The Physics Teacher

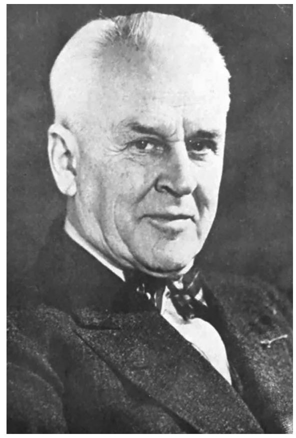
Robert A. Millikan and the Oil Drop Experiment

Cite as: Phys. Teach. **57**, 442 (2019); https://doi.org/10.1119/1.5126819
Published Online: 19 September 2019

Isabel Bishop, Siyu Xian and Steve Feller

Robert A. Millikan and the Oil Drop Experiment

Isabel Bishop, Siyu Xian, and Steve Feller, Coe College, Cedar Rapids, IA



Robert A. Millikan. Courtesy of the Jackson County Historical Society.[1]

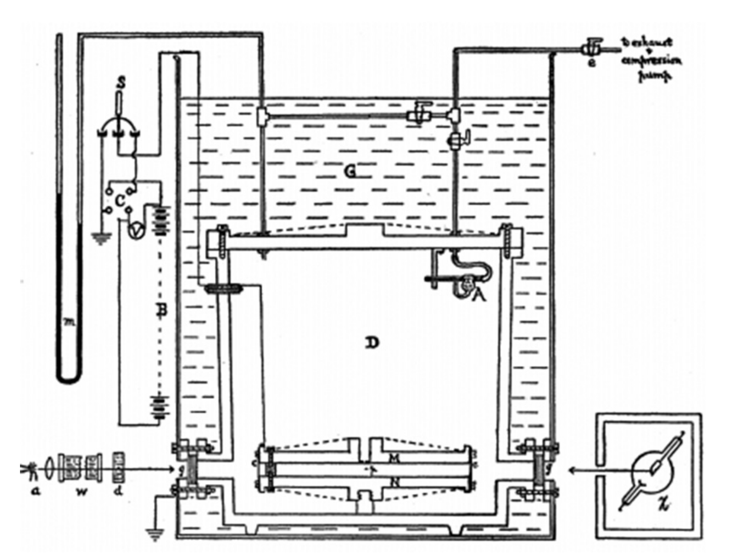
In 2018, we celebrated the sesquicentennial birthday of Robert A. Millikan, a Nobel laureate in physics who worked among the greats such as Niels Bohr and Albert Einstein. His name, however, is perhaps not as widely known. He was born in 1868 in Morrison, IL, and moved with his family to the small town of Maquoketa, IA, at age nine.[2] It was in this tiny Iowan town that Millikan spent his foundational years. He passed the time playing baseball and cooling off in the Maquoketa River. Millikan's interest in experimentation showed early on. Local changes to the rules of baseball sparked controversy over a new type of pitch: the curve ball. Silas Millikan, Robert's father, was a college-educated man and staunchly maintained that the curve ball was simply an optical illusion, but young Millikan knew better. With the help of brothers and cousins, Millikan set up a simple experiment to prove the point. Millikan and his family set up three poles in a line out in the yard and repeatedly pitched curveballs at one another. With careful observation, Silas could see the ball travel straight along the first two poles, then visibly curve and land on the opposite side of the third. This experiment was a small victory for Millikan, and only foreshadowed his later investment in scientific study.

His namesake experiment first took place in 1905, shortly after Einstein published his controversial and groundbreaking papers. What intrigued Millikan the most about these papers was Einstein's theory regarding the photoelectric effect.

The photoelectric effect is a phenomenon that occurs when light is shone onto a material, usually metal. At certain frequencies, the light interacts with the metal and causes electrons to be ejected from the solid. Regardless of the light intensity or the duration for which it is shone, no electrons are emitted below a certain threshold frequency. This particular phenomenon exposed a gap in the current understanding of how light behaves in the early 1900s. Einstein had essentially proposed that the accepted theory of light was wrong, and he had a new theory that could explain the photoelectric effect, as well as other light phenomena.[3]

This wasn't the first time that the properties of light had been debated. Sir Isaac Newton hotly debated with Dutch mathematician and physicist Christiaan Huygens about the composition of light in the late 1600s and early 1700s. Despite Newton's tremendous fame and public support, Huygens was finally seen as the winner of the debate just over 100 years later when scientist Thomas Young came along and created the double-slit experiment, which seemingly proved that light was, in fact, a wave.[4]

