29

Magnetic Fields

CHAPTER OUTLINE

* An asterisk indicates a question or problem new to this edition.

ANSWERS TO OBJECTIVE QUESTIONS

OQ29.1 Answers (c) and (e). The magnitude of the magnetic force experienced by a charged particle in a magnetic field is given by $F_B = |q| vB\sin\theta$, where v is the speed of the particle and θ is the angle between the direction of the particle's velocity and the direction of the magnetic field. If either $v = 0$ [choice (e)] or $\sin\theta = 0$ [choice (c)], this force has zero magnitude.

OQ29.2 The ranking is (c) > (a) = (d) > (e) > (b). We consider the quantity $F_B = |qvB \sin\theta|$, in units of e (m/s)(T). (a) $\theta = 90°$ and $F_B =$ $(1 \times 10^6)(10^{-3})(1) = 1\,000$. (b) $\theta = 0°$ and $F_B = (1 \times 10^6)(10^{-3})(0) = 0$. (c) $\theta = 90°$ and $F_B = (2 \times 10^6)(10^{-3})(1) = 2\,000$. For (d) $\theta = 90°$ and $F_B = (1 \times 10^6)(1 \times 10^{-3})(1) = 1\,000$ (e) $\theta = 45°$ and $F_B = (1 \times 10^6)(10^{-3})(0.707) = 707$.

OQ29.3 Answer (c). It is not necessarily zero. If the magnetic field is parallel or antiparallel to the velocity of the charged particle, then the particle will experience no magnetic force.

OQ29.4 Answer (c). Use the right-hand rule for the cross produce to determine the direction of the magnetic force, $\vec{\mathbf{F}}_B = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$. When the proton first enters the field, it experiences a force directed upward, toward the top of the page. This will deflect the proton upward, and as the proton's velocity changes direction, the force changes direction always staying perpendicular to the velocity. The force, being perpendicular to the motion, causes the particle to follow a circular path, with no change in speed, as long as it is in the field. After completing a half circle, the proton will exit the field traveling toward the left.

OQ29.5 Answer (c). $\vec{\mathbf{F}}_B = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$ and $\hat{\mathbf{i}} \times (-\hat{\mathbf{k}}) = \hat{\mathbf{j}}$.

OQ29.6 Answer (c). The magnetic force must balance the weight of the rod. From Equation 29.10,

$$\left|\vec{\mathbf{F}}_B\right| = \left|I\vec{\mathbf{L}} \times \vec{\mathbf{B}}\right| \to F_B = ILB\sin\theta$$

For maximum current, $\theta = 90°$, and we have $ILB\sin 90° = mg$, from which we obtain

$$I = \frac{mg}{LB} = \frac{(0.050\ 0\ \text{kg})(9.80\ \text{m/s}^2)}{(1.00\ \text{m})(0.100\ \text{T})} = 4.90\ \text{A}$$

OQ29.7 (**i**) Answer (b). The magnitude of the magnetic force experienced by the electron is given by $F_B = |q|vB\sin\theta = evB$ because $|q| = |-e| = e$, and the angle between the electron's velocity and the magnetic field is $\theta =$ 90°. We see that force is proportion to speed.

(**ii**) Answer (a). According to Equation 29.3, $r = mv/qB$; thus, electron A has a smaller radius of curvature.

OQ29.8 (**i**) Answer (c).

(**ii**) Answer (c). $F_E = |q|E$ and $F_B = |q|vB\sin\theta$.

(**iii**) Answer (c). $\vec{\mathbf{F}} = q\vec{\mathbf{E}}$ and $\vec{\mathbf{F}}_B = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$.

(**iv**) Answer (a). $\vec{\mathbf{F}} = q\vec{\mathbf{E}}$ and $\vec{\mathbf{F}}_B = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$.

(**v**) Answer (d). But $F_B = |q|vB\sin\theta$ is zero if $\theta = \pm 90°$.

(**vi**) Answer (b). $F_B = |q|vB\sin\theta$ is non-zero unless $\theta = \pm 90°$.

(**vii**) Answer (b). Because $\vec{\mathbf{F}}_B = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$ is perpendicular to the particle's velocity.

(**viii**) Answer (b). $F_B = |q|vB\sin\theta$.

OQ29.9 Answer (c). The magnitude of the magnetic force experienced by the electron is given by $F_B = |q|vB\sin\theta$, where the angle between the electron's velocity and the magnetic field is $\theta = 55.0°$, and the magnitude of the electron's (negative) charge is $|q| = |-e| = e$. The magnitude of the force is

$$\begin{aligned} F_B &= |q|vB\sin\theta \\ &= \left(1.60\times10^{-19}\ \text{C}\right)\left(2.50\times10^{6}\ \text{m/s}\right)\left(3.00\times10^{-5}\ \text{T}\right)\sin 55.0° \\ &= 9.83\times10^{-18}\ \text{N} \end{aligned}$$

Use the right-hand rule for the cross produce to determine the direction of the magnetic force, $\vec{\mathbf{F}}_B = q\vec{\mathbf{v}}\times\vec{\mathbf{B}}$. The force is upward on a positive charge but downward on a negative charge.

OQ29.10 Answers (d) and (e). The force that a magnetic field exerts on a moving charge is always perpendicular to both the direction of the field and the direction of the particle's motion. Since the force is perpendicular to the direction of motion, it does no work on the particle and hence does not alter its speed. Because the speed is unchanged, both the kinetic energy and the magnitude of the linear momentum will be constant.

OQ29.11 Answer (d). The electrons will feel a constant electric force and a magnetic force that will change in direction and in magnitude as their speed changes.

OQ29.12 (a) Yes, as described by $\vec{\mathbf{F}} = q\vec{\mathbf{E}}$. (b) No, because, as described by

$$\vec{\mathbf{F}}_B = q\vec{\mathbf{v}}\times\vec{\mathbf{B}},\ \text{when}\ v = 0,\ F_B = 0.$$

(c) Yes. $\vec{\mathbf{F}} = q\vec{\mathbf{E}}$ does not depend upon velocity. (d) Yes, because the velocity and magnetic field are perpendicular. (e) No, because the wire is uncharged. (f) Yes, because the current and magnetic field are perpendicular. (g) Yes. (h) Yes.

OQ22.13 Ranking $A_A > A_C > A_B$. The torque exerted on a single turn coil carrying current I by a magnetic field B is $\tau = BIA\sin\theta$. The normal perpendicular to the plane of each coil is also perpendicular to the direction of the magnetic field (i.e., $\theta = 90°$). Since B and I are the same for all three coils, the torques exerted on them are proportional to the area A enclosed by each of the coils. Coil A is rectangular with the largest area $A_A = (1\ \text{m})(2\ \text{m}) = 2\ \text{m}^2$. Coil C is triangular with area $A_C = \frac{1}{2}(1\ \text{m})(3\ \text{m}) = 1.5\ \text{m}^2$. By inspection of the figure, coil B encloses the smallest area.

ANSWERS TO CONCEPTUAL QUESTIONS

CQ29.1 No. Changing the velocity of a particle requires an accelerating force. The magnetic force is proportional to the speed of the particle. If the particle is not moving, there can be no magnetic force on it.

CQ29.2 If you can hook a spring balance to the particle and measure the force on it in a known electric field, then $q = F/E$ will tell you its charge. You cannot hook a spring balance to an electron. Measuring the acceleration of small particles by observing their deflection in known electric and magnetic fields can tell you the charge-to-mass ratio, but not separately the charge or mass. Both an acceleration produced by an electric field and an acceleration caused by a magnetic field depend on the properties of the particle only by being proportional to the ratio q/m.

CQ29.3 Yes. If the magnetic field is perpendicular to the plane of the loop, then it exerts no torque on the loop.

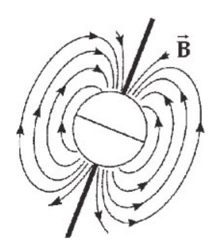
CQ29.4 Send the particle through the uniform field and look at its path. If the path of the particle is parabolic, then the field must be electric, as the electric field exerts a constant force on a charged particle, independent of its velocity. If you shoot a proton through an electric field, it will feel a constant force in the same direction as the electric field—it's similar to throwing a ball through a gravitational field.

If the path of the particle is helical or circular, then the field is magnetic.

If the path of the particle is straight, then observe the speed of the particle. If the particle accelerates, then the field is electric, as a constant force on a proton with or against its motion will make its speed change. If the speed remains constant, then the field is magnetic.

CQ29.5 If the current loop feels a torque, it must be caused by a magnetic field. If the current loop feels no torque, try a different orientation—the torque is zero if the field is along the axis of the loop.

CQ29.6 The Earth's magnetic field exerts force on a charged incoming cosmic ray, tending to make it spiral around a magnetic field line. If the particle energy is low enough, the spiral will be tight enough that the particle will first hit some matter as it follows a field line down into the atmosphere or to the surface at a high geographic latitude.



ANS. FIG. P29.6

CQ29.7 If they are projected in the same direction into the same magnetic field, the charges are of opposite sign.

SOLUTIONS TO END-OF-CHAPTER PROBLEMS

Section 29.1 Analysis Model: Particle in a Field (Magnetic)

***P29.1** Gravitational force:

$$F_g = mg = (9.11\times10^{-31}\text{ kg})(9.80\text{ m/s}^2)$$
$$= \boxed{8.93\times10^{-30}\text{ N down}}$$

Electric force:

$$F_e = qE = (-1.60\times10^{-19}\text{ C})(100\text{ N/C down})$$
$$= \boxed{1.60\times10^{-17}\text{ N up}}$$

Magnetic force:

$$\vec{\mathbf{F}}_B = q\vec{\mathbf{v}}\times\vec{\mathbf{B}} = (-1.60\times10^{-19}\text{ C})\left(6.00\times10^6\text{ m/s }\hat{\mathbf{E}}\right)\times\left(50.0\times10^{-6}\text{ N}\cdot\text{s/C}\cdot\text{m }\hat{\mathbf{N}}\right)$$
$$= -4.80\times10^{-17}\text{ N up} = \boxed{4.80\times10^{-17}\text{ N down}}$$

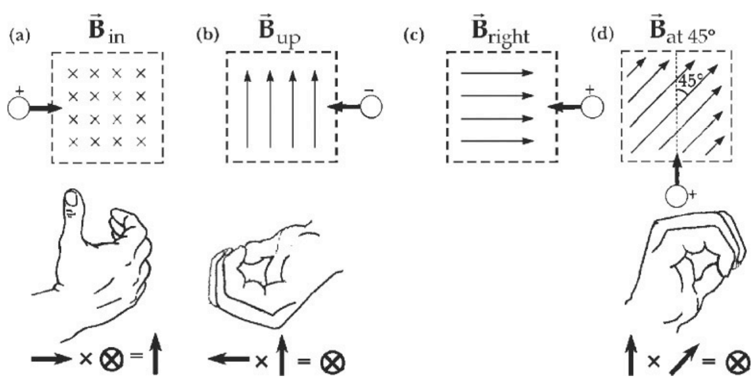
P29.2 See ANS. FIG. P29.2 for right-hand rule diagrams for each of the situations.

(a) up

(b) out of the page, since the charge is negative.

(c) no deflection

(d) into the page



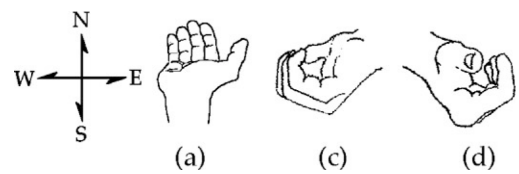
ANS. FIG. P29.2

P29.3 To find the direction of the magnetic field, we use $\vec{\mathbf{F}}_B = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$. Since the particle is positively charged, we can use the right hand rule. In this case, we start with the fingers of the right hand in the direction of $\vec{\mathbf{v}}$ and the thumb pointing in the direction of $\vec{\mathbf{F}}$. As we start closing the hand, our fingers point in the direction of $\vec{\mathbf{B}}$ after they have moved 90°. The results are

(a) into the page (b) toward the right

(c) toward the bottom of the page

P29.4 At the equator, the Earth's magnetic field is horizontally north. Because an electron has negative charge, $\vec{\mathbf{F}} = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$ is opposite in direction to $\vec{\mathbf{v}} \times \vec{\mathbf{B}}$. Figures are drawn looking down.



ANS. FIG. P29.4

(a) Down × North = East, so the force is directed West.

(b) North × North = sin 0° = 0: Zero deflection.

(c) West × North = Down, so the force is directed Up.

(d) Southeast × North = Up, so the force is Down.

P29.5 We use $\vec{\mathbf{F}}_B = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$. Consider a three-dimensional coordinate system with the *xy* plane in the plane of this page, the $+x$ direction toward the right edge of the page and the $+y$ direction toward the top of the page. Then, the z axis is perpendicular to the page with the $+z$ direction being upward, out of the page. The magnetic field is directed in the $+x$ direction, toward the right.

(a) When a proton (positively charged) moves in the $+y$ direction, the right-hand rule gives the direction of the magnetic force as into the page or in the $-z$ direction.

(b) With velocity in the $-y$ direction, the right-hand rule gives the direction of the force on the proton as out of the page, in the $+z$ direction.

(c) When the proton moves in the $+x$ direction, parallel to the magnetic field, the magnitude of the magnetic force it experiences is $F = qvB\sin(0°) = 0$. The magnetic force is zero in this case.

P29.6 The magnitude of the force on a moving charge in a magnetic field is $F_B = qvB\sin\theta$, so

$$\theta = \sin^{-1}\left[\frac{F_B}{qvB}\right]$$

$$\theta = \sin^{-1}\left[\frac{8.20\times10^{-13}\ \text{N}}{\left(1.60\times10^{-19}\ \text{C}\right)\left(4.00\times10^{6}\ \text{m/s}\right)(1.70\ \text{T})}\right]$$

$$= \boxed{48.9° \text{ or } 131°}$$

P29.7 We first find the speed of the electron from the isolated system model:

$$(\Delta K + \Delta U)_i = (\Delta K + \Delta U)_f \rightarrow \frac{1}{2}mv^2 = e\Delta V:$$

$$v = \sqrt{\frac{2e\Delta V}{m}} = \sqrt{\frac{2\left(1.60\times10^{-19}\ \text{C}\right)\left(2\ 400\ \text{J/C}\right)}{9.11\times10^{-31}\ \text{kg}}} = 2.90\times10^{7}\ \text{m/s}$$

(a) $F_{B,\,\text{max}} = qvB = \left(1.60\times10^{-19}\ \text{C}\right)\left(2.90\times10^{7}\ \text{m/s}\right)(1.70\ \text{T})$

$$= \boxed{7.90\times10^{-12}\ \text{N}}$$

(b) $F_{B,\,\text{min}} = \boxed{0}$ occurs when $\vec{\mathbf{v}}$ is either parallel to or anti-parallel to $\vec{\mathbf{B}}$.

