Section 7.6: The Millikan Oil Drop Experiment

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1. Given: r = 110 cm = 1.10 m; N = 1.2 × 10^8; e = 1.602 × 10^{-19} C; k = 8.99 × 10^9 N·m^2/C^2
Required: F_E
Analysis: Determine the magnitude of the charge on each sphere using $q = Ne$. The charges will be positive because the spheres have a deficit of electrons. Then calculate the force of repulsion,

$$F_E = \frac{kq_1q_2}{r^2}.$$

Solution:

$$\begin{aligned} q &= Ne \\ &= (1.2\times10^8)(1.602\times10^{-19}\text{ C}) \\ q &= 1.92\times10^{-11}\text{ C (one extra digit carried)} \end{aligned}$$

$$\begin{aligned} F_E &= \frac{kq_1q_2}{r^2} \\ &= \frac{\left(8.99\times10^9\ \frac{\text{N}\cdot\cancel{\text{m}^2}}{\cancel{\text{C}^2}}\right)(1.92\times10^{-11}\ \cancel{\text{C}})(1.92\times10^{-11}\ \cancel{\text{C}})}{(1.10\ \cancel{\text{m}})^2} \\ F_E &= 2.7\times10^{-12}\text{ N} \end{aligned}$$

Statement: The force of repulsion between the two plastic spheres is 2.7 × 10^{-12} N.

2. Given: m = 2.48 × 10^{-15} kg; Δd = 1.7 cm = 0.017 m; ΔV_b = 260 V; e = 1.602 × 10^{-19} C; g = 9.8 m/s^2
Required: q; N
Analysis: Determine the charge on the oil drop, $q = \frac{mg\Delta d}{\Delta V_b}$. Then calculate the number of excess electrons, $q = Ne$; $N = \frac{q}{e}$. The top plate is positively charged, so the field between the plates points downward. However, the electric force is balancing the gravitational force, so the particle is moving against the electric field. Therefore the charge will be negative.
Solution: Determine the charge on the oil drop:

$$\begin{aligned} q &= \frac{mg\Delta d}{\Delta V_b} \\ &= \frac{(2.48\times10^{-15}\ \cancel{\text{kg}})\left(9.8\ \frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\right)(0.017\ \cancel{\text{m}})}{260\ \cancel{\text{kg}}\cdot\frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\cdot\frac{\cancel{\text{m}}}{\text{C}}} \\ q &= 1.589\times10^{-18}\text{ C (two extra digits carried)} \\ q &= 1.6\times10^{-18}\text{ C} \end{aligned}$$

The charge on the oil drop is –1.6 × 10^{-18} C.

Determine the excess of electrons:

$$N = \frac{q}{e}$$
$$= \frac{1.589 \times 10^{-18}\ \cancel{\text{C}}}{1.602 \times 10^{-19}\ \cancel{\text{C}}}$$
$$N = 10$$

Statement: The charge on the oil drop is -1.6×10^{-18} C. The oil drop has an excess of 10 electrons, or $-10e$.

3. Given: $\varepsilon = 1.0 \times 10^2$ N/C; $m = 2.4 \times 10^{-15}$ kg; $e = 1.602 \times 10^{-19}$ C; $g = 9.8$ m/s^2

Required: q

Analysis: $q = \frac{mg}{\varepsilon}$. The ionosphere is positively charged, so Earth's electric field points toward Earth's surface. The electric force is balancing the gravitational force, so the particle is moving against the electric field. Therefore the charge will be negative.

