from a student survey, Kruglak (1972) considered the oil drop experiment to be the most frustrating in the undergraduate laboratory. Nevertheless, Kruglak at the same time recognized its positive aspect: "few experiments epitomize better for students the experimental method and develop an empathy for the challenges and vicissitudes of the physicist" (p. 768). A major concern of laboratory instructors has been the selection of appropriate drops. Heald (1974) mentioned that a major difficulty with the experiment was the possibility of bias in the selection of "suitable" drops, and the philosophical problems of dealing with data that violate one's preconceptions. Kapusta (1975) referred to a dilemma faced by Millikan himself:

> The important variables that are measured are the rise and fall times of the drop moving through a known distance. Some of the drops have much higher velocities than others. Should one choose to observe the fast drops, the slow drops, or those of intermediate velocities? (p. 799)

It is reasonable to suggest that laboratory instructors, based on their empirical experience, understand Millikan's method of excluding drops that were more prone to experimental errors and hence the selection of the drops.

More recently Jones (1995) has provided the following guidelines for drop selection.

> Once a drop has been timed, the results of the calculation are printed to the screen and to a line printer. Immediate charge calculation aids in drop selection ... Rather than averaging the times and then computing the charge, the charge is computed from each pair of timings and the resultant charges are averaged. Timings which are immediately known to be mistakes can be marked on the record and removed from the average by simple key pressing. (p. 970)

Interestingly, Millikan (1910) used average values of times of ascent and descent measured on different drops. Ehrenhaft (1910) critiqued Millikan's methodology by calculating the charge on each drop from each pair of Millikan's observations and showed how Millikan's method of calculation led to contradictory results. In the light of this criticism, Millikan (1913) made appropriate changes to his methodology and the selection of the drops.

A review of the relevant literature indicates that although laboratory instructors do not mention the Millikan-Ehrenhaft controversy, they are generally aware of the difficulties associated with the experiment and especially with respect to the selection of the appropriate drops.

The Oil Drop Experiment as Viewed by Physics Textbooks and Laboratory Manuals

In a recent study, Rodríguez and Niaz (2001) analyzed the presentation of the oil drop experiment (based on a series of criteria) in general physics textbooks and laboratory manuals (all published in the United States). Of the 40 textbooks analyzed, none mentioned the Millikan-Ehrenhaft controversy, and only one, Olenick, Apostol, and Goodstein (1986) mentioned the problematic nature of Millikan's experiment. Textbooks not only ignore the controversy, but give the impression that Millikan performed a simple, beautiful, reliable, and valid experiment (Marion, 1981). According to one textbook, "Indeed, Millikan's experiment was extremely accurate" (Greenwood, 1983, p. 158). Some textbooks explicitly denied that the drops studied by Millikan had fractional charges (Fishbane, Gasiorowicz, & Thornton, 1994; Rohlf, 1994; Sears & Zemansky, 1977; Sears, Zemansky, & Young, 1988). Some textbooks considered Millikan's experiment to be conclusive evidence of the quantization of the electrical charge, which seems to be corroborated by having been awarded the Nobel prize in 1923 (Halliday, Resnick, & Krane, 1994; Jones & Childers, 1990; Sears et al., 1988; Serway, 1997). These results show the degree to which textbooks can at times not only distort historical facts, but also ignore the real spirit of scientific discovery.

Given the complexity of the oil drop experiment, it was expected that the laboratory manuals would perhaps refer to the difficulties associated with the selection of the appropriate drops. It is important to note that the complexity of the experiment did contribute to the controversy. However, laboratory manuals could ignore the controversy and still refer to the complexity of the experiment. Of the 11 laboratory manuals analyzed, none mentioned the Millikan-Ehrenhaft controversy. This is surprising given that that the controversy was based primarily on laboratory techniques used by Millikan and Ehrenhaft. The nearest any manual came to recognizing the difficulties associated with the experiment and hence the controversy was the following: "The principle of the oil drop experiment was quite simple ... but it was no easy task to use it to obtain high precision results, as those students who have tried to use it in undergraduate experiments will confirm" (Petley, 1985, p. 104). Three manuals made a simple mention of the experimental variables that made the experiment difficult, especially with respect to the selection of appropriate drops, of which the following is an example.