P29.8 The force on a charged particle is proportional to the vector product of the velocity and the magnetic field:

$$\vec{\mathbf{F}}_B = q\vec{\mathbf{v}}\times\vec{\mathbf{B}} = (1.60\times10^{-19}\ \text{C})\left[(2\hat{\mathbf{i}} - 4\hat{\mathbf{j}} + \hat{\mathbf{k}})(\text{m/s})\times(\hat{\mathbf{i}} + 2\hat{\mathbf{j}} - \hat{\mathbf{k}})\ \text{T}\right]$$

Since 1 C · m · T/s = 1 N, we can write this in determinant form as:

$$\vec{\mathbf{F}}_B = (1.60\times10^{-19}\ \text{N})\begin{vmatrix} \hat{\mathbf{i}} & \hat{\mathbf{j}} & \hat{\mathbf{k}} \\ 2 & -4 & 1 \\ 1 & 2 & -1 \end{vmatrix}$$

Expanding the determinant as described in Equation 11.8, we have

$$\vec{\mathbf{F}}_{B,x} = (1.60\times10^{-19}\ \text{N})\left[(-4)(-1) - (1)(2)\right]\hat{\mathbf{i}}$$

$$\vec{\mathbf{F}}_{B,y} = (1.60\times10^{-19}\ \text{N})\left[(1)(1) - (2)(-1)\right]\hat{\mathbf{j}}$$

$$\vec{\mathbf{F}}_{B,z} = (1.60\times10^{-19}\ \text{N})\left[(2)(2) - (1)(-4)\right]\hat{\mathbf{k}}$$

Again in unit-vector notation,

$$\vec{\mathbf{F}}_B = (1.60\times10^{-19}\ \text{N})(2\hat{\mathbf{i}} + 3\hat{\mathbf{j}} + 8\hat{\mathbf{k}})$$
$$= \left(3.20\hat{\mathbf{i}} + 4.80\hat{\mathbf{j}} + 12.8\hat{\mathbf{k}}\right)\times10^{-19}\ \text{N}$$

$$\left|\vec{\mathbf{F}}_B\right| = \left(\sqrt{3.20^2 + 4.80^2 + 12.8^2}\right)\times 10^{-19}\ \text{N} = \boxed{13.2\times10^{-19}\ \text{N}}$$

P29.9 (a) The magnetic force is given by

$$F = qvB\sin\theta$$
$$= \left(1.60\times10^{-19}\ \text{C}\right)\left(5.02\times10^{6}\ \text{m/s}\right)(0.180\ \text{T})\sin(60.0°)$$
$$= \boxed{1.25\times10^{-13}\ \text{N}}$$

(b) From Newton's second law,

$$a = \frac{F}{m} = \frac{1.25\times10^{-13}\ \text{N}}{1.67\times10^{-27}\ \text{kg}} = \boxed{7.50\times10^{13}\ \text{m/s}^2}$$

P29.10 (a) The proton experiences maximum force when it moves perpendicular to the magnetic field, and the magnitude of this maximum force is

$$F_{\text{max}} = qvB\sin 90°$$
$$= \left(1.60\times10^{-19}\ \text{C}\right)\left(6.00\times10^{6}\ \text{m/s}\right)(1.50\ \text{T})(1)$$
$$= \boxed{1.44\times10^{-12}\ \text{N}}$$

(b) From Newton's second law,

$$a_{\text{max}} = \frac{F_{\text{max}}}{m_p} = \frac{1.44\times10^{-12}\ \text{N}}{1.67\times10^{-27}\ \text{kg}} = \boxed{8.62\times10^{14}\ \text{m/s}^2}$$

(c) Since the magnitude of the charge of an electron is the same as that of a proton, a force would be exerted on the electron that had the same magnitude as the force on a proton, but in the opposite direction because of its negative charge.

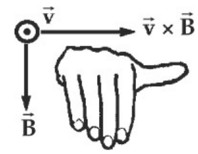
(d) The acceleration of the electron would be much greater than that of the proton because the mass of the electron is much smaller.

P29.11 $F = ma = \left(1.67\times10^{-27}\ \text{kg}\right)\left(2.00\times10^{13}\ \text{m/s}^2\right) = 3.34\times10^{-14}\ \text{N} = qvB\sin 90°$

$$B = \frac{F}{qv} = \frac{3.34\times10^{-14}\ \text{N}}{\left(1.60\times10^{-19}\ \text{C}\right)\left(1.00\times10^{7}\ \text{m/s}\right)} = 2.09\times10^{-2}\ \text{T} = 20.9\times10^{-3}\ \text{T}$$
$$= 20.9\ \text{mT}$$

From ANS. FIG. P29.11, the right-hand rule shows that B must be in the $-y$ direction to yield a force in the $+x$ direction when v is in the z direction. Therefore,

$$\boxed{\vec{\mathbf{B}} = -20.9\,\hat{\mathbf{j}}\text{ mT}}$$



ANS. FIG. P29.11

P29.12 The problem implies that the particle undergoes a deflection perpendicular to its motion as if the force direction remained constant. Treat this as a projectile motion problem where the particle travels in the horizontal direction but is displaced vertically 0.150 m at a constant acceleration.

We find the acceleration from

$$\Delta y = \frac{1}{2}a_y\Delta t^2 \rightarrow a_y = \frac{2\Delta y}{\Delta t^2} = \frac{2(0.150\text{ m})}{(1.00\text{ s})^2} = 0.300\text{ m/s}^2$$

Then, from Newton's second law,

$$F_y = ma_y = qvB$$

$$q = \frac{ma_y}{vB} = \frac{(1.50\times10^{-3}\text{ kg})(0.300\text{ m/s}^2)}{(1.50\times10^{4}\text{ m/s})(0.150\times10^{-3}\text{ T})}$$

$$= 2.00\times10^{-4}\text{ C} = 200.\times10^{-6}\text{ C} = \boxed{200\ \mu\text{C}}$$

Section 29.2 Motion of a Charged Particle in a Uniform Magnetic Field

P29.13 (a) The magnetic force acting on the electron provides the centripetal acceleration, holding the electron in the circular path. Therefore, $F = |q|vB\sin 90° = m_e v^2/r$, or

$$r = \frac{m_e v}{eB} = \frac{(9.11\times10^{-31}\text{ kg})(1.50\times10^{7}\text{ m/s})}{(1.60\times10^{-19}\text{ C})(2.00\times10^{-3}\text{ T})}$$

$$= 0.042\ 7\text{ m} = \boxed{4.27\text{ cm}}$$

(b) The time to complete one revolution around the orbit (i.e., the period) is

$$T = \frac{\text{distance traveled}}{\text{constant speed}} = \frac{2\pi r}{v} = \frac{2\pi(0.042\ 7\text{ m})}{1.50\times10^{7}\text{ m/s}} = \boxed{1.79\times10^{-8}\text{ s}}$$

P29.14 Find the initial horizontal velocity component of an electron in the beam:

$$\frac{1}{2}mv_{xi}^2 = |q|\Delta V$$

$$v_{xi} = v = \sqrt{\frac{2|q|\Delta V}{m}} = \sqrt{\frac{2(1.60\times10^{-19}\text{C})\ (2\,500\text{ V})}{9.11\times10^{-31}\text{ kg}}}$$

$$= 2.96\times10^{7}\text{ m/s}$$

Gravitational deflection: The electron's horizontal component of velocity does not change, so its time of flight to the screen is

$$\Delta t = \frac{\Delta x}{v} = \frac{0.350\text{ m}}{2.96\times10^{7}\text{ m/s}} = 1.18\times10^{-8}\text{ s}$$

Its vertical deflection is downward:

$$y = \frac{1}{2}g(\Delta t)^2 = \frac{1}{2}\left(9.80\text{ m/s}^2\right)\left(1.18\times10^{-8}\text{ s}\right)^2 = 6.84\times10^{-16}\text{ m}$$

which is unobservably small.

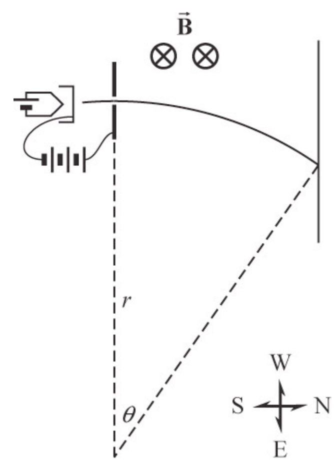
(a) $\boxed{6.84\times10^{-16}\text{ m}}$

(b) $\boxed{\text{down}}$

Magnetic deflection: Use the cross product to find the initial direction of the magnetic force on an electron:

velocity (north) × magnetic field (down) = –west = east.

Because the direction of the magnetic force direction is always perpendicular to the velocity, the electron is deflected so that it curves toward the east in a circular path with radius *r*—see ANS. FIG. 29.14(a):



ANS. FIG. P29.14(a)

$$r = \frac{mv}{|q|B} = \frac{m}{|q|B}\sqrt{\frac{2|q|\Delta V}{m}}$$

$$= \frac{1}{B}\sqrt{\frac{2m\Delta V}{|q|}} = \frac{1}{20.0\times10^{-6}\text{ T}}\sqrt{\frac{2\left(9.11\times10^{-31}\text{ kg}\right)(2\,500\text{ V})}{\left(1.60\times10^{-19}\text{ C}\right)}}$$

$$\simeq 8.44\text{ m}$$

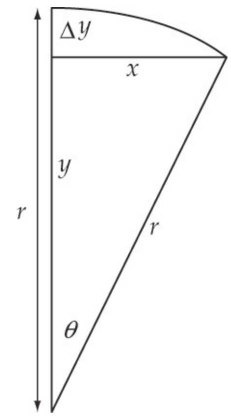
The path of the beam to the screen

subtends at the center of curvature an angle θ, as shown in ANS. FIG. 29.14(b):

$$\theta = \sin^{-1}\left(\frac{x}{r}\right) = \sin^{-1}\left(\frac{0.350\text{ m}}{8.44\text{ m}}\right) = 2.38°$$

The deflection to the east is

$$\begin{aligned}\Delta y &= r(1-\cos\theta)\\ &= (8.44\text{ m})(1-\cos 2.38°)\\ &= 0.007\ 26\text{ m} = 7.26\text{ mm}\end{aligned}$$



ANS. FIG. P29.14(b)

(c) $\boxed{7.26\text{ mm}}$

(d) $\boxed{\text{east}}$

The speed of an electron in the beam remains constant, but its velocity direction changes as it travels along the path, and the force direction changes because it is always perpendicular to the velocity; therefore an electron does not move as a projectile with constant vector acceleration perpendicular to a constant northward component of velocity.

(e) $\boxed{\text{The beam moves on an arc of a circle rather than on a parabola.}}$

However, an electron's northward velocity component stays nearly constant, changing from $v_x = v$ to $v_x = v \cos 2.38°$. The relative change is

$$\frac{\Delta v_x}{v_x} = \frac{v\cos 2.38° - v}{v} = (1-\cos 2.38°) = 0.000\ 863 \simeq 0.000\ 9$$

that is,

(f) Its northward velocity component stays constant within 0.09%. It is a good approximation to think of it as moving on a parabola as it really moves on a circle.

P29.15 An electric field changes the speed of each particle according to $(K + U)_i = (K + U)_f$. Therefore, noting that the particles start from rest, we can write

$$q\Delta V = \frac{1}{2}mv^2$$

After they are fired, the particles have the magnetic field change their direction as described by $\sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$:

$$qvB \sin 90° = \frac{mv^2}{r} \quad \text{thus} \quad r = \frac{mv}{qB} = \frac{m}{qB}\sqrt{\frac{2q\Delta V}{m}} = \frac{1}{B}\sqrt{\frac{2m\Delta V}{q}}$$

For the protons, $r_p = \frac{1}{B}\sqrt{\frac{2m_p\Delta V}{e}}$

(a) For the deuterons,

$$r_d = \frac{1}{B}\sqrt{\frac{2(2m_p)\Delta V}{e}} = \boxed{\sqrt{2}r_p}$$

(b) For the alpha particles,

$$r_\alpha = \frac{1}{B}\sqrt{\frac{2(4m_p)\Delta V}{2e}} = \boxed{\sqrt{2}r_p}$$

P29.16 (a) The magnetic force provides the centripetal force to keep the particle moving on a circle:

$$\sum F = ma \quad \rightarrow \quad qvB\sin 90.0° = \frac{mv^2}{R} \qquad \textbf{[1]}$$

and the kinetic energy of the particle is

$$K = \frac{1}{2}mv^2 \qquad \textbf{[2]}$$

Both equations have the same term mv^2 in common:

From [1], $mv^2 = qvBR$, and from [2], $mv^2 = 2K$.

Setting these equal to each other gives

$$mv^2 = qvBR = 2K \quad \rightarrow \quad \boxed{v = \frac{2K}{qBR}}$$

(b) From [1], we have $m = \frac{qBR}{v}$. Using our result from (a), we get

$$m = \frac{qBR}{v} = qBR\left(\frac{qBR}{2K}\right) = \boxed{\frac{q^2B^2R^2}{2K}}$$

P29.17 For each electron, $|q|vB\sin 90.0° = \frac{mv^2}{r}$ and $v = \frac{eBr}{m}$.

The electrons have no internal structure to absorb energy, so the collision must be perfectly elastic:

$$K = \frac{1}{2}m_e v_{1i}^2 + 0 = \frac{1}{2}m_e v_{1f}^2 + \frac{1}{2}m_e v_{2f}^2$$

$$K = \frac{1}{2}m_e\left(\frac{e^2B^2R_1^2}{m_e^2}\right) + \frac{1}{2}m\left(\frac{e^2B^2R_2^2}{m_e^2}\right) = \frac{e^2B^2}{2m_e}\left(R_1^2 + R_2^2\right)$$

$$K = \frac{\left(1.60\times10^{-19}\ \text{C}\right)^2(0.044\ 0\ \text{T})^2}{2\left(9.11\times10^{-31}\ \text{kg}\right)} \times\left[(0.010\ 0\ \text{m})^2 + (0.024\ 0\ \text{m})^2\right]$$

$$= 1.84\times10^{-14}\ \text{J} = \boxed{115\ \text{keV}}$$

P29.18 For each electron, $|q|vB\sin 90.0° = \frac{mv^2}{r}$ and $v = \frac{eBr}{m}$.

