7.6 The Millikan Oil Drop Experiment

Physicists now know that each fundamental particle has a characteristic electric charge that does not change. In fact, the amount of charge is part of the definition of the kind of particle. At the start of the twentieth century, though, physicists still had many questions about the charge of fundamental particles. A big question was, is there a smallest unit of charge that nature will allow, and if so, what is the value of this charge? In this section, you will read about a brilliant experiment aimed at answering this question that resulted in the first measurement of the charge of the electron.

Figure 1 Robert Millikan

fundamental physical constant a measurable natural value that never varies and can be determined by experimentation

elementary charge (*e*) the magnitude of the electric charge carried by a proton, equal to the absolute value of the electric charge of an electron

Millikan's Experiment

Physicist Robert Millikan (**Figure 1**) set out in 1909 to examine the existence of fundamental charge using a series of experiments. Millikan's work demonstrated that the electron is a fundamental particle with a unique charge. This electric charge is considered one of a few **fundamental physical constants**—measurable values that can be determined by demonstration and do not vary—that define natural laws.

Millikan hypothesized that an **elementary charge**, *e*, the smallest unit of charge in nature, did exist, and that the charge of the electron equalled this elementary charge. To measure the charge, Millikan used a fine mist of oil droplets sprayed from an atomizer similar to what you may find on perfume bottles. The droplets picked up electric charges due to friction when sprayed from the atomizer. Millikan further hypothesized that the amount of charge any one drop picked up would be a whole-number multiple of the fundamental charge.

To measure the charge on a drop, Millikan used a device called an electrical microbalance. He allowed the oil drops to fall into a region between two oppositely charged parallel plates. The charges on the plates mean that there is an electric field in the space between the plates, which creates a potential difference between the top plate and the bottom plate. Millikan connected the plates to a series of adjustable batteries so that he could adjust the magnitude of the electric field and, therefore, the electric force on the droplets. By adjusting the electric force to balance the downward gravitational force, Millikan could bring a charged drop of oil to rest in the region between the plates (**Figure 2**).

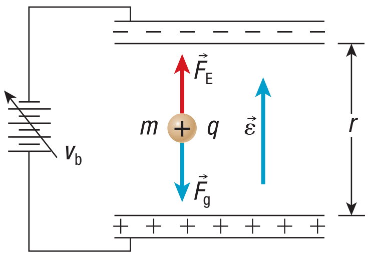

Figure 2 A charged oil drop will be suspended between two charged plates when the electric force on the drop balances the gravitational force.

We can understand how Millikan used the electrical microbalance to determine the charge on an oil drop by comparing the electric and gravitational forces. For a drop of charge q, the electric force from the field $\vec{\varepsilon}$ is

$$\vec{F}_E = q\vec{\varepsilon}$$

If we assume that the charge is positive, then we can charge the plates so that the electric field points upward and gives an upward force to the drop. We can then carefully adjust the potential difference so that the falling drop comes to rest between the plates. When this happens, the electric force balances the gravitational force, and the magnitudes will be equal:

$$F_E = F_g$$

$$q\varepsilon = mg$$

In Section 7.4, you learned that the electric field between two charged plates depends on the potential difference ΔV as

$$\varepsilon = \frac{\Delta V}{\Delta d}$$

where Δd is the plate separation distance. Therefore, we can solve for the electric charge of the drop as

$$q = \frac{mg}{\varepsilon}$$

$$q = \frac{mg\Delta d}{\Delta V_b}$$

where ΔV_b is the special value of potential difference that balances the drop.

If we assume that we can measure the potential difference of our batteries and the plate separation, then we will know the charge of the drop if we can measure the drop's mass.

To measure the mass of a drop, Millikan simply switched off the electric field and observed the final speed of the drop as it fell onto the bottom plate. From the final speed, he could calculate the mass of the drop if he accounted for both the gravitational force and the force due to air friction. With this information, he could determine the charge on the drop.

Millikan repeated his experiment many times, balancing a drop, measuring the voltage, letting the drop fall, and measuring its final speed. When he analyzed the data, he discovered the hypothesized pattern. The values of the charges he measured were whole-number multiples of some smallest value, and no drops had less charge than this value. Millikan concluded that this charge value equalled the elementary charge of the electron. In fact, we now think of this positive number as the charge of the proton, but the absolute value is the same for electrons.