> Determine the number of electrons on the drop or the number gained or lost by rough inspection of the data. This will be easy if the drop carried relatively few electrons. Hence, it is advisable to select a drop which moves upward in the electrical field at a slow rate. (Meiners, Eppenstein, & Moore, 1969, p. 381)

One manual simply stated, "Some patience may be required to find a drop with the size and charge that give a velocity convenient for observation" (Ingersoll, Martin, & Rouse, 1953, p. 179). It appears that the selection of the appropriate drop is crucial for students to get valid results, and yet none of the manuals provides a rationale to facilitate understanding.

Review of the relevant literature indicates that general physics textbooks and undergraduate laboratory manuals not only present an image of science devoid of controversy and conflict, but also ignore the complexity of the experiment. It is reasonable to suggest that by including Millikan's methodology with an explicit reference to the controversy with Ehrenhaft, textbooks could help to stimulate an environment that "actuates discovery, inflames controversy, and sustains the students' efforts to understand what he is being taught" (Polanyi, 1964, p. 257).

The Oil Drop Experiment as Viewed by Chemistry Textbooks

Niaz (2000) has analyzed the presentation of the oil drop experiment (based on a series of criteria) in general chemistry textbooks. Of the 31 textbooks (all published in the US) analyzed none mentioned the Millikan-Ehrenhaft controversy or the problematic nature of the experiment. None of the textbooks referred to a crucial aspect of the oil drop experiment, that is, in the face of anomalous data a scientist perseveres with his guiding assumptions, holding its falsification in abeyance (Holton, 1978). It could be argued that textbooks are not supposed to teach scientific research methodology. Although it may seem surprising, this is what most textbooks do by emphasizing the traditional scientific method, that is, scientists do experiments that help them to test hypotheses, laws, and theories. In the case of the oil drop experiment, if the traditional scientific method had been followed, Ehrenhaft's (having impeccable credentials as an experimentalist) results and not Millikan's would have been accepted by the scientific community.

A review of the relevant literature indicates that general chemistry textbooks ignore the role played by controversy, and so Ehrenhaft's contribution has been conveniently forgotten. This leads to the pedagogic implication that Silverman (1992) has expressed cogently: "Science instruction that ignores the element of controversy in science gives an erroneous impression of how scientists actually work—a sterile impression not likely to fire the imagination and foster the curiosity of students" (p. 164).

Conclusion

The evidence presented in this investigation suggests that the oil drop experiment is difficult to perform even today, primarily because it is difficult to select the appropriate drops, and this aspect is recognized by physicists, philosophers of science, and physics laboratory instructors. In contrast, authors of physics textbooks, laboratory manuals, and chemistry textbooks ignore the complexity and the controversial nature of the experiment. Textbooks can highlight the difference between the methodologies of Millikan and Ehrenhaft to illustrate how progress in science is characterized by competition among rival interpretations of data. Holton (1978) has expressed the controversy with respect to the oil drop experiment in cogent terms: "It appeared that the same observational record could be used to demonstrate the plausibility of two diametrically opposite theories, held with great conviction by two well-equipped proponents and their respective collaborators" (pp. 199-200). In science education Matthews (1994) has pointed out that epistemologically, it is not the experiment that is important, but rather the controversy, which constitutes another chapter in the long struggle between theoretical constructs (Millikan's presuppositions) and experimental evidence (Ehrenhaft's data). More recently, Holton (2000, Personal communication, September 25) has been more categorical with respect to the role played by controversies in scientific progress and their importance for the classroom:

> The introduction of the history and methodology of physics into the physics classroom, not least in terms of important controversies—is completely congenial to me ... and Millikan's case is certainly a well documented case that would lend itself to this purpose.

Finally, it is suggested that future research in science education test the hypothesis that the inclusion of the controversy and the complexity of the oil drop experiment in textbooks and manuals could enhance students' conceptual understanding.

Editor's Note

1. Millikan, Robert Andrews 1868-1953. US physicist, awarded a Nobel prize 1923 for his determination of the electric charge on an electron 1913. His experiment, which took five years to perfect, involved observing oil droplets charged by external radiation, falling under gravity between two horizontal metal plates connected to a high-voltage supply. By varying the voltage, he was able to make the electrostatic field between the plates balance the gravitational field so that some droplets became stationary and floated. If a droplet of weight W is held stationary between plates separated by a distance d and carrying a potential

difference V, the charge, e, on the drop is equal to Wd/V. (*Hutchinson Encyclopedia*, 1995, p. 695).

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