The electrons have no internal structure to absorb energy, so the collision must be perfectly elastic:

$$K = \frac{1}{2}m_e v_{1i}^2 + 0 = \frac{1}{2}m_e v_{1f}^2 + \frac{1}{2}m_e v_{2f}^2$$

$$K = \frac{1}{2}m_e\left(\frac{e^2B^2r_1^2}{m_e{}^2}\right) + \frac{1}{2}m_e\left(\frac{e^2B^2r_2^2}{m_e{}^2}\right) = \boxed{\frac{e^2B^2}{2m_e}\left(r_1^2 + r_2^2\right)}$$

P29.19 (a) We begin with $qvB = \frac{mv^2}{R}$, or $qRB = mv$.

But, $L = mvR = qR^2B$.

Therefore,

$$R = \sqrt{\frac{L}{qB}} = \sqrt{\frac{4.00\times10^{-25}\ \text{J}\cdot\text{s}}{\left(1.60\times10^{-19}\ \text{C}\right)\left(1.00\times10^{-3}\ \text{T}\right)}} = 0.050\ 0\ \text{m}$$

$$= \boxed{5.00\ \text{cm}}$$

(b) Thus,

$$v = \frac{L}{mR} = \frac{4.00\times10^{-25}\ \text{J}\cdot\text{s}}{\left(9.11\times10^{-31}\ \text{kg}\right)(0.050\ 0\ \text{m})} = \boxed{8.78\times10^6\ \text{m/s}}$$

P29.20 (a) We must use a right-handed coordinate system, so treat north as the positive x direction, up as the positive y direction, and east as the positive z direction. The ball's initial velocity is north, and is given by

$$\vec{\mathbf{v}}_i = v_{xi}\hat{\mathbf{i}} + v_{yi}\hat{\mathbf{j}} = v\hat{\mathbf{i}}$$

and the magnetic field is west,

$$\vec{\mathbf{B}} = -B\hat{\mathbf{k}}$$

The trajectory of the ball is that of an object moving under the influence of gravity: projectile motion. The ball's final velocity is

$$\vec{\mathbf{v}}_f = v_{xf}\hat{\mathbf{i}} + v_{yf}\hat{\mathbf{j}} = v\hat{\mathbf{i}} + v_{yf}\hat{\mathbf{j}}$$

where v = 20.0 m/s, because under gravity, the horizontal component of velocity does not change.

We find the final y component of velocity of the ball after it falls a distance h and just before it hits the ground:

$$v_{yf}^2 = v_{yi}^2 + 2a_y\left(y_f - y_i\right)$$

Substituting and solving,

$$v_{yf}^2 = 0 + 2(-g)(-h) \quad \rightarrow \quad v_{yf} = -\sqrt{2gh}$$

The force on the ball just before it hits the ground is

$$\begin{aligned}\vec{\mathbf{F}}_B &= Q\vec{\mathbf{v}} \times \vec{\mathbf{B}} = Q\left(v\hat{\mathbf{i}} + v_{yf}\hat{\mathbf{j}}\right) \times \left(-B\hat{\mathbf{k}}\right) = Q\left(v\hat{\mathbf{i}} - \sqrt{2gh}\hat{\mathbf{j}}\right) \times \left(-B\hat{\mathbf{k}}\right) \\ &= -QBv\left(\hat{\mathbf{i}} \times \hat{\mathbf{k}}\right) + QB\sqrt{2gh}\left(\hat{\mathbf{j}} \times \hat{\mathbf{k}}\right) = -QBv\left(-\hat{\mathbf{j}}\right) + QB\sqrt{2gh}\left(\hat{\mathbf{i}}\right) \\ &= QB\left[\sqrt{2gh}\hat{\mathbf{i}} + v\hat{\mathbf{j}}\right] \\ &= \left(5.00 \times 10^{-6}\ \text{C}\right)(0.010\,0\ \text{T}) \\ &\qquad \times \left[\sqrt{2\left(9.80\ \text{m/s}^2\right)(20.0\ \text{m})}\hat{\mathbf{i}} + (20.0\ \text{m/s})\hat{\mathbf{j}}\right] \\ &= \boxed{\left(0.990 \times 10^{-6}\hat{\mathbf{i}} + 1.00 \times 10^{-6}\hat{\mathbf{j}}\right)\text{N}}\end{aligned}$$

(b) We find the time interval the ball takes to reach the ground under the acceleration due to gravity:

$$\Delta y = h = \frac{1}{2}g\Delta t^2 \rightarrow \Delta t = \sqrt{\frac{2h}{g}} = \sqrt{\frac{2(20.0\ \text{m})}{9.80\ \text{m/s}^2}} = 2.02\ \text{s}$$

We can estimate an extreme upper bound in the change in the ball's horizontal velocity caused by the magnetic force by assuming the average horizontal component of the force to be half its final maximum horizontal value of 0.990×10^{-6} N. For such an average horizontal component over the entire fall, the change in the horizontal velocity would be less than

$$\begin{aligned}\Delta v_x &= a_x\Delta t = \frac{F_x}{m}\Delta t = \frac{0.5\left(0.990 \times 10^{-6}\ \text{N}\right)}{0.0300\ \text{kg}}(2.02\ \text{s}) \\ &= 3.33 \times 10^{-5}\ \text{m/s}\end{aligned}$$

Compare this to the initial value of 20.0 m/s:

$$\frac{20.0\ \text{m/s}}{3.33\times 10^{-5}\ \text{m/s}} \approx 10^{6}$$

Yes. In the vertical direction, the gravitational force on the ball is 0.294 N, five orders of magnitude larger than the magnetic force. In the horizontal direction, the change in the horizontal component of velocity due to the magnetic force is six orders of magnitude smaller than the horizontal velocity component.

P29.21 By conservation of energy for the proton-electric field system in the process that set the proton moving, its kinetic energy is

$$E = \frac{1}{2}mv^2 = e\Delta V$$

so its speed is

$$v = \sqrt{\frac{2e\Delta V}{m}}$$

Now Newton's second law for its circular motion in the magnetic field gives

$$\sum F = ma \text{ which becomes } \frac{mv^2}{R} = evB\sin 90^\circ.$$

so $$B = \frac{mv}{eR} = \frac{m}{eR}\sqrt{\frac{2e\Delta V}{m}} = \frac{1}{R}\sqrt{\frac{2m\Delta V}{e}}.$$

and

$$B = \left(\frac{1}{5.80\times 10^{10}\ \text{m}}\right)\sqrt{\frac{2\left(1.67\times 10^{-27}\ \text{kg}\right)\left(10.0\times 10^{6}\ \text{V}\right)}{1.60\times 10^{-19}\ \text{C}}}$$

$$= \boxed{7.88\times 10^{-12}\ \text{T}}$$

P29.22 (a) The boundary between a region of strong magnetic field and a region of zero field cannot be perfectly sharp, but we ignore the thickness of the transition zone. In the field the electron moves on an arc of a circle:

$$\sum F = ma: \quad |q|vB\sin 90^\circ = \frac{mv^2}{r}$$

$$\frac{v}{r} = \omega = \frac{|q|B}{m} = \frac{\left(1.60\times 10^{-19}\ \text{C}\right)\left(10^{-3}\ \text{N}\cdot\text{s/C}\cdot\text{m}\right)}{9.11\times 10^{-31}\ \text{kg}}$$

$$= 1.76\times 10^{8}\ \text{rad/s}$$

The time for one half revolution is, from $\Delta\theta = \omega\Delta t$,

$$\Delta t = \frac{\Delta\theta}{\omega} = \frac{\pi \text{ rad}}{1.76\times10^{8}\ \text{rad/s}} = \boxed{1.79\times10^{-8}\ \text{s}}$$

(b) The maximum depth of penetration is the radius of the path. The magnetic force cannot alter the kinetic energy of the electron.

Then,

$$v = \omega r = \left(1.76\times10^{8}\ \text{s}^{-1}\right)(0.020\ 0\ \text{m}) = 3.51\times10^{6}\ \text{m/s}$$

and

$$K = \frac{1}{2}mv^2 = \frac{1}{2}\left(9.11\times10^{-31}\ \text{kg}\right)\left(3.51\times10^{6}\ \text{m/s}\right)^2$$

$$= 5.62\times10^{-18}\ \text{J} = \frac{5.62\times10^{-18}\ \text{J}}{1.60\times10^{-19}\ \text{J/eV}} = \boxed{35.1\ \text{eV}}$$

P29.23 To find the ratio of the masses, we first use conservation of energy to find the velocity of each particle after it has been accelerated by the potential drop:

$$\frac{1}{2}mv^2 = q(\Delta V) \quad \text{so} \quad v = \sqrt{\frac{2q(\Delta V)}{m}}$$

The radius of the particles' orbits is given by

$$r = \frac{mv}{qB} = \frac{m\sqrt{2q(\Delta V)/m}}{qB}$$

Squaring gives, for the first particle,

$$r^2 = \frac{m}{q}\cdot\frac{2(\Delta V)}{B^2}$$

and, for the second particle,

$$(r')^2 = \frac{m'}{q'}\cdot\frac{2(\Delta V)}{B^2}$$

Solving for the masses gives

$$m = \frac{qB^2r^2}{2(\Delta V)} \quad \text{and} \quad (m') = \frac{(q')B^2(r')^2}{2(\Delta V)}$$

so

$$\frac{m'}{m} = \frac{q'}{q}\cdot\frac{(r')^2}{r^2} = \left(\frac{2e}{e}\right)\left(\frac{2R}{R}\right)^2 = \boxed{8}$$

Section 29.3 Applications Involving Charged Particles Moving in a Magnetic Field

P29.24 (a) The name "cyclotron frequency" refers to the angular frequency or angular speed

$$\omega = \frac{qB}{m}$$

For protons,

$$\omega = \frac{(1.60 \times 10^{-19}\ \text{C})(0.450\ \text{T})}{1.67 \times 10^{-27}\ \text{kg}} = \boxed{4.31\times 10^{7}\ \text{rad/s}}$$

(b) The path radius is $R = \frac{mv}{Bq}$.

Just before the protons escape, their speed is

$$v = \frac{BqR}{m} = \frac{(0.450\ \text{T})(1.60\times 10^{-19}\ \text{C})(1.20\ \text{m})}{1.67\times 10^{-27}\ \text{kg}} = \boxed{5.17\times 10^{7}\ \text{m/s}}$$

P29.25 In the velocity selector,

$$v = \frac{E}{B} = \frac{2\ 500\ \text{V/m}}{0.035\ 0\ \text{T}} = 7.14\times 10^{4}\ \text{m/s}$$

In the deflection chamber,

$$r = \frac{mv}{qB} = \frac{(2.18\times 10^{-26}\ \text{kg})(7.14\times 10^{4}\ \text{m/s})}{(1.60\times 10^{-19}\ \text{C})(0.035\ 0\ \text{T})} = \boxed{0.278\ \text{m}}$$

P29.26 We first determine the velocity of the particles from

$$K = \frac{1}{2}mv^2 = q(\Delta V)$$

so $$v = \sqrt{\frac{2q(\Delta V)}{m}}$$

Then, from

$$\left|\vec{\mathbf{F}}_B\right| = \left|q\vec{\mathbf{v}}\times\vec{\mathbf{B}}\right| = \frac{mv^2}{r}$$

we solve for the radius:

$$r = \frac{mv}{qB} = \frac{m}{q}\frac{\sqrt{2q(\Delta V)/m}}{B} = \frac{1}{B}\sqrt{\frac{2m(\Delta V)}{q}}$$

(a) Substituting numerical values for uranium-238,

$$r_{238} = \left(\frac{1}{1.20\text{ T}}\right)\sqrt{\frac{2\left[238\left(1.66\times10^{-27}\text{ kg}\right)\right]\left(2\,000\text{ V}\right)}{1.60\times10^{-19}\text{ C}}}$$

$$= 8.28\times10^{-2}\text{ m} = \boxed{8.28\text{ cm}}$$

(b) For uranium-235 ions,

$$r_{235} = \left(\frac{1}{1.20\text{ T}}\right)\sqrt{\frac{2\left[235\left(1.66\times10^{-27}\text{ kg}\right)\right]\left(2\,000\text{ V}\right)}{1.60\times10^{-19}\text{ C}}}$$

$$= 8.23\times10^{-2}\text{ m} = \boxed{8.23\text{ cm}}$$

(c) From $r = \frac{1}{B}\sqrt{\frac{2m(\Delta V)}{q}}$, we see for two different masses m_A and m_B of the same charge q, the ratio of the path radii is $\frac{r_B}{r_A} = \sqrt{\frac{m_B}{m_A}}$.

(d) The ratio of the path radii is independent of ΔV.

(e) The ratio of the path radii is independent of B.