After 100 years of relative certainty about the nature of light, Einstein's proposition was met with disbelief, and even outrage. Einstein not only discarded the accepted theory, but also the accepted process of scientific development. At this time, the accepted mode of advancing scientific theories was to build off the foundation of previous theories, subtly tweaking what we knew to get to the true nature of the universe.[2] Einstein's theory discarded the current theory altogether and proposed something new: that light was



KEY

D	Brass, pressure sealed vessel up to 15 atmospheres	**d**	Chloride cell
m	Mercury manometer acting as a standard barometer at atmospheric pressure	**p**	The oil droplet
M,N	Condenser plates	**G**	Temperature bath of gas-engine oil (40 litres)
g	Glass windows (3 in total, only 2 shown in diagram)	$\mathcal{Z}$	Röntgen ray emitter
w	Water cell	**A**	Atomizer
		e	Small tube delivering dry, dust-free air to the atomizer
		c	Ebonite strip encircling the condenser plates

Fig. 1. Diagram of apparatus from Millikan's publication in *The Physical Review* with key.

 DOI: 10.1119/1.5126819

made of small packets of energy, photons, and could act both as a wave and a particle. As Millikan put it: "To throw this all overboard without even attempting to incorporate it into some new form of theory was clearly impossible."[2]

However, there was one other thing Einstein's theory relied on: the electron. This fundamental particle was first theorized by British scientist J. J. Thompson in 1897, and had only just begun to be accepted throughout the scientific community.[5] There were still a number of prominent scientists at this time who plainly did not believe in the existence of the electron.[6] J. J. Thompson's 1897 experiment using cathode rays had identified the existence of such particles, but he was only able to determine the ratio of e/m , and estimates of charge e that were not entirely reliable, as they were made based on assumptions about the average masses of many other particles.[5] Measuring a consistent smallest charge was the key component to proving the existence of the electron as a fundamental particle.[7]

Enter the Millikan Oil Drop Experiment. Hailed as one of the most beautiful scientific experiments of all time,[8] the oil drop experiment is graceful, simple, and ingenious.

The experiment starts with two metal plates, an x-ray source, and an atomizer. The metal plates are suspended parallel to one another, and a small hole is drilled in the top. The plates are then charged, negatively on the bottom plate and positively on the top. An atomizer sprays tiny droplets of liquid over the top of the first plate and some are filtered through the small hole in the middle. As they fall, the droplets pass through and pick up charge due to the x-rays. Millikan's setup[9] is shown in Fig. 1. Millikan first used water, but quickly found that the atomized water droplets would evaporate too quickly to get accurate measurements. He needed a better solution. It was with the help of one of his graduate students, Harvey Fletcher, that Millikan realized oil droplets were the solution. Oil wouldn't evaporate, but would still be liquid enough to be atomized and run through the apparatus.

The forces acting on the droplet can be easily visualized using free-body diagrams (Figs. 2-4), which are also effective tools for understanding some of the mathematics behind Millikan's work. First, Millikan measured the droplets with no charge. The droplets would accelerate until reaching terminal velocity. With a simple measurement and a few known values, Millikan was able to determine the mass of the oil droplet through the following equations. Only two forces act upon the droplet in this scenario: gravitational force,

$$F_g = \frac{4}{3}\pi r^3 g(\rho - \rho_{air}), \tag{1}$$

and the viscous force,

$$F_v = 6\eta r v_t. \tag{2}$$

The variables are as follows: r is the radius of the droplet, g the acceleration due to gravity, ρ is the density of oil, and ρ_{air} is the density of air, η is the viscosity of air, and v_t is the terminal velocity of the droplet. Figure 2 demonstrates the relationship between these forces on a single droplet.

At terminal velocity, with no other forces acting upon the droplet,

$$F_v = F_g. \tag{3}$$

Thus

$$r^2 = \frac{9\eta v_t}{2\pi g(\rho - \rho_{air})}, \tag{4}$$

By measuring v_t, with all other values known, Millikan determined the radius of the droplet and, subsequently, the mass.

Next, Millikan observed the droplets with charge. Adjusting the electric field between the two plates can cause the droplets to rise, fall faster, or even stop moving entirely. This is due to the force of the electric field on the charged droplets,

$$F_E = qE, \tag{5}$$

where q is the charge on the droplet and E is the magnitude of the electric field,

$$E = V/d, \tag{6}$$

where d is the distance between the two plates and V is the voltage across the plates.

