The Millikan Experiment: Determining the Elementary Charge

One of the main characteristics of fundamental particles is their electric charge. In this section, you will learn about a brilliant experiment investigating nature's elementary charge, namely, the charge of the electron.

At the turn of the twentieth century, when our understanding of electric forces was beginning to increase, two fundamental questions arose regarding the nature of electric charge:

1. Does there exist, in nature, a smallest unit of electric charge of which other units are simple multiples?

2. If so, what is this elementary charge, and what is its magnitude, in coulombs?

Lab Exercise 7.5.1, in the Lab Activities section at the end of this chapter, allows you to calculate the elementary charge.

To answer these questions, the American Nobel laureate Robert Andrews Millikan (**Figure 1**) devised and performed a series of creative experiments. He reasoned that the elementary charge would be the charge on an individual electron. He assumed, further, that when tiny oil drops are sprayed in a fine mist from an atomizer, they become electrically charged by friction, some acquiring an excess of a few electrons, others acquiring a deficit. Although there was no way of knowing how many extra electrons there were on any given oil drop or how many were missing, Millikan hypothesized that if he were able to measure the total charge on any oil drop, it would have to be some small integral multiple of the elementary charge.

To measure this charge, Millikan made use of the uniform electric field in the region between two oppositely charged parallel plates. He charged the plates by connecting each to opposite terminals of a large bank of storage batteries whose potential difference could be varied. Millikan was able to use this apparatus, called an *electrical microbalance,* to isolate and suspend charged oil drops, and ultimately to measure the total charge on each.

Once a mist of oil drops is sprayed through a small hole in the upper plate in a Millikan apparatus, it is possible, by carefully adjusting the potential difference between the plates, to "balance" a particular droplet that has the same sign as the charge on the lower plate. When the droplet is balanced, the gravitational force pulling it down equals the electric force pulling it up (**Figure 2**).

For a positively charged drop of mass m and charge q, the electric force acts upward if the lower plate is positively charged:

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

where $\vec{\varepsilon}$ is the electric field between the plates.

When the droplet is in balance,

$$F_E = F_g$$
$$q\varepsilon = mg$$

But in Section 7.4, we learned that the electric field in the region between two parallel plates is constant and has a magnitude given by

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

where ΔV is the electric potential difference between the plates, and r is the separation between the plates.
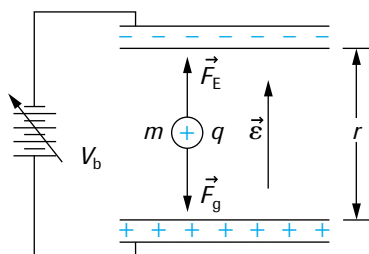
Figure 1
Robert Millikan (1868–1953)

Figure 2
When the total force on the oil droplet is zero, the electric force up is equal in magnitude to the gravitational force down.

Consequently, for an oil drop of mass m and charge q, balanced by a potential difference $\Delta V = \Delta V_b$,

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

$$q = \frac{mgr}{\Delta V_b}$$

where ΔV_b is the balancing value of electric potential difference between the plates.

Thus, it is possible to determine the total charge on an oil drop if its mass is known. The mass of any individual drop may be determined by measuring the terminal speed with which it falls when the electric balancing force is removed (when the batteries are disconnected) and only gravity and friction are acting on it.

By measuring the terminal speed of an oil droplet as it falls under the force of gravity, Millikan was able to calculate its mass. Then, by measuring the value of potential difference between the plates necessary to balance the droplet, he was able to calculate the total electric charge on the droplet.

Millikan repeated the experiment over and over, meticulously balancing a charged oil droplet, measuring its balancing voltage, and then allowing the droplet to fall under gravity and measuring its terminal speed. The list of values he determined for the total electric charge on each of the drops studied contained a significant pattern: all the values were simple multiples of some smallest value. Many of the droplets had this smallest value of charge on them, but none had less. Millikan concluded that this smallest value represented the smallest quantity of electric charge possible, the charge on an electron, or the elementary charge. Accurate measurements of the elementary charge have yielded values close to Millikan's. The currently accepted value for the elementary charge, commonly called e, is, to four significant digits,

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

Knowing the value of the elementary charge enables us to understand the nature of electric charge on a fundamental level. In Section 7.1, we noted that all electric charges in solids are due to an excess or deficit of electrons. If we now know a value for the charge on an individual electron, we can calculate the number of excess or deficit electrons that constitute any observed electric charge.

An object with an excess (or deficit) of N electrons has a charge q that is given by

$$q = Ne$$

▶ **SAMPLE** problem **1**

Calculate the charge on a small sphere with an excess of 5.0×10^{14} electrons.