P29.27 Note that the "cyclotron frequency" is an angular speed. The motion of the proton is described by

$\sum F = ma$:

$$|q|vB\sin 90° = \frac{mv^2}{r}$$

$$|q|B = m\frac{v}{r} = m\omega$$

(a) $$\omega = \frac{|q|B}{m} = \frac{\left(1.60\times10^{-19}\text{ C}\right)\left(0.800\text{ N}\cdot\text{s/C}\cdot\text{m}\right)}{\left(1.67\times10^{-27}\text{ kg}\right)}\left(\frac{\text{kg}\cdot\text{m}}{\text{N}\cdot\text{s}^2}\right)$$

$$= \boxed{7.66\times10^{7}\text{ rad/s}}$$

(b) $$v = \omega r = \left(7.66\times10^{7}\text{ rad/s}\right)\left(0.350\text{ m}\right)\left(\frac{1}{1\text{ rad}}\right) = \boxed{2.68\times10^{7}\text{ m/s}}$$

(c) $$K = \frac{1}{2}mv^2 = \frac{1}{2}\left(1.67\times10^{-27}\text{ kg}\right)\left(2.68\times10^{7}\text{ m/s}\right)^2\left(\frac{1\text{ eV}}{1.6\times10^{-19}\text{ J}}\right)$$

$$= \boxed{3.76\times10^{6}\text{ eV}}$$

(d) The kinetic energy of the proton changes by $\Delta K = e\Delta V = e(600\text{ V}) =$ 600 eV twice during each revolution, so the number of revolutions is

$$\frac{3.76\times 10^6\text{ eV}}{2(600\text{ eV})} = \boxed{3.13\times 10^3\text{ revolutions}}$$

(e) From $\theta = \omega\,\Delta t$,

$$\Delta t = \frac{\theta}{\omega} = \frac{3.13\times 10^3\text{ rev}}{7.66\times 10^7\text{ rad/s}}\left(\frac{2\pi\text{ rad}}{1\text{ rev}}\right) = \boxed{2.57\times 10^{-4}\text{ s}}$$

P29.28 (a) The path radius is $r = mv/qB$, which we can write in terms of the (kinetic) energy E of the particle:

$$E = K = \frac{1}{2}mv^2 \qquad \rightarrow \qquad v = \left(\frac{2E}{m}\right)^{1/2}$$

so
$$r = \frac{mv}{qB} = \frac{m}{qB}\left(\frac{2E}{m}\right)^{1/2} = \frac{m}{qB}\left(\frac{2}{m}\right)^{1/2}E^{1/2} = \frac{m^{1/2}2^{1/2}}{qB}E^{1/2}$$

Differentiating, we get,

$$\frac{dr}{dt} = \frac{m^{1/2}2^{1/2}}{qB}\frac{d\left(E^{1/2}\right)}{dt} = \frac{m^{1/2}2^{1/2}}{qB}\left[\frac{1}{2}\left(E^{-1/2}\right)\frac{dE}{dt}\right]$$

$$= \frac{m^{1/2}2^{1/2}}{qB}\frac{1}{2}\left[\left(\frac{1}{2}mv^2\right)^{-1/2}\right]\frac{dE}{dt}$$

$$= \frac{m^{1/2}2^{1/2}}{qB}\frac{1}{2}\left[\frac{2^{1/2}}{m^{1/2}v}\right]\frac{dE}{dt} = \frac{1}{qBv}\frac{dE}{dt}$$

From the relation $r = mv/qB$, we have $v = qBr/m$, which we substitute:

$$\frac{dr}{dt} = \frac{1}{qBv}\frac{dE}{dt} = \frac{1}{qB}\frac{m}{qBr}\frac{dE}{dt} = \frac{m}{q^2B^2}\frac{1}{r}\frac{dE}{dt}$$

From the relation for the particle's average rate of increase in energy (given in the problem), we have

$$\frac{dr}{dt} = \frac{m}{q^2B^2}\frac{1}{r}\left(\frac{q^2B\Delta V}{\pi m}\right) = \frac{1}{r}\frac{\Delta V}{\pi B}$$

(b) The dashed red line in Figure 29.16a spirals around many times, with its turns relatively far apart on the inside and closer together on the outside. This demonstrates the $1/r$ behavior of the rate of change in radius exhibited by the result in part (a).

(c) $$\frac{dr}{dt} = \frac{1}{r}\frac{\Delta V}{\pi B} = \frac{1}{0.350\text{ m}}\frac{600\text{ V}}{\pi\,(0.800\text{ T})} = \boxed{682\text{ m/s}}$$

(d) We use the approximation

$$\Delta r \simeq \frac{dr}{dt}\Delta t = \frac{dr}{dt}T = \left(\frac{1}{r}\frac{\Delta V}{\pi B}\right)\left(\frac{2\pi m}{qB}\right) = \frac{2\Delta V m}{rqB^2}$$

$$= \frac{2(600\text{ V})(1.67\times10^{-27}\text{ kg})}{(0.350\text{ m})(1.60\times10^{-19}\text{ C})(0.800\text{ T})^2}$$

$$= 5.59\times10^{-5}\text{ m} = \boxed{55.9\ \mu\text{m}}$$

P29.29 Fro the electron to travel undeflected, we require $F_B = F_e$, so

$$qvB = qE$$

where $v = \sqrt{\frac{2K}{m}}$ and K is kinetic energy of the electron. Then,

$$E = vB = \sqrt{\frac{2K}{m}}B = \sqrt{\frac{2(750\text{ eV})(1.60\times10^{-19}\text{ J/eV})}{9.11\times10^{-31}\text{ kg}}}(0.015\,0\text{ T})$$

$$= \boxed{244\text{ kV/m}}$$

P29.30 (a) Yes: The constituent of the beam is present in all kinds of atoms.

(b) Yes: Everything in the beam has a single charge-to-mass ratio.

(c) In a charged macroscopic object most of the atoms are uncharged. A molecule never has all of its atoms ionized. Any atom other than hydrogen contains neutrons and so has more mass per charge if it is ionized than hydrogen does. The greatest charge-to-mass ratio Thomson could expect was then for ionized hydrogen,

$$1.6\times10^{-19}\text{ C}/1.67\times10^{-27}\text{ kg}$$

smaller than the value e/m he measured,

$$1.6\times10^{-19}\text{ C}/9.11\times10^{-31}\text{ kg}$$

by 1 836 times. The particles in his beam could not be whole atoms, but rather must be much smaller in mass.

(d) With kinetic energy 100 eV, an electron has speed given by

$$\frac{1}{2}mv^2 = 100\text{ eV}$$

from which we obtain

$$v = \sqrt{\frac{2(100\ \text{eV})(1.6\times10^{-19}\ \text{J/eV})}{9.11\times10^{-31}\ \text{kg}}} = 5.93\times10^{6}\ \text{m/s}$$

The time interval to travel 40.0 cm is

$$\Delta t = \frac{\Delta x}{v} = \frac{0.400\ \text{m}}{5.93\times10^{6}\ \text{m/s}} = 6.75\times10^{-8}\ \text{s}$$

If it is fired horizontally it will fall vertically by

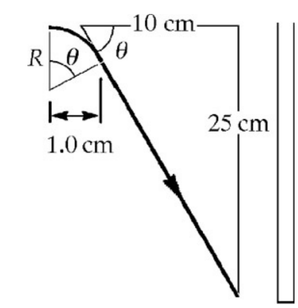
$$y = \frac{1}{2}gt^2 = \frac{1}{2}(9.80\ \text{m/s}^2)(6.75\times10^{-8}\ \text{s})^2 = 2.24\times10^{-14}\ \text{m}$$

an immeasurably small amount. An electron with higher energy falls by a smaller amount.

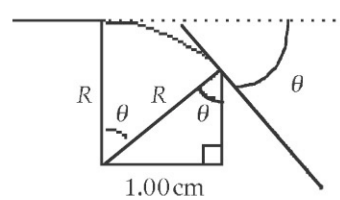
No. The particles move with speed on the order of ten million meters per second, so they fall by an immeasurably small amount over a distance of less than 1 m.

P29.31 From the large triangle in ANS. FIG. P29.31(a):

$$\theta = \tan^{-1}\left(\frac{25.0}{10.0}\right) = 68.2°$$



ANS. FIG. P29.31(a)



ANS. FIG. P29.31(b)

The electron beam, at the point where it enters the magnetic field region, travels to the right, but the beam, at the point it where emerges from the magnetic field region, has been deflected from its original direction by angle θ. Because the radius R is always perpendicular to the path, the radii drawn to these points form the same angle θ with each other. The length of the hypotenuse of the small right triangle appearing in ANS. FIG. P29.31(a) – shown in close-up in ANS. FIG. P29.31(b) – equals the radius R, and the base of the triangle equals the width of the magnetic field region, 1.00 cm. Therefore,

$$R = \frac{1.00\ \text{cm}}{\sin 68.2°} = 1.08\ \text{cm}$$

Ignoring relativistic correction, the kinetic energy of the electrons is

$$\frac{1}{2}mv^2 = q\Delta V$$

so
$$v=\sqrt{\frac{2q\Delta V}{m}}=\sqrt{\frac{2\left(1.60\times10^{-19}\text{ C}\right)\left(50.0\times10^{3}\text{ V}\right)\Delta V}{9.11\times10^{-31}\text{ kg}}}$$
$$=1.33\times10^{8}\text{ m/s}$$

From Newton's second law, $\frac{mv^2}{R}=qvB$, we find the magnetic field:

$$B=\frac{mv}{|q|R}=\frac{\left(9.11\times10^{-31}\text{ kg}\right)\left(1.33\times10^{8}\text{ m/s}\right)}{\left(1.60\times10^{-19}\text{ C}\right)\left(1.08\times10^{-2}\text{ m}\right)}=\boxed{70.0\text{ mT}}$$

Section 29.4 Magnetic Force on a Current-Carrying Conductor

P29.32 (a) The magnitude of the magnetic force is given by

$$F=ILB\sin\theta=(3.00\text{ A})(0.140\text{ m})(0.280\text{ T})\sin 90°=\boxed{0.118\text{ N}}$$

(b) Neither the direction of the magnetic field nor that of the current is given. Both must be known in order to determine the direction of the magnetic force. In this problem, you can only say that the force is perpendicular to both the wire and the field.

P29.33 (a) From $F=BIL\sin\theta$, the magnetic field is

$$B=\frac{F/L}{I\sin\theta}=\frac{0.120\text{ N/m}}{(15.0\text{ A})\sin 90°}=\boxed{8.00\times10^{-3}\text{ T}}$$

(b) The magnetic field must be in the $+z$ direction to produce a force in the $-y$ direction when the current is in the $+x$ direction.

P29.34 (a) $F_B=ILB\sin\theta=(5.00\text{ A})(2.80\text{ m})(0.390\text{ T})\sin 60.0°=\boxed{4.73\text{ N}}$

(b) $F_B=(5.00\text{ A})(2.80\text{ m})(0.390\text{ T})\sin 90.0°=\boxed{5.46\text{ N}}$

(c) $F_B=(5.00\text{ A})(2.80\text{ m})(0.390\text{ T})\sin 120°=\boxed{4.73\text{ N}}$

P22.35 The vector magnetic force on the wire is

$$\vec{\mathbf{F}}_B=I\vec{\ell}\times\vec{\mathbf{B}}=(2.40\text{ A})(0.750\text{ m})\hat{\mathbf{i}}\times(1.60\text{ T})\hat{\mathbf{k}}=\boxed{\left(-2.88\hat{\mathbf{j}}\right)\text{ N}}$$

P22.36 At all points on the wire, the magnetic force is upward and the gravitational force is downward. For the entire length L of the wire, apply the particle in equilibrium model, assuming that the wire is levitated as claimed, and then solve for the required magnetic field B:

$$\sum F = F_B - F_g = 0 \quad \rightarrow \quad mg = ILB \quad \rightarrow \quad B = \frac{mg}{IL}$$

Express the mass of the wire in terms of the density of copper and its volume and the current in terms of the power delivered to the wire of resistance R:

$$B = \frac{(\rho_{\text{Cu}}V)g}{\left(\sqrt{P/R}\right)L} = \frac{\rho_{\text{Cu}}Vg}{L}\sqrt{\frac{R}{P}}$$

Substitute for the volume of the wire and its resistance in terms of its length L and area A:

$$B = \frac{\rho_{\text{Cu}}(AL)g}{L}\sqrt{\frac{\rho L/A}{P}} = \rho_{\text{Cu}}g\sqrt{\frac{\rho LA}{P}}$$

where ρ is the resistivity of copper. Express the length L of the wire in terms of the radius of the Earth and the area A of the wire in terms of its radius:

$$B = \rho_{\text{Cu}}g\sqrt{\frac{\rho(2\pi R_E)(\pi r^2)}{P}} = \pi\rho_{\text{Cu}}gr\sqrt{\frac{2\rho R_E}{P}}$$

Substitute numerical values:

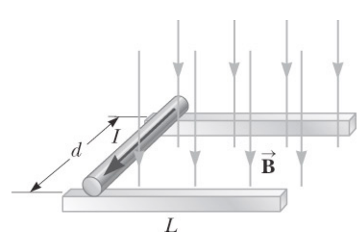
$$B = \pi\left(8.92\times 10^3 \text{ kg/m}^3\right)\left(9.80 \text{ m/s}^2\right)\left(1.00\times 10^{-3} \text{ m}\right) \times\sqrt{\frac{2\left(1.7\times 10^{-8}\ \Omega\cdot\text{m}\right)\left(6.37\times 10^6 \text{ m}\right)}{100\times 10^6 \text{ W}}}$$

$$= 1.28\times 10^{-2} \text{ T}$$

This field magnitude is far larger than that of the Earth, which is about 30 μT at the equator. Therefore, this wire could not be levitated in the Earth's magnetic field as described.

P29.37 Refer to ANS. FIG. P29.37. The rod feels force

$$\vec{\mathbf{F}}_B = I\left(\vec{\mathbf{L}}\times\vec{\mathbf{B}}\right) = Id\left(\hat{\mathbf{k}}\right)\times B\left(-\hat{\mathbf{j}}\right) = IdB\left(\hat{\mathbf{i}}\right)$$



ANS. FIG. P29.37

From the work-energy theorem, we have

$$\left(K_{\text{trans}} + K_{\text{rot}}\right)_i + \Delta E = \left(K_{\text{trans}} + K_{\text{rot}}\right)_f$$

$$0+0+F_B L\cos\theta = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$$

or $$IdBL\cos 0° = \frac{1}{2}mv^2 + \frac{1}{2}\left(\frac{1}{2}mR^2\right)\left(\frac{v}{R}\right)^2$$

and $$IdBL = \frac{3}{4}mv^2$$

$$v = \sqrt{\frac{4IdBL}{3m}} = \sqrt{\frac{4(48.0\text{ A})(0.120\text{ m})(0.240\text{ T})(0.450\text{ m})}{3(0.720\text{ kg})}}$$

$$= \boxed{1.07\text{ m/s}}$$

P29.38 Refer to ANS. FIG. P29.37 above. The rod feels force

$$\vec{\mathbf{F}}_B = I\left(\vec{\mathbf{d}}\times\vec{\mathbf{B}}\right) = Id\left(\hat{\mathbf{k}}\right)\times B\left(-\hat{\mathbf{j}}\right) = IdB\left(\hat{\mathbf{i}}\right)$$

From the work-energy theorem, we have

$$\left(K_{\text{trans}} + K_{\text{rot}}\right)_i + \Delta E = \left(K_{\text{trans}} + K_{\text{rot}}\right)_f$$

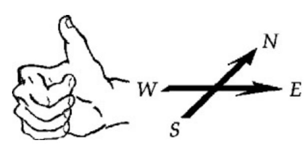
$$0+0+F_B L\cos\theta = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$$

$$(IBL)d\cos 0° = \frac{1}{2}mv^2 + \frac{1}{2}\left(\frac{1}{2}mR^2\right)\left(\frac{v}{R}\right)^2$$

Solving for the velocity gives

$$v = \boxed{\sqrt{\frac{4IdBL}{3m}}}$$

P29.39 (a) The magnetic force must be upward to lift the wire. For current in the south direction, the magnetic field must be $\boxed{\text{east}}$ to produce an upward force, as shown by the right-hand rule in the figure.