By switching the direction of the field, the droplets rise and

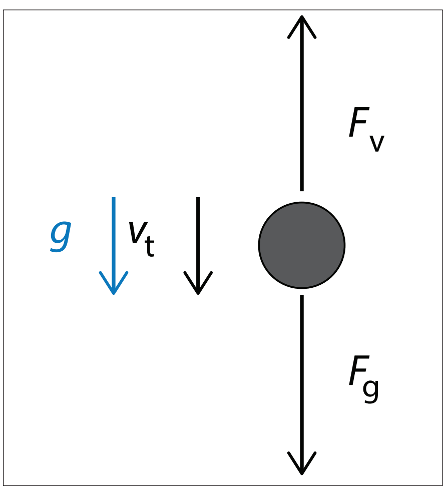


Fig. 2. Free-body diagram of an oil droplet in free fall.

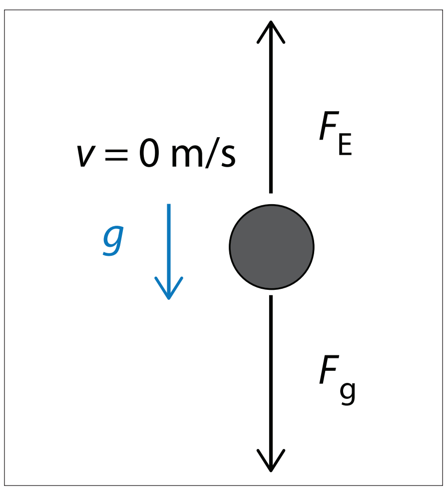


Fig. 3. Free-body diagram where an oil droplet is suspended in the electric field.

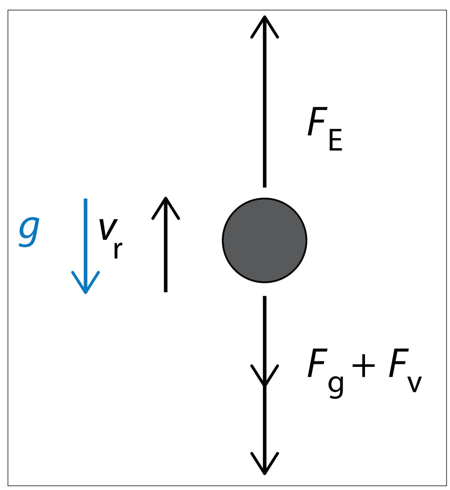


Fig. 4. Free-body diagram of the oil droplet rising in the electric field.

Fig. 5. Photos of Millikan's Nobel Prize (left) and Nobel Scroll (right), courtesy of Caltech archives.[11,12]

fall, and Millikan used this to isolate a single droplet for observation. When the magnitude of the field is adjusted so the droplet no longer falls,

$$F_E = F_g, \tag{7}$$

as illustrated by Fig. 3.
Thus

$$q = \frac{F_g d}{V}. \tag{8}$$

And so, the charge on an individual droplet can be calculated since the force of gravity, distance, and potential difference are known quantities; q can also be determined by observing the droplets when they rise. Millikan determined the velocity by measuring the amount of time each droplet took to rise a certain distance in the viewfinder. Figure 4 illustrates that the velocity is again constant, and the forces acting on the droplet are again in equilibrium. This time, there is also the viscous force to take into consideration, which depends on the velocity at which the droplet rises.

With no other forces acting on the droplet,

$$F_E = F_g + F_v. \tag{9}$$

Using Eqs. (2) and (3), the force of gravity is

$$F_g = 6\pi \eta r v_t, \tag{10}$$

and the viscous force is

$$F_v = 6\pi \eta r v_r, \tag{11}$$

where v_r is the terminal velocity of the droplet as it rises. Thus

$$q = \frac{6\pi \eta r (v_t + v_r) d}{V}. \tag{12}$$

Millikan measured 58 droplets over the course of 60 consecutive days, collecting data with painstaking precision.[9] By comparing the differences of charge between each droplet, Millikan was able to determine that the charge of the droplet was always an integer multiple of a minimum charge: the charge of the electron.

An ingeniously simple experiment and a bit of arithmetic was all Millikan needed to measure the elusive fundamental particle. After viewing Millikan's work with the oil drop experiment, naysayers could no longer doubt the existence of the electron and its status as a particle. Millikan determined the charge of the electron to be $4.77 \pm 0.009 \times 10^{-10}$ electrostatic units (1.592×10^{-19} coulombs). These values were drawn with such precision that the experiment was not improved upon for several years.[2] His calculations are within 1% of today's current accepted value of the electron's charge.