Later experiments by other researchers confirmed Millikan's results and improved the accuracy of his findings. The current accepted value of the elementary charge e to four significant digits is

$$e = 1.602 \times 10^{-19}\ \text{C}$$

With this value, we can connect the charge of an object and the difference in the number of electrons versus protons in the object. If an object has N more protons than electrons, it has a charge q given by

$$q = Ne$$

The following Tutorial examines problems involving the elementary charge.

Investigation 7.6.1

The Millikan Experiment (page 367)
In Investigation 7.6.1, you will recreate Millikan's famous experiment using hands-on and online models.

Tutorial 1 Solving Problems Related to the Elementary Charge

Sample Problem 1: Calculating the Charge on an Object

Calculate the charge on a small sphere with an excess of 3.2×10^{14} electrons.

Given: $N = 3.2 \times 10^{14}$ electrons

Required: q

Analysis: $q = Ne$; note that in this case $e = -1.602 \times 10^{-19}$ C because we are dealing with electrons.

Solution:
$$q = Ne$$
$$= (3.2 \times 10^{14})(-1.602 \times 10^{-19}\ \text{C})$$
$$q = -5.1 \times 10^{-5}\ \text{C}$$

Statement: The charge on the sphere is -5.1×10^{-5} C.

Sample Problem 2: The Elementary Charge and an Oil Drop

In a Millikan-type experiment, two horizontal plates maintained at a potential difference of 360 V are separated by 2.5 cm. A latex sphere with a mass of 1.41×10^{-15} kg hangs between the plates, the upper plate of which is positive.

(a) Is the sphere negatively or positively charged?

(b) Calculate the magnitude of the charge on the latex sphere.

(c) Determine the number of excess or deficit particles on the sphere.

Solution

(a) The electric field lines run from positive charges to negative charges, so the field between the plates points downward. We know that protons will move in the same direction as an electric field and that electrons will move in the opposite direction to the electric field. The electric force on the sphere must point upward to balance the gravitational force, so the sphere's charge must be negative.

(b) **Given:** $r = 2.5\ \text{cm} = 2.5 \times 10^{-2}$ m; $m = 1.41 \times 10^{-15}$ kg; $\Delta V_b = 360$ V

Required: q

Analysis: When the sphere is balanced, the electric force balances the gravitational force. So, we can use the equation for solving for the electric charge of the oil drop used in Millikan's oil drop experiment: $q = \dfrac{mg\Delta d}{\Delta V_b}$.

Note that 1 V = 1 N·m/C and 1 N = 1 kg·m/s^2.

Solution: $q = \frac{mg\Delta d}{\Delta V_b}$

$$= \frac{(1.41 \times 10^{-15}\ \text{kg})\left(9.8\ \frac{\text{m}}{\text{s}^2}\right)(2.5 \times 10^{-2}\ \text{m})}{360\ \text{kg} \cdot \frac{\text{m}}{\text{s}^2} \cdot \frac{\text{m}}{\text{C}}}$$

$q = 9.596 \times 10^{-19}$ C (two extra digits carried)

The actual charge is negative. This value gives the magnitude of the charge.

Statement: The magnitude of the charge on the latex sphere is 9.6×10^{-19} C.

(c) **Given:** $q = 9.596 \times 10^{-19}$ C

Required: N

Analysis: Use the equation that connects the charge of an object with the number of excess protons in the object: $q = Ne$.

Solution: $q = Ne$

$$N = \frac{q}{e}$$

$$= \frac{9.596 \times 10^{-19}\ \text{C}}{1.602 \times 10^{-19}\ \text{C}}$$

$$N = 6$$

Since the sphere has a negative charge, the excess charges are electrons.

Statement: There are 6 excess electrons on the sphere.

Practice

1. Calculate the force of repulsion between two plastic spheres placed 110 cm apart. Each sphere has a deficit of 1.2×10^8 electrons. T/I [ans: 2.7×10^{-12} N]
2. An oil drop with a mass of 2.48×10^{-15} kg is balanced between two parallel, horizontal plates 1.7 cm apart, maintained at a potential difference of 260 V. The upper plate is positive. Calculate the charge on the drop in coulombs and as a multiple of the elementary charge. Determine whether there is an excess or a deficit of electrons. T/I [ans: -1.6×10^{-18} C; $-10e$; 10 excess electrons]
3. Due to the positive charge of Earth's ionosphere, Earth's surface is surrounded by an electric field similar to the field surrounding a negatively charged sphere. The magnitude of this field is approximately 1.0×10^2 N/C. What charge would an oil drop with a mass of 2.4×10^{-15} kg need in order to remain suspended by Earth's electric field? Give your answer in both coulombs and as a multiple of the elementary charge. T/I [ans: -2.4×10^{-16} C; $-1.5 \times 10^3 e$]

Charge of a Proton

The elementary charge is the electric charge of a proton, which is equal in magnitude to the absolute value of the electric charge of the electron. Careful experimentation has consistently shown that the two particles have charges that are equal in magnitude. This result is actually a surprise, because the electron and proton have very little else in common, including their masses and the roles they play in the structure of matter.