Solution

$N = 5.0 \times 10^{14}$

$q = ?$

$$\begin{aligned} q &= Ne \\ &= (5.0 \times 10^{14})(1.6 \times 10^{-19} \text{ C}) \\ q &= 8.0 \times 10^{-5} \text{ C} \end{aligned}$$

The charge on the sphere is -8.0×10^{-5} C (negative because of the excess of electrons).

SAMPLE problem 2

In a Millikan-type experiment, two horizontal plates are 2.5 cm apart. A latex sphere, of mass 1.5×10^{-15} kg, remains stationary when the potential difference between the plates is 460 V with the upper plate positive.

(a) Is the sphere charged negatively or positively?

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

(c) How many excess or deficit electrons does the sphere have?

Solution

$r = 2.5$ cm $q = ?$

$m = 1.5 \times 10^{-15}$ kg $N = ?$

$\Delta V = 460$ V

(a) The electric force must be up, to balance the downward force of gravity. Since the upper plate is positive, the latex sphere must be charged negatively to be attracted to the upper plate and repelled by the lower plate. The electric field is downward, giving an upward force on a negative charge.

(b) When the sphere is balanced,

$$F_E = F_g$$
$$q\varepsilon = mg$$

But $\varepsilon = \dfrac{\Delta V}{r}$. Therefore,

$$\frac{q\Delta V}{r} = mg$$
$$q = \frac{mgr}{\Delta V}$$
$$= \frac{(1.5 \times 10^{-15} \text{ kg})(9.8 \text{ m/s}^2)(2.5 \times 10^{-2} \text{ m})}{460 \text{ V}}$$
$$q = 8.0 \times 10^{-19} \text{ C}$$

The magnitude of the charge is 8.0×10^{-19} C.

(c)
$$N = \frac{q}{e}$$
$$= \frac{8.0 \times 10^{-19} \text{ C}}{1.6 \times 10^{-19} \text{ C}}$$
$$N = 5$$

The sphere has 5 excess electrons (since the charge is negative).

▶ *Practice*

Understanding Concepts

Answers

1. 5.0×10^{11} electrons

2. 2.3×10^{-12} N

3. 29 N/C; -14.0 V

1. Calculate the number of electrons that must be removed from a neutral, isolated conducting sphere to give it a positive charge of 8.0×10^{-8} C.

2. Calculate the force of electric repulsion between two small spheres placed 1.0 m apart if each has a deficit of 1.0×10^8 electrons.

3. A small object has an excess of 5.00×10^9 electrons. Calculate the magnitude of the electric field intensity and the electric potential at a distance of 0.500 m from the object.

4. Two large, horizontal metal plates are separated by 0.050 m. A small plastic sphere is suspended halfway between them. The sphere experiences an upward electric force of 4.5×10^{-15} N, just sufficient to balance its weight.
   (a) If the charge on the sphere is 6.4×10^{-19} C, what is the potential difference between the plates?
   (b) Calculate the mass of the sphere.

5. An oil drop of mass 4.95×10^{-15} kg is balanced between two large, horizontal parallel plates 1.0 cm apart, maintained at a potential difference of 510 V. The upper plate is positive. Calculate the charge on the drop, both in coulombs and as a multiple of the elementary charge, and state whether there is an excess or deficit of electrons.

6. Delicate measurements reveal Earth to be surrounded by an electric field similar to the field around a negatively charged sphere. At Earth's surface, this field has a magnitude of approximately 1.0×10^2 N/C. What charge would an oil drop of mass 2.0×10^{-15} kg need in order to remain suspended by Earth's electric field? Give your answer both in coulombs and as a multiple of the elementary charge.

Answers
4. (a) 3.5×10^2 V
   (b) 4.6×10^{-16} kg
5. 9.6×10^{-19} C; $6e$; excess
6. -2.0×10^{-16} C; $-1.2 \times 10^3 e$

Charge of the Proton

The proton and the electron are believed to have charges equal in magnitude but opposite in sign. Modern experiments have revealed that the ratio of the magnitudes of the two charges is essentially 1, since the difference in coulombs does not differ by more than 10^{-20}, an extremely small number to say the least. But this is not obvious for particle physicists. One reason for the curiosity is that, other than the similarity in the charge of the two particles they are quite different. Unlike the electron, the proton does have a complex structure. And like most other heavy subatomic particles, it is comprised of other fundamental entities called quarks. Quarks themselves have charges of $\pm\frac{1}{3}e$ and $\pm\frac{2}{3}e$. However, this does not change our view of what the fundamental charge should be since quarks have not been found to exist in a free state under ordinary conditions. All known fundamental particles do have charges that are integral multiples of e. (Quarks will be studied further in Chapter 13.)