It took Millikan six years to perfect the oil drop experiment.[10] From Millikan's measurement of the fundamental charge, we have also measured the mass of the electron and improved values for Planck's constant. These contributions laid the groundwork for the Bohr model of the atom and were fundamental to proving Einstein's theory on the photoelectric effect. Einstein and Bohr received the Nobel Prize in 1921 and 1922, respectively. Finally, in 1923 Millikan was awarded the Nobel Prize (Fig. 5) in recognition of his work in determining the fundamental charge of electricity, in addition to his work on the photoelectric effect. He went on to do even more groundbreaking work, participating in the founding of the California Institute of Technology, pioneering the field of cosmic radiation and even coining the term "cosmic ray."[13] Some have even argued that Millikan's impact as a teacher was one of his greatest contributions to the world of science. Throughout 2018-19, the small town of Maquoketa, IA, celebrated his amazing accomplishments.

Led by a small group of volunteers working with the Jackson County Historical Society, several educational community events were organized to teach and celebrate not only Millikan's contributions to the field of modern physics, but his other great accomplishments as an administrator, writer, and educator. Some highlights include: several brown bag lunch lectures on Millikan's life, the fundraising and donation of a modern rendition of the oil drop experiment to Robert Millikan's own high school, and a grand finale celebration hosted by Maquoketa's United Church of Christ, where Millikan's father was once a congressional minister. To inquire about future events, or for more information, contact the Jackson County Historical Society or visit online at www.jciahs.com.

References

1. "Robert Millikan," Jackson County Historical Society, http://www.jciahs.com (2018).
2. Robert A. Millikan, *The Autobiography of Robert A. Millikan* (Prentice-Hall Inc., 1950).
3. Albert Einstein, "On a heuristic point of view concerning the production and transformation of light," *Annalen der Physik* **17** (1905).
4. "A Brief History of Light," International Year of Light, UNESCO (2015).
5. Michael Schirber, "Focus: Landmarks—Millikan measures the

electron's charge," *Phys.* **5**, 9 (Jan. 2012).

6. Harvey Fletcher, "My work with Millikan on the oildrop experiment," *Phys. Today* **35** (6), 43 (June 1982).
7. Millikan was not the only scientist around this time attempting to find the charge of the electron. In his 1911 paper, Millikan compared his values for the fundamental charge to those determined by other prominent scientists like Erich Regener and Ernest Rutherford, using other methods. See Robert Millikan, "A new modification of the cloud method of determining the elementary electrical charge and the most probable value of that charge," *Phil. Mag.* **6**, 209 (Jan.-June 1910), and Ernest Rutherford, "The nature of α particles from radioactive substances," *Phil. Mag.* **6**, 281 (Jan.-June 1909).
8. George Johnson, "Here they are, science's 10 Most Beautiful Experiments," *The New York Times* (Sept. 2002).
9. R. A. Millikan, "On the elementary electrical charge and the Avogadro constant," *Phys. Rev.* **2**, 109–143 (Aug. 1913).
10. "New Maquoketa Club Hears Report on Famous Resident," Jackson County Historical Society (1939).
11. "Robert A. Millikan's Nobel Prize," Caltech Image Archive (2018).
12. "Robert A. Millikan's Nobel Scroll (Left Side)," Caltech Image Archive (2018).
13. M. De Maria et al., "The discovery of cosmic rays: Rivalries and controversies between Europe and the United States," *Hist. Stud. Phys. Biol. Sci.* **22**, 165–192 (1991).

Works consulted

– Keith Bonin, "Measuring the electric charge: Millikan's experiment," Wake Forest University (2009).

– Soumitra Das, "Millikan's Oil Drop Experiment," YouTube (Oct. 2013), http://www.youtube.com/watch?v=ijHKu6iXiRk.

Isabel Bishop *graduated Coe College in 2019 with a physics BA and a minor in art. She was a member of the Maquoketa, IA Robert Millikan Sesquicentennial Committee. As a member of SPS, she was an intern at the American Physical Society where she explored art as an engagement tool for physics; for more details see www.physicscentral.com/explore/art. At Coe she did research on quantifying the tendency of melts to form glasses and presented this work at the University of Cambridge (UK).*

Siyu Xian *holds a physics BA from Coe College. He was a member of the Maquoketa, IA Robert Millikan Sesquicentennial Committee. At Coe he did calorimetric research on glasses with Prof. Mario Affatigato. Furthermore, in 2015 he published paper in the* International Journal of Applied Glass Science *on electronically conductive vanadate glasses.*

Professor **Steve Feller** *has taught physics for 40 years at Coe College in Cedar Rapids, IA. He has had the pleasure to work with his Coe College colleagues with more than 350 students in research on glass. For much of his career he has been active within SPS/Sigma Pi Sigma having served two terms on the national council of the joint society and two terms as president of Sigma Pi Sigma. Since 2008 he has been chair or co-chair of the Sigma Pi Sigma Physics Congress, also known as Physcon. He is a fellow of both the American Ceramic Society and the British Society of Glass Technology.*
sfeller@coe.edu