ANS. FIG. P29.39

(b) $F_B = ILB\sin\theta$ with $F_B = F_g = mg$

$$mg = ILB\sin\theta \quad \text{so} \quad \frac{m}{L}g = IB\sin\theta \quad \rightarrow \quad B = \frac{m}{L}\frac{g}{I\sin\theta}$$

$$B = \frac{m}{L}\frac{g}{I\sin\theta} = \left(\frac{0.500\times10^{-3}\text{ kg}}{1.00\times10^{-2}\text{ m}}\right)\left(\frac{9.80\text{ m/s}^2}{(2.00\text{ A})\sin 90.0°}\right) = \boxed{0.245\text{ T}}$$

P29.40 (a) The magnetic force and the gravitational force both act on the wire.

(b) When the magnetic force is upward and balances the downward gravitational force, the net force on the wire is zero, and the wire can move upward at constant velocity.

(c) The minimum magnetic filed would be perpendicular to the current in the wire so that the magnetic force is a maximum. For the magnetic force to be directed upward when the current is toward the left, $\vec{\mathbf{B}}$ must be directed out of the page. Then,

$$F_B = ILB_{\text{min}} \sin 90° = mg$$

from which we obtain

$$B_{\text{min}} = \frac{mg}{IL} = \frac{(0.015\ 0\ \text{kg})(9.80\ \text{m/s}^2)}{(5.00\ \text{A})(0.150\ \text{m})}$$
$$= \boxed{0.196\ \text{T, out of the page}}$$

(d) If the field exceeds 0.200 T, the upward magnetic force exceeds the downward gravitational force, so the wire accelerates upward.

P29.41 (a) The magnitude of the force is

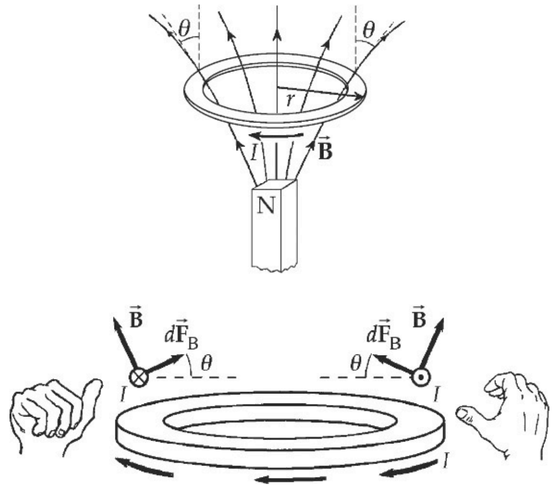
$$F = ILB \sin\theta$$
$$= (2.20 \times 10^3\ \text{A})(58.0\ \text{m})(5.00 \times 10^{-5}\ \text{N})\sin 65.0°$$
$$= \boxed{5.78\ \text{N}}$$

(b) By the right-hand rule, the direction of the magnetic force is into the page.

P29.42 (a) Refer to ANS. FIG. P29.42. The magnetic field is perpendicular to all line elements $d\vec{\mathbf{s}}$ on the ring, so the magnetic force $d\vec{\mathbf{F}} = Id\vec{\mathbf{s}} \times \vec{\mathbf{B}}$ on each element has magnitude $I\left|d\vec{\mathbf{s}} \times \vec{\mathbf{B}}\right| = IdsB$ and is radially inward and upward, at angle θ above the radial line. The radially inward components $IdsB \cos\theta$ tend to squeeze the ring but all cancel out because forces on opposite sides of the ring cancel in pairs. The upward components $IdsB \sin\theta$ all add to $I(2\pi r)B\sin\theta$.

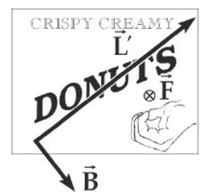
(a) magnitude: $\boxed{2\pi rIB \sin\theta}$

(b) direction: up, away from magnet



ANS. FIG. P29.42

P29.43 Take the x axis east, the y axis up, and the z axis south. The field is



ANS. FIG. P29.43

$$\vec{\mathbf{B}} = (52.0\ \mu\text{T})\cos 60.0°\left(-\hat{\mathbf{k}}\right) + (52.0\ \mu\text{T})\sin 60.0°\left(-\hat{\mathbf{j}}\right)$$

The current then has equivalent length:

$$\vec{\mathbf{L}}' = 1.40\ \text{m}\left(-\hat{\mathbf{k}}\right) + 0.850\ \text{m}\left(\hat{\mathbf{j}}\right)$$

The magnetic force is then

$$\vec{\mathbf{F}}_B = I\vec{\mathbf{L}}' \times \vec{\mathbf{B}} = (0.035\,0\ \text{A})\left(0.850\hat{\mathbf{j}} - 1.40\hat{\mathbf{k}}\right)\ \text{m} \times \left(-45.0\hat{\mathbf{j}} - 26.0\hat{\mathbf{k}}\right)10^{-6}\ \text{T}$$

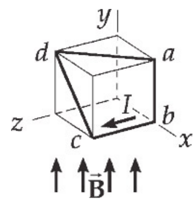
$$\vec{\mathbf{F}}_B = 3.50\times10^{-8}\ \text{N}\left(-22.1\hat{\mathbf{i}} - 63.0\hat{\mathbf{i}}\right) = 2.98\times10^{-6}\ \text{N}\left(-\hat{\mathbf{i}}\right)$$

$$= \boxed{2.98\ \mu\text{N west}}$$

P29.44 For each segment, $I = 5.00$ A and $\vec{\mathbf{B}} = 0.020\,0\hat{\mathbf{j}}$ T.

	Segment	$\vec{\ell}$	$\vec{\mathbf{F}}_B = I\left(\vec{\ell} \times \vec{\mathbf{B}}\right)$
(a)	*ab*	$-0.400\ \text{m}\ \hat{\mathbf{j}}$	$\boxed{0}$
(b)	*bc*	$0.400\ \text{m}\ \hat{\mathbf{k}}$	$\boxed{-40.0\hat{\mathbf{i}}\ \text{mN}}$
(c)	*cd*	$-0.400\ \text{m}\ \hat{\mathbf{i}} + 0.400\ \text{m}\ \hat{\mathbf{j}}$	$\boxed{-40.0\hat{\mathbf{k}}\ \text{mN}}$
(d)	*da*	$0.400\ \text{m}\ \hat{\mathbf{i}} - 0.400\ \text{m}\ \hat{\mathbf{k}}$	$\boxed{\left(40.0\hat{\mathbf{i}} + 40.0\hat{\mathbf{k}}\right)\ \text{mN}}$

(e) The forces on the four segments must add to zero, so the force on the fourth segment must be the negative of the resultant of the forces on the other three.



ANS. FIG. P29.44

Section 29.5 Torque on a Current Loop in a Uniform Magnetic Field

***P29.45** (a) From Equation 29.17, we have

$$\vec{\boldsymbol{\tau}} = \vec{\boldsymbol{\mu}} \times \vec{\mathbf{B}}$$

so $\tau = (0.10\ \text{A}\cdot\text{m}^2)(0.080\ \text{T})\sin 30° = \boxed{4.0\ \text{mN}\cdot\text{m}}$.

(b) The potential energy of a system of a magnetic moment in a magnetic field is given by Equation 29.18:

$$U = -\vec{\boldsymbol{\mu}}\cdot\vec{\mathbf{B}} = \mu B\cos\phi = (0.10\ \text{A}\cdot\text{m}^2)(0.080\ \text{T})\cos 30°$$

$$= \boxed{-6.9\ \text{mJ}}$$

***P29.46** The torque on a current loop in a magnetic field is $\tau = BIAN\sin\theta$, and maximum torque occurs when the field is directed parallel to the plane of the loop ($\theta = 90°$). Thus,

$$\tau_{\text{max}} = (0.500\ \text{T})(25.0\times 10^{-3}\ \text{A})$$

$$\times\left[\pi(5.00\times 10^{-2}\ \text{m})^2\right](50.0)\sin 90.0°$$

$$= \boxed{4.91\times 10^{-3}\ \text{N}\cdot\text{m}}$$

P29.47 (a) The field exerts torque on the needle tending to align it with the field, so the minimum energy orientation of the needle is:

pointing north at 48.0° below the horizontal

where its energy is

$$U_{\text{min}} = -\mu B\cos 0° = -(9.70\times 10^{-3}\ \text{A}\cdot\text{m}^2)(55.0\times 10^{-6}\ \text{T})$$

$$= -5.34\times 10^{-7}\ \text{J}$$

(b) It has maximum energy when pointing in the opposite direction, $\boxed{\text{south at 48.0° above the horizontal}}$

where its energy is

$$U_{max} = -\mu B\cos 180° = +\left(9.70\times10^{-3}\ \text{A}\cdot\text{m}^2\right)\left(55.0\times10^{-6}\ \text{T}\right)$$
$$= +5.34\times10^{-7}\ \text{J}$$

(c) From $U_{min} + W = U_{max}$, we have

$$W = U_{max} - U_{min} = +5.34\times10^{-7}\ \text{J} - \left(-5.34\times10^{-7}\ \text{J}\right)$$
$$= \boxed{1.07\ \mu\text{J}}$$

P29.48 (a) From the circumference of the loop, $2\pi r = 2.00$ m, we find its radius to be $r = 0.318$ m. The magnitude of the magnetic moment is then

$$\mu = IA = \left(17.0\times10^{-3}\ \text{A}\right)\left[\pi(0.318)^2\ \text{m}^2\right] = \boxed{5.41\ \text{mA}\cdot\text{m}^2}$$

(b) The torque on the loop is given by Equation 29.17, $\vec{\boldsymbol{\tau}} = \vec{\boldsymbol{\mu}}\times\vec{\mathbf{B}}$, and its magnitude is

$$\tau = \left(5.41\times10^{-3}\ \text{A}\cdot\text{m}^2\right)(0.800\ \text{T}) = \boxed{4.33\ \text{mN}\cdot\text{m}}$$

***P29.49** The area of the elliptical loop is given by $A = \pi ab$, where $a = 0.200$ m and $b = 0.150$ m. Since the field is parallel to the plane of the loop, $\theta = 90°$ and the magnitude of the torque is

$$\tau = NBIA\sin\theta$$
$$= 8\left(2.00\times10^{-4}\ \text{T}\right)(6.00\ \text{A})\left[\pi(0.200\ \text{m})(0.150\ \text{m})\right]\sin 90.0°$$
$$= \boxed{9.05\times10^{-4}\ \text{N}\cdot\text{m}}$$

The torque is directed to make the left-hand side of the loop move toward you and the right-hand side move away.

P29.50 (a) $|\vec{\boldsymbol{\tau}}| = \left|\vec{\boldsymbol{\mu}}\times\vec{\mathbf{B}}\right| = NIAB\sin\theta$

$$\tau_{max} = 80\left(10.0\times10^{-3}\ \text{A}\right)(0.025\ 0\ \text{m})(0.040\ 0\ \text{m})(0.800\ \text{T})\sin 90.0°$$
$$= \boxed{6.40\times10^{-4}\ \text{N}\cdot\text{m}}$$

(b) $$P_{max} = \tau_{max}\omega = \left(6.40\times10^{-4}\ \text{N}\cdot\text{m}\right)(3\ 600\ \text{rev/min})\left(\frac{2\pi\ \text{rad}}{1\ \text{rev}}\right)\left(\frac{1\ \text{min}}{60\ \text{s}}\right)$$
$$= \boxed{0.241\ \text{W}}$$

(c) In one half revolution the work is

$$W = U_{\max} - U_{\min} = -\mu B\cos 180° - (-\mu B\cos 0°) = 2\mu B$$
$$= 2NIAB = 2(6.40\times10^{-4}\ \text{N}\cdot\text{m}) = 1.28\times10^{-3}\ \text{J}$$

In one full revolution, $W = 2(1.28\times10^{-3}\ \text{J}) = \boxed{2.56\times10^{-3}\ \text{J}}$.

(d) The time for one revolution is $\Delta t = \dfrac{60\ \text{s}}{3600\ \text{rev}} = \dfrac{1}{60}\ \text{s}$.

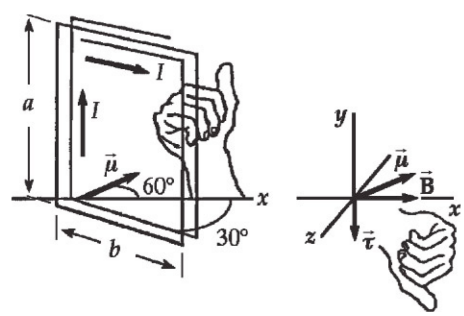
$$P_{\text{avg}} = \frac{W}{\Delta t} = \frac{2.56\times10^{-3}\ \text{J}}{(1/60)\ \text{s}} = \boxed{0.154\ \text{W}}$$

The peak power in (b) is greater by the factor $\dfrac{\pi}{2}$.

P29.51 (a) $\tau = NBAI\sin\phi$

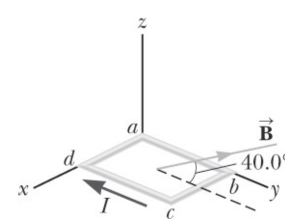
$$\tau = 100(0.800\ \text{T})(0.400\times0.300\ \text{m}^2)\times(1.20\ \text{A})\sin 60°$$
$$\tau = \boxed{9.98\ \text{N}\cdot\text{m}}$$

(b) Note that ϕ is the angle between the magnetic moment and the $\vec{\mathbf{B}}$ field. The loop will rotate so as to align the magnetic moment with the $\vec{\mathbf{B}}$ field, $\boxed{\text{clockwise as seen looking down from a position on the positive } y \text{ axis.}}$



ANS. FIG. P29.51

P29.52 (a) The current in segment *ab* is in the $+y$ direction. Thus, by the right-hand rule, the magnetic force on it is in the $\boxed{+x \text{ direction}}$.



ANS. FIG. P29.52

(b) Imagine the force on segment *ab* being concentrated at its center. Then, with a pivot at point *a* (a point on the *x* axis), this force would tend to rotate segment *ab* in a clockwise direction about the *z* axis, so the direction of this $\boxed{\text{torque is in the } -z \text{ direction}}$.

(c) The current in segment *cd* is in the –y direction, and the right-hand rule gives the direction of the magnetic force as the $\boxed{-x \text{ direction}}$.

(d) With a pivot at point *d* (a point on the x axis), the force on segment *cd* (to the left, in –x direction) would tend to rotate it counterclockwise about the z axis, and the direction of this $\boxed{\text{torque is in the } +z \text{ direction}}$.