Furthermore, physicists think of the electron as a fundamental particle with no inner workings, but they now view the proton as a combination of more fundamental particles called quarks. The proton consists of three quarks, all of which have charges that are either exactly one-third or two-thirds of the elementary charge. Despite having fractional charges, though, no experiment has detected any combination of quarks in nature that have a total charge whose magnitude is less than e. For this reason, physicists still refer to e as the elementary charge.

In fact, every subatomic particle that researchers have so far detected has a charge whose magnitude is equal to a whole-number multiple of e. Researchers also believe that the amount of charge in an isolated system is conserved like energy. Unlike energy, electric charge does not come in different types and cannot change from one form to another. No interaction can destroy or create electric charge, and the total electric charge of the universe remains constant.

7.6 Review

Summary

- Robert Millikan used his oil drop experiments to determine the magnitude of an electron's charge.
- The elementary charge, *e*, is equal to 1.602×10^{-19} C and represents the electric charge carried by a proton. This value is a fundamental physical constant. It is also the absolute value of the electric charge carried by an electron.
- The value of the charge on an electron is -1.602×10^{-19} C.
- Every subatomic particle so far detected has a charge whose magnitude is equal to a whole-number multiple of the elementary charge.

Questions

1. Calculate the number of electrons that must be removed from an uncharged object to give it a positive charge of 3.8×10^{-14} C. K/U
2. Calculate the magnitude of the electric field and the electric potential at a distance of 0.35 m from an object with an excess of 6.1×10^{6} electrons. T/I
3. Consider two parallel plates 2.00 mm apart with a potential difference of 240 V and a positively charged upper plate. A charged oil droplet with a mass of 5.88×10^{-10} kg is suspended between the plates. Determine the sign and magnitude of the electric charge on the oil droplet, and calculate the electron deficiency or excess. T/I
4. A 3.3×10^{-7} kg drop of water is suspended by a uniform 8.4×10^{3} N/C electric field directed upward. K/U T/I
   (a) Is the charge on the drop positive or negative? Explain your answer.
   (b) Calculate the electron excess or deficit on the drop.
5. A 5.2×10^{-15} kg oil drop hangs between two parallel plates (**Figure 3**). K/U T/I

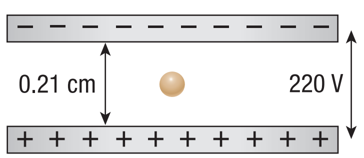

Figure 3

   (a) Calculate the oil drop's charge.
   (b) Calculate the electron excess or deficit on the drop.
6. Sphere A has a mass of 4.2×10^{-2} kg and is tethered to a wall by a thin thread. Sphere A has an excess of 1.2×10^{12} electrons. Sphere B has a deficit of 3.5×10^{12} electrons and is 0.23 m from sphere A (**Figure 4**). T/I

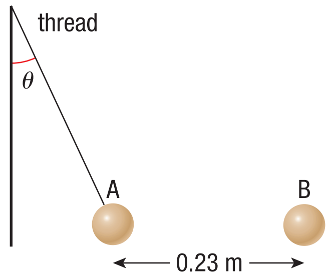

Figure 4

   (a) Determine the angle between the thread and the wall.
   (b) Determine the tension in the thread.
7. Earth has an electric field on its surface with an approximately constant magnitude of 1.0×10^{2} N/C directed toward the centre. K/U T/I A
   (a) Compare Earth's electric field and gravitational field in terms of the fields' direction and shape, and how they change as the altitude increases.
   (b) Calculate the mass of a particle that can be suspended by Earth's electric field if the particle has the elementary charge on it.
8. In a beam of sunlight coming through a window, you can often observe tiny dust particles floating in still air. Explain the cause of this effect and describe a procedure to test your answer. T/I C A