Solution: Determine the charge on the object:

$$q = \frac{mg}{\varepsilon}$$
$$= \frac{\left(2.4 \times 10^{-15}\ \cancel{\text{kg}}\right)\left(9.8\ \frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\right)}{\left(1.0 \times 10^2\ \frac{\cancel{\text{N}}}{\text{C}}\right)}$$
$$= 2.352 \times 10^{-16}\ \text{C (two extra digits carried)}$$
$$q = 2.4 \times 10^{-16}\ \text{C}$$

Determine the charge as a multiple of the elementary charge:

$$q = \frac{qe}{e}$$
$$= \frac{\left(2.352 \times 10^{-16}\ \cancel{\text{C}}\right)e}{\left(1.602 \times 10^{-19}\ \cancel{\text{C}}\right)}$$
$$q = 1.5 \times 10^3 e$$

Statement: The oil drop has a charge of -2.4×10^{-16} C, or $-1.5 \times 10^3 e$.

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1. Given: $q = 3.8 \times 10^{-14}$ C; $e = 1.602 \times 10^{-19}$ C

Required: N

Analysis:

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

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

$= \frac{3.8 \times 10^{-14}\ \cancel{C}}{1.602 \times 10^{-19}\ \cancel{C}}$

$N = 2.4 \times 10^{5}$

Statement: To give the object a positive charge of 3.8×10^{-14} C, 2.4×10^{5} C electrons must be removed.

2. Given: $r = 0.35$ m; $N = 6.1 \times 10^{6}$ C; $e = -1.602 \times 10^{-19}$ C; $k = 8.99 \times 10^{9}$ N·m^2/C^2

Required: ε; V

Analysis: Determine the charge on the object using $q = Ne$. Then calculate the magnitude of the electric field using $\varepsilon = \frac{kq}{r^2}$ and the magnitude of the electric potential using $V = -\varepsilon d$.

Solution: Determine the charge on the object:

$q = Ne$

$= (6.1 \times 10^{6})(-1.602 \times 10^{-19}\ \text{C})$

$q = -9.77 \times 10^{-13}$ C (one extra digit carried)

Determine the magnitude of the electric field:

$\varepsilon = \frac{kq}{r^2}$

$= \frac{\left(8.99 \times 10^{9}\ \frac{\text{N} \cdot \cancel{\text{m}^2}}{\text{C}^{\cancel{2}}}\right)\left(-9.77 \times 10^{-13}\ \cancel{\text{C}}\right)}{\left(0.35\ \cancel{\text{m}}\right)^2}$

$= -7.172 \times 10^{-2}$ N/C (two extra digits carried)

$\varepsilon = -7.2 \times 10^{-2}$ N/C

Determine the magnitude of the electric potential:

$V = -\varepsilon d$

$= -(-7.172 \times 10^{-2}\ \text{N/C})(0.35\ \text{m})$

$V = 2.5 \times 10^{-2}$ V

Statement: At a distance of 0.35 m, the magnitude of the electric field is 7.2×10^{-2} N/C and the magnitude of the electric potential is 2.5×10^{-2} V.

3. Given: $\Delta d = 2.00$ mm $= 2.00 \times 10^{-3}$ m; $\Delta V = 240$ V; $m = 5.88 \times 10^{-10}$ kg; $e = 1.602 \times 10^{-19}$ C; $g = 9.8$ m/s^2

Required: q; N

Analysis: Determine the charge on the oil droplet using $q = \frac{mg\,\Delta d}{\Delta V_b}$. Then determine the excess number of electrons using $q = Ne$; $N = \frac{q}{e}$. The top plate is positively charged, so the field between the plates points downward. However, the electric force is balancing the gravitational force, so the particle is moving against the electric field. Therefore the charge will be negative.

Solution: Determine the charge on the oil droplet:

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

$$= \frac{\left(5.88\times10^{-10}\ \cancel{\text{kg}}\right)\left(9.8\ \frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\right)\left(2.00\times10^{-3}\ \cancel{\text{m}}\right)}{240\ \cancel{\text{kg}}\cdot\frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\cdot\frac{\cancel{\text{m}}}{\text{C}}}$$

$= 4.802\times10^{-14}$ C (two extra digits carried)

$q = 4.8\times10^{-14}$ C

Determine the excess of electrons:

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

$$= \frac{4.802\times10^{-14}\ \cancel{\text{C}}}{1.602\times10^{-19}\ \cancel{\text{C}}}$$

$N = 3.0\times10^{5}$

Statement: The charge on the oil droplet is -4.8×10^{-14} C. The oil droplet has an excess of 3.0×10^{5} electrons.