(e) $\boxed{\text{No.}}$

(f) $\boxed{\text{Both the forces and the torques are equal in magnitude and opposite in direction, so they sum to zero and cannot affect the motion of the loop.}}$

(g) The magnetic force is perpendicular to both the direction of the current in *bc* (the +x direction) and the magnetic field. As given by the right-hand rule, this places it $\boxed{\text{in the } yz \text{ plane at } 130° \text{ counterclockwise from the } +y \text{ axis.}}$

(h) The force acting on segment *bc* tends to rotate it counterclockwise about the x axis, so the torque is in $\boxed{\text{the } +x \text{ direction}}$.

(i) $\boxed{\text{Zero.}}$ There is no torque about the x axis because the lever arm of the force on segment *ad* is zero.

(j) From the answers to (b), (d), (f), and (h), the loop tends to rotate $\boxed{\text{counterclockwise}}$ about the x axis.

(k) $\mu = IAN = (0.900 \text{ A})[(0.500 \text{ m})(0.300 \text{ m})](1) = \boxed{0.135 \text{ A} \cdot \text{m}^2}$

(l) The magnetic moment vector is perpendicular to the plane of the loop (the xy plane), and is therefore parallel to the z axis. Because the current flows clockwise around the loop, the magnetic moment vector is directed downward, in the negative z direction. This means that the angle between it and the direction of the magnetic field is $\theta = 90.0° + 40.0° = \boxed{130°}$.

(m) $\tau = \mu B \sin\theta = (0.135 \text{ A} \cdot \text{m}^2)(1.50 \text{ T})\sin(130°) = \boxed{0.155 \text{ N} \cdot \text{m}}$

P29.53 (a) From Equation 29.17, $\vec{\tau} = \vec{\mu} \times \vec{\mathbf{B}}$, so the maximum magnitude of the torque on the loop is

$$\tau = \left|\vec{\mu} \times \vec{\mathbf{B}}\right| = \mu B \sin\theta = NIAB\sin\theta$$

$$\tau_{max} = NIAB\sin 90.0°$$
$$= 1(5.00\text{ A})\left[\pi\left(0.050\,0\text{ m}\right)^2\right]\left(3.00\times10^{-3}\text{ T}\right)$$
$$= \boxed{118\ \mu\text{N}\cdot\text{m}}$$

(b) The potential energy is given by

$$U = -\vec{\boldsymbol{\mu}}\cdot\vec{\mathbf{B}}$$

so $-\mu B \le U \le +\mu B$

Now, since

$$\mu B = (NIA)B$$
$$= 1(5.00\text{ A})\left[\pi\left(0.050\,0\text{ m}\right)^2\right]\left(3.00\times10^{-3}\text{ T}\right)$$
$$= 118\ \mu\text{J}$$

the range of the potential energy is: $\boxed{-118\ \mu\text{J} \le U \le +118\ \mu\text{J}}$.

Section 29.6 The Hall Effect

P29.54 (a) $\Delta V_H = \dfrac{IB}{nqt}$ so $\dfrac{nqt}{I} = \dfrac{B}{\Delta V_H} = \dfrac{0.080\,0\text{ T}}{0.700\times10^{-6}\text{ V}} = 1.14\times10^5\ \text{T/V}$

Then, the unknown field is

$$B = \left(\frac{nqt}{I}\right)\left(\Delta V_H\right)$$
$$= \left(1.14\times10^5\ \text{T/V}\right)\left(0.330\times10^{-6}\text{ V}\right) = 0.037\,7\text{ T} = \boxed{37.7\text{ mT}}$$

(b) $\dfrac{nqt}{I} = 1.14\times10^5\ \text{T/V}$ so

$$n = \left(1.14\times10^5\ \text{T/V}\right)\frac{I}{qt}$$
$$= \left(1.14\times10^5\ \text{T/V}\right)\left[\frac{0.120\text{ A}}{\left(1.60\times10^{-19}\text{ C}\right)\left(2.00\times10^{-3}\text{ m}\right)}\right]$$
$$= \boxed{4.29\times10^{25}\text{ m}^{-3}}$$

P29.55 The magnetic field can be found from the Hall effect voltage, Equation 29.22:

$$\Delta V_{\mathrm{H}} = \frac{IB}{nqt}$$

Solving for the magnetic field gives

$$B = \frac{nqt(\Delta V_{\mathrm{H}})}{I}$$

$$= \frac{(8.46\times10^{28}\ \mathrm{m}^{-3})(1.60\times10^{-19}\ \mathrm{C})(0.500\times10^{-2}\ \mathrm{m})(5.10\times10^{-12}\ \mathrm{V})}{8.00\ \mathrm{A}}$$

$$B = 4.31\times10^{-5}\ \mathrm{T} = \boxed{43.1\ \mu\mathrm{T}}$$

Additional Problems

P29.56 From $\sum F = ma$, we have

$$qvB\sin 90.0° = \frac{mv^2}{r}$$

therefore, the angular frequency for each ion is

$$\frac{v}{r} = \omega = \frac{qB}{m} = 2\pi f$$

and

$$\Delta\omega = \omega_{12} - \omega_{14} = qB\left(\frac{1}{m_{12}} - \frac{1}{m_{14}}\right)$$

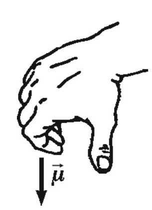
$$= \frac{(1.60\times10^{-19}\ \mathrm{C})(2.40\ \mathrm{T})}{(1.66\times10^{-27}\ \mathrm{kg/u})}\left(\frac{1}{12.0\ \mathrm{u}} - \frac{1}{14.0\ \mathrm{u}}\right)$$

$$\Delta\omega = 2.75\times10^{6}\ \mathrm{s}^{-1} = \boxed{2.75\ \mathrm{Mrad/s}}$$

P29.57 (a) The current carried by the electron is $I = \dfrac{ev}{2\pi r}$, and the magnetic moment is given by

$$\mu = IA = \left(\frac{ev}{2\pi r}\right)\pi r^2$$

$$= \boxed{9.27\times10^{-24}\ \mathrm{A}\cdot\mathrm{m}^2}$$



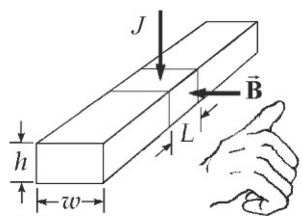
ANS. FIG. P29.57

The Bohr model predicts the correct magnetic moment. However, the "planetary model" is seriously deficient in other regards.

(b) Because the electron is (–), its [conventional] current is clockwise, as seen from above, and μ points $\boxed{\text{downward}}$.

P29.58 (a) Define vector $\vec{\mathbf{h}}$ to have the downward direction of the current, and vector $\vec{\mathbf{L}}$ to be along the pipe into the page as shown. The $\boxed{\text{electric current experiences a magnetic force}}$:

$I\left(\vec{\mathbf{h}}\times\vec{\mathbf{B}}\right)$ in the direction of $\vec{\mathbf{L}}$.



ANS. FIG. P29.58

(b) The sodium, consisting of ions and electrons, flows along the pipe transporting no net charge. But inside the section of length L, electrons drift upward to constitute downward electric current $J \times (\text{area}) = J\,Lw$.

The current then feels a magnetic force $I\left|\vec{\mathbf{h}}\times\vec{\mathbf{B}}\right| = JLwhB\sin 90°$.

This force along the pipe axis will make the fluid move, exerting pressure

$$\frac{F}{\text{area}} = \frac{JLwhB}{hw} = \boxed{JLB}$$

(c) $\boxed{\text{Charge moves within the fluid inside the length } L\text{, but charge does not accumulate: the fluid is not charged after it leaves the pump.}}$

(d) $\boxed{\text{It is not current-carrying,}}$ and

(e) $\boxed{\text{it is not magnetized.}}$

P29.59 (a) The net force is the Lorentz force given by

$$\vec{\mathbf{F}} = q\vec{\mathbf{E}} + q\vec{\mathbf{v}} \times \vec{\mathbf{B}} = q\left(\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}}\right)$$

$$\vec{\mathbf{F}} = \left(3.20 \times 10^{-19}\right)$$

$$\left[\left(4\hat{\mathbf{i}} - 1\hat{\mathbf{j}} - 2\hat{\mathbf{k}}\right) + \left(2\hat{\mathbf{i}} + 3\hat{\mathbf{j}} - 1\hat{\mathbf{k}}\right) \times \left(2\hat{\mathbf{i}} + 4\hat{\mathbf{j}} + 1\hat{\mathbf{k}}\right)\right] \text{ N}$$

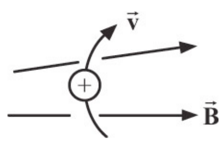
Carrying out the indicated operations, we find:

$$\vec{\mathbf{F}} = \boxed{\left(3.52\hat{\mathbf{i}} - 1.60\hat{\mathbf{j}}\right) \times 10^{-18} \text{ N}}$$

(b) $\theta = \cos^{-1}\left(\dfrac{F_x}{F}\right) = \cos^{-1}\left(\dfrac{3.52}{\sqrt{(3.52)^2 + (1.60)^2}}\right) = \boxed{24.4°}$

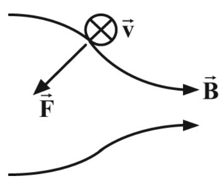
below the $+x$ axis.

P29.60 (a) At the moment shown in Figure 29.11, the particle must be moving upward in order for the magnetic force on it to be  into the page, toward the center of this turn of its spiral path. Throughout its motion it circulates clockwise.



ANS. FIG. P29.60(a)

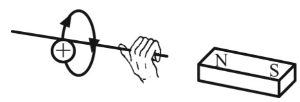
(b) After the particle has passed the middle of the bottle and moves into the region of increasing magnetic field, the magnetic force on it has a component to the left (as well as a radially inward component) as shown. This force in the $-x$ direction slows and reverses the particle's motion along the axis.



ANS. FIG. P29.60(b)

(c) The magnetic force is perpendicular to the velocity and does no work on the particle. The particle keeps constant kinetic energy. As its axial velocity component decreases, its tangential velocity component increases.

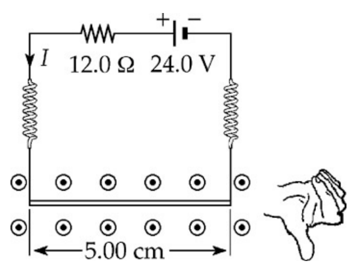
(d) The orbiting particle constitutes a loop of current in the yz plane and therefore a magnetic dipole moment $IA = \frac{q}{T}A$ in the $-x$ direction. It is like a little bar magnet with its N pole on the left.



ANS. FIG. P29.60(d)

P29.61 Let Δx_1 be the elongation due to the weight of the wire and let Δx_2 be the additional elongation of the springs when the magnetic field is turned on. Then $F_{\text{magnetic}} = 2k\Delta x_2$ where k is the force constant of the spring and can be determined from $k = \frac{mg}{2\Delta x_1}$. (The factor 2 is included in the two previous equations since there are 2 springs in parallel.) Combining these two equations, we find

$$F_{\text{magnetic}} = 2\left(\frac{mg}{2\Delta x_1}\right)\Delta x_2 = \frac{mg\Delta x_2}{\Delta x_1}; \text{ but } \left|\vec{\mathbf{F}}_B\right| = I\left|\vec{\mathbf{L}} \times \vec{\mathbf{B}}\right| = ILB$$



ANS. FIG. P29.61

Therefore, where $I = \frac{24.0 \text{ V}}{12.0 \text{ Ω}} = 2.00 \text{ A}$,

$$B = \frac{mg\Delta x_2}{IL\Delta x_1} = \frac{(0.100 \text{ kg})(9.80 \text{ m/s}^2)(3.00 \times 10^{-3} \text{ m})}{(2.00 \text{ A})(0.050\,0 \text{ m})(5.00 \times 10^{-3} \text{ m})}$$

$$= \boxed{0.588 \text{ T}}$$

P29.62 (a) The particle moves in an arc of a circle with radius

$$r = \frac{mv}{qB} = \frac{1.67 \times 10^{-27} \text{ kg} \;\; 3 \times 10^{7} \text{ m/s} \;\; \text{C m}}{1.6 \times 10^{-19} \text{ C} \;\; 25 \times 10^{-6} \text{ N s}} = \boxed{12.5 \text{ km}}$$

(b) It will not arrive at the center, but will perform a hairpin turn and go back parallel to its original direction.

P29.63 Let v_i represent the original speed of the alpha particle. Let v_α and v_p represent the particles' speeds after the collision. We have conservation of momentum

$$4m_p v_i = 4m_p v_\alpha + m_p v_p \quad \rightarrow \quad 4v_i = 4v_\alpha + v_p$$

and the relative velocity equation

$$v_{1i} - v_{2i} = v_{2f} - v_{1f} \quad \rightarrow \quad v_i - 0 = v_p - v_\alpha$$

Eliminating v_i,

$$4v_p - 4v_\alpha = 4v_\alpha + v_p \quad \rightarrow \quad 3v_p = 8v_\alpha \quad \rightarrow \quad v_\alpha = \frac{3}{8}v_p$$

For the proton's motion in the magnetic field,

$$\sum F = ma \quad \rightarrow \quad ev_p B\sin 90° = \frac{m_p v_p^2}{R} \quad \rightarrow \quad \frac{eBR}{m_p} = v_p$$

For the alpha particle,

$$2ev_\alpha B\sin 90° = \frac{4m_p v_\alpha^2}{r_\alpha}$$

and the radius of the alpha particle's trajectory is given by

$$r_\alpha = \frac{2m_p v_\alpha}{eB} = \frac{2m_p}{eB}\frac{3}{8}v_p = \frac{2m_p}{eB}\frac{3}{8}\frac{eBR}{m_p} = \boxed{\frac{3}{4}R}$$

P29.64 (a) If $\vec{\mathbf{B}} = B_x\hat{\mathbf{i}} + B_y\hat{\mathbf{j}} + B_z\hat{\mathbf{k}}$, then

$$\vec{\mathbf{F}}_B = q\vec{\mathbf{v}}\times\vec{\mathbf{B}} = e\left(v_i\hat{\mathbf{i}}\right)\times\left(B_x\hat{\mathbf{i}} + B_y\hat{\mathbf{j}} + B_z\hat{\mathbf{k}}\right) = 0 + ev_iB_y\hat{\mathbf{k}} - ev_iB_z\hat{\mathbf{j}}$$

Since the force actually experienced is $\vec{\mathbf{F}}_B = F_i\hat{\mathbf{j}}$, observe that

$\boxed{B_x \text{ could have any value}}$, $\boxed{B_y = 0}$, and $\boxed{B_z = -\frac{F_i}{ev_i}}$.