At first, one might think that Millikan just discovered the magnitude of the charge on the electron that happens to be the same as the charge on the proton. However, his discovery has greater implications. In fact, every subatomic particle that has been observed to date (only a small number exist) has a charge that is a whole number multiple of this truly "fundamental" charge. It appears that charge is quantized, meaning it appears in specific amounts, whether positive or negative. This might not seem so surprising when we remember that matter also comes in specific packages (particles), so why not the charge associated with those particles? However, unlike mass, which can be changed into energy (which is really another form of mass) or vice versa in chemical and nuclear reactions, charge is always conserved and cannot be changed into another quantity.

SUMMARY *The Millikan Experiment: Determining the Elementary Charge*

- There exists a smallest unit of electric charge, called the elementary charge, e, of which other units are simple multiples; $e = 1.602 \times 10^{-19}$ C.

Understanding Concepts

1. Sphere A with charge $-3q$ is 1.5 m from another identical sphere B with charge $+5q$. The two spheres are brought into contact and then separated by a distance of 1.5 m; the magnitude of the force between the spheres is 8.1×10^{-2} N.
   (a) Find the number of electrons transferred from one sphere to the other. Explain which way they moved.
   (b) Find the magnitude of the electric field and the electric potential midway between the two spheres.
   (c) Determine the magnitude of the initial electric force between the spheres.

2. A small drop of water, of mass 4.3×10^{-9} kg, is suspended motionless by a uniform electric field of 9.2×10^2 N/C [up].
   (a) Is the charge on the drop positive or negative? Explain.
   (b) Find the number of extra electrons or protons on the drop.

3. An oil drop, of mass 4.7×10^{-15} kg, is suspended between two parallel plates, as in **Figure 3**.
   (a) Calculate the charge on the oil drop.
   (b) Calculate the number of elementary charges required to make up this charge.
   (c) Does the oil drop have a deficit or excess of electrons? Explain your answer.
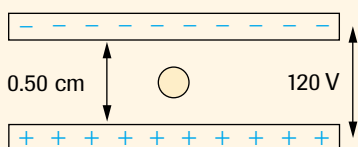

0.50 cm   120 V

Figure 3

4. Two small, equally charged objects have the same mass of 2.0×10^{-5} kg. Find the possible charges on each object if the electric force cancels the gravitational force between each object.

5. Sphere A of mass 5.0×10^{-2} kg has an excess of 1.0×10^{12} electrons. Sphere B has a deficit of 4.5×10^{12} electrons. The two spheres are separated by 0.12 m, as in **Figure 4**.
   (a) Find the angle between the thread and the vertical.
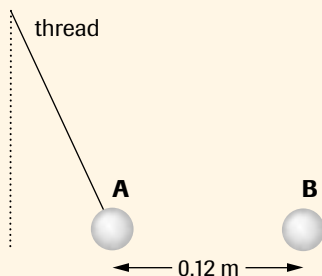   (b) Find the tension in the thread.

thread

A   B

← 0.12 m →

Figure 4

Applying Inquiry Skills

6. When Millikan began his investigation, he used water droplets rather than oil. He later switched to oil droplets because he experienced problems when examining the water. (He found it difficult to suspend the water droplets for any length of time.)
   (a) Why might it be more difficult to keep water droplets suspended than oil droplets? (*Hint:* Consider changes of state.)
   (b) Describe what would be observed when doing an experiment of this nature with water.
   (c) Another scientist might have assumed that other problems were causing the observed results using water. Explain one of these false assumptions.

7. An investigator determines the charges on several different oil droplets with apparatus similar to Millikan's and claims that the data in **Table 1** are accurate to the number of digits shown.

Table 1

Oil Drop	Charge (C)
1	6.40×10^{-19}
2	1.80×10^{-18}
3	1.08×10^{-18}
4	1.44×10^{-18}
5	2.16×10^{-18}

   (a) Without using any prior knowledge about the fundamental charge, describe a procedure that could be used to find the value of a fundamental charge, assuming that all charges in nature are integral multiples of this charge.
   (b) Use the procedure to determine the fundamental charge.
   (c) Can the scientist be certain that this value is the fundamental charge? Explain your answer.
   (d) We know the value of the fundamental charge. Discuss the experimental results and explain any problems.

Making Connections

8. Earth actually has an electric field of 1.0×10^2 N/C at its surface pointing toward the centre.
   (a) A uniformly charged sphere produces an electric field outside the object exactly the same as the field that would be produced if the charge is concentrated at the centre of the field. Assume Earth is uniformly charged. What is the type and magnitude of the charge on Earth?
   (b) Compare Earth's electric field and gravitational field in terms of (i) direction and shape, (ii) effect on objects, and (iii) how it changes as height increases.
   (c) What is the largest mass that can be suspended by the electric field of Earth if the particle has the elementary charge on it?
   (d) Could the electric field of Earth be used to suspend (i) a proton and (ii) an electron? Explain your reasoning.

9. In still air under direct sunlight, tiny dust particles can often be observed to float. Explain how this happens. How could you test your answer?