4. (a) The charge on the drop is positive because the force needed to suspend the drop is in the same direction as the field.

(b) Given: $m = 3.3 \times 10^{-7}$ kg; $\varepsilon = 8.4 \times 10^{3}$ N/C; $e = 1.602 \times 10^{-19}$ C; $g = 9.8$ m/s^2

Required: N

Analysis: $q = \frac{mg}{\varepsilon}$; $q = Ne$; $N = \frac{q}{e}$

Solution: Determine the charge on the object:

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

$$= \frac{\left(3.3\times10^{-7}\ \cancel{\text{kg}}\right)\left(9.8\ \frac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\right)}{\left(8.4\times10^{3}\ \frac{\cancel{\text{N}}}{\text{C}}\right)}$$

$q = 3.85\times10^{-10}$ C (one extra digit carried)

Determine the deficit of electrons:

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

$$= \frac{3.85\times10^{-10}\ \cancel{\text{C}}}{1.602\times10^{-19}\ \cancel{\text{C}}}$$

$N = 2.4\times10^{9}$

Statement: The drop of water has a deficit of 2.4×10^{9} electrons.

5. (a) Given: $m = 5.2 \times 10^{-15}$ kg; $\Delta d = 0.21$ cm $= 2.1 \times 10^{-3}$ m; $\Delta V = 220$ V; $g = 9.8$ m/s^2
Required: q

Analysis: $q = \dfrac{mg\,\Delta d}{\Delta V_{\text{b}}}$. The bottom plate is positively charged, so the field between the plates points upward. However, the electric force is balancing the gravitational force, so the particle is moving against the electric field. Therefore the charge will be positive.

Solution:
$$
\begin{aligned}
q &= \frac{mg\,\Delta d}{\Delta V_{\text{b}}} \\
&= \frac{\left(5.2\times10^{-15}\ \cancel{\text{kg}}\right)\left(9.8\ \dfrac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\right)\left(2.1\times10^{-3}\ \cancel{\text{m}}\right)}{220\ \cancel{\text{kg}}\cdot\dfrac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\cdot\dfrac{\cancel{\text{m}}}{\text{C}}} \\
&= 4.864\times10^{-19}\ \text{C (two extra digits carried)} \\
q &= 4.9\times10^{-19}\ \text{C}
\end{aligned}
$$

Statement: The charge on the oil drop is 4.9×10^{-19} C.

(b) Given: $q = 4.864 \times 10^{-19}$ C; $e = 1.602 \times 10^{-19}$ C
Required: N

Analysis: $q = Ne$; $N = \dfrac{q}{e}$

Solution:
$$
\begin{aligned}
N &= \frac{q}{e} \\
&= \frac{4.864\times10^{-19}\ \cancel{\text{C}}}{1.602\times10^{-19}\ \cancel{\text{C}}} \\
N &= 3
\end{aligned}
$$

Statement: The oil drop has a deficit of 3 electrons.

6. Given: $m_{\text{A}} = 4.2 \times 10^{-2}$ kg; $N_{\text{A}} = 1.2 \times 10^{12}$; $N_{\text{B}} = 3.5 \times 10^{12}$; $r = 0.23$ m; $e = 1.602 \times 10^{-19}$ C; $k = 8.99 \times 10^9$ N·m^2/C^2; $g = 9.8$ m/s^2
Required: θ

Analysis: The angle between the wall and the thread is also the angle of the tension force on sphere A. The only other forces on sphere A are due to gravity and electric attraction. Use $q = Ne$ to determine the charges, $F_{\text{E}} = \dfrac{kq_1q_2}{r^2}$ to determine the electric force, and $F_{\text{g}} = mg$ to determine the gravitational force. Use the tangent ratio to determine the angle of the tension force.