(b) If $\vec{\mathbf{v}} = -v_i\hat{\mathbf{i}}$, then

$$\vec{\mathbf{F}}_B = q\vec{\mathbf{v}}\times\vec{\mathbf{B}} = e\left(-v_i\hat{\mathbf{i}}\right)\times\left(B_x\hat{\mathbf{i}} + 0\hat{\mathbf{j}} - \frac{F_i}{ev_i}\hat{\mathbf{k}}\right) = \boxed{-F_i\hat{\mathbf{j}}}$$

(c) If $q = -e$ and $\vec{\mathbf{v}} = -v_i\hat{\mathbf{i}}$, then

$$\vec{\mathbf{F}}_B = q\vec{\mathbf{v}}\times\vec{\mathbf{B}} = -e\left(-v_i\hat{\mathbf{i}}\right)\times\left(B_x\hat{\mathbf{i}} + 0\hat{\mathbf{j}} - \frac{F_i}{ev_i}\hat{\mathbf{k}}\right) = \boxed{+F_i\hat{\mathbf{j}}}$$

Reversing either the velocity or the sign of the charge reverses the force.

P29.65 From the particle in equilibrium model,

$$\sum F_y = 0: \quad +n - mg = 0$$

$$\sum F_x = 0: \quad -f_k + F_B = -\mu_k n + IBd\sin 90.0° = 0$$

Solving for the magnetic field gives

$$B = \frac{\mu_k mg}{Id} = \frac{0.100(0.200\ \text{kg})(9.80\ \text{m/s}^2)}{(10.0\ \text{A})(0.500\ \text{m})} = \boxed{39.2\ \text{mT}}$$

P29.66 From the particle in equilibrium model,

$$\sum F_y = 0: \quad +n - mg = 0$$

$$\sum F_x = 0: \quad -f_k + F_B = -\mu_k n + IBd\sin 90.0° = 0$$

Solving for the magnetic field gives

$$B = \boxed{\frac{\mu_k mg}{Id}}$$

P29.67 (a) The field should be in the +z-direction, perpendicular to the final as well as to the initial velocity, and with $\hat{\mathbf{i}} \times \hat{\mathbf{k}} = -\hat{\mathbf{j}}$ as the direction of the initial force.

(b) $$r = \frac{mv}{qB} = \frac{(1.67 \times 10^{-27}\ \text{kg})(20 \times 10^6\ \text{m/s})}{(1.60 \times 10^{-19}\ \text{C})(0.3\ \text{N}\cdot\text{s/C}\cdot\text{m})} = \boxed{0.696\ \text{m}}$$

(c) The path is a quarter circle, of length

$$s = \theta r = \left(\frac{\pi}{2}\right)(0.696\ \text{m}) = \boxed{1.09\ \text{m}}$$

(d) $$\Delta t = \frac{1.09\ \text{m}}{20.0 \times 10^6\ \text{m/s}} = \boxed{54.7\ \text{ns}}$$

P29.68 Suppose the input power is 120 W = (120 V)I, which gives a current of

$$\boxed{I \sim 1\ \text{A} = 10^0\ \text{A}}$$

Also suppose

$$\omega = 2\,000\ \text{rev/min}\left(\frac{1\ \text{min}}{60\ \text{s}}\right)\left(\frac{2\pi\ \text{rad}}{1\ \text{rev}}\right) \sim 200\ \text{rad/s}$$

and the output power is

$$20\ \text{W} = \tau\omega = \tau(200\ \text{rad/s})$$

The torque is then $\boxed{\tau \sim 10^{-1}\ \text{N}\cdot\text{m}}$

Suppose the area is about (3 cm) × (4 cm), or $\boxed{A \sim 10^{-3}\ \text{m}^2}$

Suppose that the field is $\boxed{B \sim 10^{-1}\ \text{T}}$

Then, the number of turns in the coil may be found from

$\tau \cong NIAB$:

$$0.1\ \text{N}\cdot\text{m} \sim N(1\ \text{C/s})\left(10^{-3}\ \text{m}^2\right)\left(10^{-1}\ \text{N}\cdot\text{s/C}\cdot\text{m}\right)$$

giving $\boxed{N \sim 10^3}$

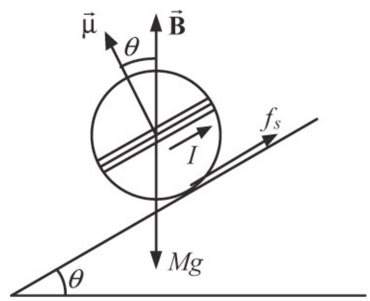
The results are:

(a) $\boxed{B \sim 10^{-1}\ \text{T}}$ (b) $\boxed{\tau \sim 10^{-1}\ \text{N}\cdot\text{m}}$ (c) $\boxed{I \sim 1\ \text{A} = 10^0\ \text{A}}$

(d) $\boxed{A \sim 10^{-3}\ \text{m}^2}$ (e) $\boxed{N \sim 10^3}$

P29.69 The sphere is in translational equilibrium; thus

$$f_s - Mg\sin\theta = 0 \qquad \textbf{[1]}$$



ANS. FIG. P29.69

The sphere is also in rotational equilibrium. If torques are taken about the center of the sphere, the magnetic field produces a clockwise torque of magnitude $\mu B\sin\theta$, and the frictional force a counterclockwise torque of magnitude f_sR, where R is the radius of the sphere. Thus,

$$f_sR - \mu B\sin\theta = 0 \qquad \textbf{[2]}$$

From [1], we obtain $f_s = Mg\sin\theta$. Substituting this into [2], the sin θ term will cancel—see part (b) below. One obtains

$$\mu B = MgR \qquad \textbf{[3]}$$

Now, $\mu = NI\pi R^2$. Thus [3] gives

(a) $$I = \frac{Mg}{\pi NBR} = \frac{(0.080\ 0\ \text{kg})\left(9.80\ \text{m/s}^2\right)}{\pi(5)(0.350\ \text{T})(0.200\ \text{m})} =$$

$\boxed{0.713\ \text{A counterclockwise as seen from above}}$

(b) Substitute [1] into [2] and use $\mu = NIA = NI\pi R^2$:

$$f_sR - \mu B\sin\theta = 0$$

$$\left(Mg\cancel{\sin\theta}\right)R = \mu B\cancel{\sin\theta}$$

$$MgR = \mu B = \left(NI\pi R^2\right)B$$

solving for the current gives

$$I = \frac{Mg}{\pi NBR}$$

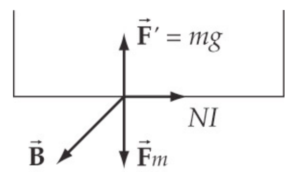
The current is clearly independent of θ.

P29.70 The radius of the circular path followed by the particle is

$$r = \frac{mv}{qB} = \frac{\left(2.00 \times 10^{-13}\ \text{kg}\right)\left(2.00 \times 10^{5}\ \text{m/s}\right)}{\left(1.00 \times 10^{-6}\ \text{C}\right)(0.400\ \text{T})} = 0.100\ \text{m}$$

This is exactly equal to the length h of the field region. Therefore, the particle will not exit the field at the top, but rather will complete a semicircle in the magnetic field region and will exit at the bottom, traveling in the opposite direction with the same speed.

P29.71 (a) When switch S is closed, a total current NI (current I in a total of N conductors) flows toward the right through the lower side of the coil. This results in a downward force of magnitude $F_m = B(NI)w$ being exerted on the coil by the magnetic field, with the requirement that the balance exert a upward force $F' = mg$ on the coil to bring the system back into balance.



ANS. FIG. P29.71

For the system to be restored to balance, it is necessary that

$$F_m = F' \quad \text{or} \quad B(NI)w = mg, \quad \text{giving} \quad B = \boxed{mg/NIw}$$

(b) The magnetic field exerts forces of equal magnitude and opposite directions on the two sides of the coils, so the forces cancel each other and do not affect the balance of the system. Hence, the vertical dimension of the coil is not needed.

(c) $$B = \frac{mg}{NIw} = \frac{\left(20.0\times10^{-3}\ \text{kg}\right)\left(9.80\ \text{m/s}^2\right)}{(50)(0.300\ \text{A})\left(5.00\times10^{-2}\ \text{m}\right)} = \boxed{0.261\ \text{T}}$$

P29.72 (a) The magnetic force acting on ions in the blood stream will deflect positive charges toward point A and negative charges toward point B. This separation of charges produces an electric field directed from A toward B. At equilibrium, the electric force caused by this field must balance the magnetic force, so

$$qvB = qE = q\left(\frac{\Delta V}{d}\right)$$

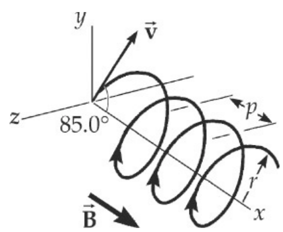
which gives

$$v = \frac{\Delta V}{Bd} = \frac{160\times10^{-6}\ \text{V}}{(0.040\ 0\ \text{T})\left(3.00\times10^{-3}\ \text{m}\right)} = \boxed{1.33\ \text{m/s}}$$

(b) Positive ions carried by the blood flow experience an upward force resulting in the upper wall of the blood vessel at electrode *A* becoming positively charged and the lower wall of the blood vessel at electrode *B* becoming negatively charged.

(c) No. Negative ions moving in the direction of v would be deflected toward point *B*, giving *A* a higher potential than *B*. Positive ions moving in the direction of v would be deflected toward *A*, again giving *A* a higher potential than *B*. Therefore, the sign of the potential difference does not depend on whether the ions in the blood are positively or negatively charged.

P29.73 Let v_x and $v_\perp$ be the components of the velocity of the positron parallel to and perpendicular to the direction of the magnetic field.



ANS. FIG. P29.73

(a) The pitch of trajectory is the distance moved along *x* by the positron during each period, *T* (determined by the cyclotron frequency):

$$p = v_x T = (v\cos 85.0°)\left(\frac{2\pi m}{Bq}\right)$$

$$p = \frac{\left(5.00\times10^{6}\right)(\cos 85.0°)(2\pi)\left(9.11\times10^{-31}\right)}{0.150\left(1.60\times10^{-19}\right)} = \boxed{1.04\times10^{-4}\ \text{m}}$$

(b) The equation about circular motion in a magnetic field still applies to the radius of the spiral:

$$r = \frac{mv_\perp}{Bq} = \frac{mv\sin 85.0°}{Bq}$$

$$r = \frac{(9.11\times10^{-31})(5.00\times10^{6})(\sin 85.0°)}{(0.150)(1.60\times10^{-19})} = \boxed{1.89\times10^{-4}\ \text{m}}$$

P29.74 (a) The torque on the dipole $\vec{\tau} = \vec{\mu}\times\vec{\mathbf{B}}$ has magnitude $\mu B \sin\theta \approx \mu B\theta$, proportional to the angular displacement if the angle is small. It is a restoring torque, tending to turn the dipole toward its equilibrium orientation. Then the statement that its motion is simple harmonic is true for small angular displacements.

(b) The statement is true only for small angular displacements for which $\sin\theta \approx \theta$.

(c) $\tau = I\alpha$ becomes

$$-\mu B\theta = I\, d^2\theta/dt^2 \quad\rightarrow\quad d^2\theta/dt^2 = -(\mu B/I)\theta = -\omega^2\theta$$

where $\omega = (\mu B/I)^{1/2}$ is the angular frequency and

$$f = \omega/2\pi = \frac{1}{2\pi}\sqrt{\frac{\mu B}{I}}$$

is the frequency in hertz.

(d) The equilibrium orientation of the needle shows the direction of the field. In a stronger field, the frequency is higher. The frequency is easy to measure precisely over a wide range of values.

(e) From part (c), we see that the frequency is proportional to the square root of the magnetic field strength:

$$\frac{f_2}{f_1} = \sqrt{\frac{B_2}{B_1}} \rightarrow \frac{B_2}{B_1} = \left(\frac{f_2}{f_1}\right)^2$$

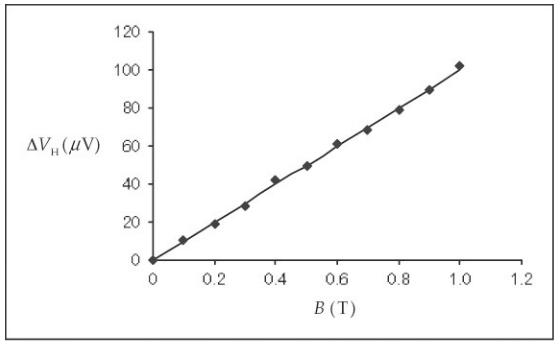
Therefore,

$$B_2 = B_1\left(\frac{f_2}{f_1}\right)^2 = (39.2\times10^{-6}\ \text{T})\left(\frac{4.90\ \text{Hz}}{0.680\ \text{Hz}}\right)^2$$

$$= 2.04\times10^{-3}\ \text{T} = \boxed{2.04\ \text{mT}}$$

P29.75 (a) See the graph in ANS. FIG. P29.75. The Hall voltage is directly proportional to the magnetic field. A least-square fit to the data gives the equation of the best fitting line as:

$$\boxed{\begin{array}{c}\Delta V_H = (1.00\times10^{-4})B \\ \text{where } \Delta V_H \text{ is in volts and } B \text{ is in teslas.}\end{array}}$$



ANS. FIG. P29.75

(b) Comparing the equation of the line which fits the data to

$$\Delta V_{\mathrm{H}} = \left(\frac{1}{nqt}\right)B$$

observe that the slope: $\frac{I}{nqt} = 1.00\times10^{-4}$, or

$$t = \frac{I}{nq\left(1.00\times10^{-4}\right)}$$

Then, if $I = 0.200$ A, $q = 1.60\times10^{-19}$ C, and $n = 1.00\times10^{26}$ m^{-3}, the thickness of the sample is

$$t = \frac{0.200\text{ A}}{\left(1.00\times10^{26}\text{ m}^{-3}\right)\left(1.60\times10^{-19}\text{ C}\right)\left(1.00\times10^{-4}\text{ V/T}\right)}$$

$$= 1.25\times10^{-4}\text{ m} = \boxed{0.125\text{ mm}}$$

P29.76 Call the length of the rod L and the tension in each wire alone $\frac{T}{2}$.

Then, at equilibrium:

$$\sum F_x = T\sin\theta - ILB\sin 90.0° = 0 \quad\text{or}\quad T\sin\theta = ILB$$

$$\sum F_y = T\cos\theta - mg = 0 \quad\text{or}\quad T\cos\theta = mg$$

combining the equations gives

$$\tan\theta = \frac{ILB}{mg} = \frac{IB}{(m/L)g}$$

solving for the magnetic field,

$$B = \frac{(m/L)g}{I}\tan\theta = \boxed{\frac{\lambda g}{I}\tan\theta}$$

Challenge Problems

P29.77 $|\tau| = IAB$ where the effective current due to the orbiting electrons is $I = \dfrac{\Delta q}{\Delta t} = \dfrac{q}{T}$ and the period of the motion is $T = \dfrac{2\pi R}{v}$.