Solution: Determine the charge on each sphere:
$$
\begin{aligned}
q_{\text{A}} &= N_{\text{A}}e \\
&= (1.2\times10^{12})(1.602\times10^{-19}\ \text{C}) \\
q_{\text{A}} &= 1.92\times10^{-7}\ \text{C (one extra digit carried)}
\end{aligned}
$$
$$
\begin{aligned}
q_{\text{B}} &= N_{\text{B}}e \\
&= (3.5\times10^{12})(1.602\times10^{-19}\ \text{C}) \\
q_{\text{B}} &= 5.61\times10^{-7}\ \text{C (one extra digit carried)}
\end{aligned}
$$

Determine the electric force:

$$F_E = \frac{kq_1q_2}{r^2}$$

$$= \frac{\left(8.99\times10^9\ \frac{\text{N}\cdot\cancel{\text{m}^2}}{\cancel{\text{C}^2}}\right)\left(1.92\times10^{-7}\ \cancel{\text{C}}\right)\left(5.61\times10^{-7}\ \cancel{\text{C}}\right)}{\left(0.23\ \cancel{\text{m}}\right)^2}$$

$F_E = 1.830\times10^{-2}$ N (two extra digits carried)

Determine the force of gravity:

$$F_g = m_A g$$

$$= \left(4.2\times10^{-2}\ \text{kg}\right)\left(9.8\ \text{m/s}^2\right)$$

$F_g = 4.116\times10^{-1}$ N (two extra digits carried)

Use the tangent ratio to determine the angle of the tension force:

$$\tan\theta = \left(\frac{F_E}{F_g}\right)$$

$$\theta = \tan^{-1}\left(\frac{F_E}{F_g}\right)$$

$$= \tan^{-1}\left(\frac{1.830\times10^{-2}\ \cancel{\text{N}}}{4.116\times10^{-1}\ \cancel{\text{N}}}\right)$$

$= 2.544°$ (two extra digits carried)

$\theta = 2.5°$

Statement: The thread is at an angle of 2.5° from the wall.

(b) Given: $\theta = 2.544°$; $F_g = 4.116 \times 10^{-1}$ N

Required: F_T

Analysis: $\cos\theta = \frac{F_g}{F_T}$

$$F_T = \frac{F_g}{\cos\theta}$$

Solution: $F_T = \frac{F_g}{\cos\theta}$

$$= \frac{4.116\times10^{-1}\ \text{N}}{\cos 2.544°}$$

$F_T = 0.41$ N

Statement: The tension in the thread is 0.41 N [up the thread].

7. (a) Both Earth's electric field and gravitational field point in the same direction and have approximately the same shape. The change in Earth's electric field and gravitational field is the same as the altitude increases, because both follow the inverse-square law.

(b) Given: $\varepsilon = 1.0 \times 10^2$ N/C; $q = 1.602 \times 10^{-19}$ C; $g = 9.8$ m/s^2
Required: m

Analysis: $q = \dfrac{mg}{\varepsilon}$

$$m = \frac{q\varepsilon}{g}$$

Solution: $m = \dfrac{q\varepsilon}{g}$

$$= \frac{\left(1.602 \times 10^{-19}\ \cancel{\text{C}}\right)\left(1.0 \times 10^{2}\ \dfrac{\text{kg}}{\cancel{\text{C}}} \cdot \dfrac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\right)}{\left(9.8\ \dfrac{\cancel{\text{m}}}{\cancel{\text{s}^2}}\right)}$$

$$m = 1.6 \times 10^{-18}\ \text{kg}$$

Statement: The mass of a particle with an elementary charge on it that can be suspended by Earth's electric field is 1.6×10^{-18} kg.

8. The tiny dust particles observed in a beam of sunlight may have become charged by friction and are now suspended by Earth's electric field or some other nearby electric field. I could test the answer by charging another object, such as a balloon or a piece of fabric, and testing whether the particles are attracted or repelled by the object without coming into contact. If so, then the particles have a charge.