The electron's speed in its orbit is found by requiring $\dfrac{k_e q^2}{R^2} = \dfrac{mv^2}{R}$ or

$$v = q\sqrt{\frac{k_e}{mR}}$$

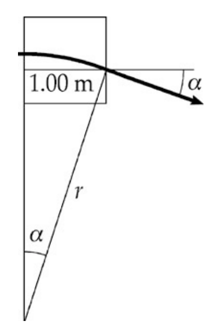
Substituting this expression for v into the equation for T, we find

$$\begin{aligned} T &= 2\pi\sqrt{\frac{mR^3}{q^2 k_e}} \\ &= 2\pi\sqrt{\frac{(9.11\times10^{-31}\ \text{kg})(5.29\times10^{-11}\ \text{m})^3}{(1.60\times10^{-19}\ \text{C})^2(8.99\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)}} \\ &= 1.52\times10^{-16}\ \text{s} \end{aligned}$$

Therefore,

$$\begin{aligned} |\tau| &= \left(\frac{q}{T}\right)AB = \left(\frac{1.60\times10^{-19}\ \text{C}}{1.52\times10^{-16}\ \text{s}}\right)\left[\pi(5.29\times10^{-11}\ \text{m})^2\right](0.400\ \text{T}) \\ &= \boxed{3.70\times10^{-24}\ \text{N}\cdot\text{m}} \end{aligned}$$

P29.78 The magnetic force on each proton, $\vec{\mathbf{F}}_B = q\vec{\mathbf{v}}\times\vec{\mathbf{B}} = qvB\sin 90°$ downward and perpendicular to the velocity vector, causes centripetal acceleration, guiding it into a circular path of radius r, with



ANS. FIG. P29.78

$$qvB = \frac{mv^2}{r}$$

and $$r = \frac{mv}{qB}$$

We compute this radius by first finding the proton's speed from $K = \dfrac{1}{2}mv^2$:

$$\begin{aligned} v &= \sqrt{\frac{2K}{m}} = \sqrt{\frac{2(5.00\times10^6\ \text{eV})(1.60\times10^{-19}\ \text{J/eV})}{1.67\times10^{-27}\ \text{kg}}} \\ &= 3.10\times10^7\ \text{m/s} \end{aligned}$$

Now, $$r = \frac{mv}{qB} = \frac{\left(1.67\times10^{-27}\ \text{kg}\right)\left(3.10\times10^{7}\ \text{m/s}\right)}{\left(1.60\times10^{-19}\ \text{C}\right)\left(0.050\,0\ \text{N}\cdot\text{s/C}\cdot\text{m}\right)} = 6.46\ \text{m}.$$

(a) From ANS. FIG. P29.78 observe that

$$\sin\alpha = \frac{1.00\ \text{m}}{r} = \frac{1\ \text{m}}{6.46\ \text{m}}$$

$$\boxed{\alpha = 8.90^\circ}$$

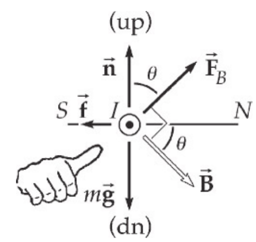
(b) The magnitude of the proton momentum stays constant, and its final y component is

$$-\left(1.67\times10^{-27}\ \text{kg}\right)\left(3.10\times10^{7}\ \text{m/s}\right)\sin 8.90^\circ$$

$$= \boxed{-8.00\times10^{-21}\ \text{kg}\cdot\text{m/s}}$$

P29.79 A key to solving this problem is that reducing the normal force will reduce the friction force:

$F_B = BIL$ or $B = \dfrac{F_B}{IL}$.



ANS. FIG. P29.79

When the wire is just able to move,

$$\sum F_y = n + F_B\cos\theta - mg = 0$$

so $$n = mg - F_B\cos\theta$$

and $$f = \mu\left(mg - F_B\cos\theta\right)$$

Also, $$\sum F_x = F_B\sin\theta - f = 0$$

so $$F_B\sin\theta = f:\ F_B\sin\theta = \mu\left(mg - F_B\cos\theta\right)\ \text{and}\ F_B = \frac{\mu mg}{\sin\theta + \mu\cos\theta}$$

We minimize B by minimizing F_B:

$$\frac{dF_B}{d\theta} = -\left(\mu mg\right)\frac{\cos\theta - \mu\sin\theta}{\left(\sin\theta + \mu\cos\theta\right)^2} = 0 \Rightarrow \mu\sin\theta = \cos\theta$$

Thus, $\theta = \tan^{-1}\left(\dfrac{1}{\mu}\right) = \tan^{-1}(5.00) = 78.7^\circ$ for the smallest field, and

$$B = \frac{F_B}{IL} = \left(\frac{\mu g}{I}\right)\frac{(m/L)}{\sin\theta + \mu\cos\theta}$$

$$B_{\text{min}} = \left[\frac{(0.200)\left(9.80\ \text{m/s}^2\right)}{1.50\ \text{A}}\right]\frac{0.100\ \text{kg/m}}{\sin 78.7^\circ + (0.200)\cos 78.7^\circ}$$

$$= 0.128\ \text{T}$$

The answers are

(a) magnitude: $\boxed{0.128 \text{ T}}$ and

(b) direction: $\boxed{78.7° \text{ below the horizontal}}$

P29.80 (a) The kinetic energy of the proton in joules is

$$K = \frac{1}{2}mv^2 = 6.00 \text{ MeV} = \left(6.00\times10^6 \text{ eV}\right)\left(1.60\times10^{-19} \text{ J/eV}\right)$$
$$= 9.60\times10^{-13} \text{ J}$$

From which we find the proton's velocity to be

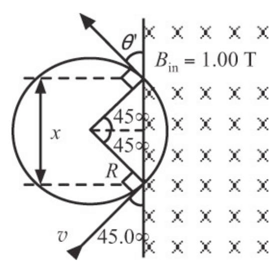
$$v = \sqrt{\frac{2\left(9.60\times10^{-13} \text{ J}\right)}{1.67\times10^{-27} \text{ kg}}} = 3.39\times10^7 \text{ m/s}$$

We can find the radius of the proton's orbit from

$$F_B = qvB = \frac{mv^2}{R}$$

so $$R = \frac{mv}{qB} = \frac{\left(1.67\times10^{-27} \text{ kg}\right)\left(3.39\times10^7 \text{ m/s}\right)}{\left(1.60\times10^{-19} \text{ C}\right)\left(1.00 \text{ T}\right)} = 0.354 \text{ m}$$

Then, from the diagram, $x = 2R\sin 45.0° = 2(0.354 \text{ m})\sin 45.0° =$ $\boxed{0.501 \text{ m}}$.



ANS. FIG. P29.80

(b) From ANS. FIG. P29.80, observe that $\theta' = \boxed{45.0°}$.

ANSWERS TO EVEN-NUMBERED PROBLEMS

P29.2 (a) up; (b) out of the page, since the charge is negative; (c) no deflection; (d) into the page

P29.4 (a) west; (b) zero deflection; (c) up; (d) down

P29.6 48.9° or 131°

P29.8 13.2×10^{-19} N

P29.10 (a) 1.44×10^{-12} N; (b) 8.62×10^{14} m/s^2; (c) A force would be exerted on the electron that had the same magnitude as the force on a proton but in the opposite direction because of its negative charge; (d) The acceleration of the electron would be much greater than that of the proton because the mass of the electron is much smaller.

P29.12 200 μC

P29.14 (a) 6.84×10^{-16} m; (b) down; (c) 7.26 mm; (d) east; (e) The beam moves on an arc of a circle rather than on a parabola; (f) Its northward velocity component stays constant within 0.09%. It is a good approximation to think of it as moving on a parabola as it really moves on a circle.

P29.16 (a) $v = \dfrac{2K}{qBR}$; (b) $\dfrac{q^2B^2R^2}{2K}$

P29.18 $\dfrac{e^2B^2}{2m_e}\left(r_1^2 + r_2^2\right)$

P29.20 (a) $\left(0.990 \times 10^{-6}\,\hat{\mathbf{i}} + 1.00 \times 10^{-6}\,\hat{\mathbf{j}}\right)$ N; (b) Yes. In the vertical direction, the gravitational force on the ball is 0.294 N, five orders of magnitude larger than the magnetic force. In the horizontal direction, the change in the horizontal component of velocity due to the magnetic force is six orders of magnitude smaller than the horizontal velocity component.

P29.22 1.79×10^{-8} s; (b) 35.1 eV

P29.24 4.31×10^{7} rad/s; (b) 5.17×10^{7} m/s

P29.26 (a) 8.28 cm; (b) 8.23 cm; (c) From $r = \dfrac{1}{B}\sqrt{\dfrac{2m(\Delta V)}{q}}$, we see for two different masses m_A and m_B of the same charge q, the ratio of the path radii is $\dfrac{r_B}{r_A} = \sqrt{\dfrac{m_B}{m_B}}$; (d) The ratio of the path radii is independent of ΔV; (e) The ratio of the path radii is independent of B.

P29.28 (a) See P29.28 for full explanation; (b) The dashed red line in Figure P29.16(a) spirals around many times, with it turns relatively far apart on the inside and closer together on the outside. This demonstrates the $1/r$ behavior of the rate of change in radius exhibited by the result in part (a); (c) 682 m/s; (d) 55.9 μm

P29.30 (a) Yes. The constituent of the beam is present in all kinds of atoms; (b) Yes. Everything in the beam has single charge-to-mass ratio; (c) In a charged macroscopic object most of the atoms are uncharged. A molecule never has all of its atoms ionized. Any atoms other than hydrogen contain neutrons and so has more mass per charge if it is ionized than hydrogen does. The greatest charge-to-mass ratio Thomson could expect was then for ionized hydrogen, 1.6×10^{-19} C/1.67×10^{-27} kg, smaller than the value e/m he measured, 1.6×10^{-19} C/9.11×10^{-31} kg, by 1 836 times. The particles in his beam could not be whole atoms but rather must be much smaller in mass; (d) No. The particles move with speed on the order of ten million meters per second, so they fall by an immeasurably small amount over a distance of less than 1 m.

P29.32 (a) 0.118 N; (b) Neither the direction of the magnetic field nor that of the current is given. Both must be known in order to determine the direction of the magnetic force.

P29.34 (a) 4.73 N; (b) 5.46 N; (c) 4.73 N

P29.36 See P29.36 for full explanation.

P29.38 $\sqrt{\dfrac{4IdBL}{3m}}$

P29.40 The magnetic force and the gravitational force both act on the wire; (b) When the magnetic force is upward and balances the downward gravitational force, the net force on the wire is zero, and the wire can move can move upward at constant velocity; (c) 0.196 T, out of the page; (d) If the field exceeds 0.20 T, the upward magnetic force exceeds the downward gravitational force, so the wire accelerates upward.

P29.42 (a) $2\pi rIB \sin\theta$; (b) up, away from magnet

P29.44 (a) 0; (b) $-40.0\hat{\mathbf{i}}$ mN; (c) $-40.0\hat{\mathbf{k}}$ mN; (d) $\left(40.0\hat{\mathbf{i}} + 40.0\hat{\mathbf{k}}\right)$ mN; (e) The forces on the four segments must add to zero, so the force on the fourth segment must be the negative of the resultant of the forces on the other three.

P29.46 4.91×10^{-3} N · m

P29.48 (a) 5.41 mA · m^2; (b) 4.33 mN · m

P29.50 (a) 6.40×10^{-4} N · m; (b) 0.241 W; (c) 2.56×10^{-3} J; (d) 0.154 W

P29.52 (a) $+x$ direction; (b) torque is in the $-z$ direction; (c) $-x$ direction; (d) torque is in the $+z$ direction; (e) No; (f) Both the forces and the torques are equal in magnitude and opposite in direction, so they sum to zero and cannot affect the motion of the loop; (g) in the yz plane at 130° counterclockwise from the $+y$ axis; (h) the $+x$ direction; (i) zero; (j) counterclockwise; (k) $0.135\ \text{A}\cdot\text{m}^2$; (l) 130°; (m) $0.155\ \text{N}\cdot\text{m}$

P29.54 (a) 37.7 mT; (b) $4.29\times10^{25}\ \text{m}^{-3}$

P29.56 2.75 Mrad/s

P29.58 (a) The electric current experiences a magnetic force; (b) JLB; (c) Charge moves within the fluid inside the length L, but charge does not accumulate: the fluid is not charged after it leaves the pump; (d) It is not current-carrying; (e) It is not magnetized.

P29.60 (a–d) See P29.60 for full explanation.

P29.62 (a) 12.5 km; (b) It will not arrive at the center but will perform a hairpin turn and go back parallel to its original direction.

P29.64 (a) B_x could have any value, $B_y = 0$, $B_z = -\dfrac{F_i}{ev_i}$; (b) $-F_i\hat{\mathbf{j}}$; (c) $+F_i\hat{\mathbf{j}}$

P29.66 $\dfrac{\mu_k mg}{Id}$

P29.68 (a) $B \sim 10^{-1}$ T; (b) $\tau \sim 10^{-1}\ \text{N}\cdot\text{m}$; (c) $I \sim 1\ \text{A} = 10^0\ \text{A}$; (d) $A \sim 10^{-3}\ \text{m}^2$; (e) $N \sim 10^3$

P29.70 The particle will not exit the field at the top but rather will complete a semicircle in the magnetic field region and will exit at the bottom, traveling in the opposite direction with the same speed.

P29.72 (a) 1.33 m/s; (b) Positive ions carried by the blood flow experience an upward force resulting in the upper wall of the blood vessel at electrode A becoming positively charged and the lower wall of the blood vessel at electrode B becoming negatively charged; (b) No. Negative ions moving in the direction of v would be deflected toward point B, giving A a higher potential than B. Positive ions moving in the direction of v would be deflected toward A, again giving A a higher potential than B. Therefore, the sign of the potential difference does not depend on whether the ions in the blood are positively or negatively charged.

P29.74 (a) See P29.74(a) for full explanation; (b) The statement is true only for small angular displacements for which sin $\theta \approx \theta$; (c) See P29.74(c) for full explanation; (d) The equilibrium orientation of the needle shows the direction of the field. In a stronger field, the frequency is higher. The frequency is easy to measure precisely over a wide range of values; (e) 2.04 mT

P29.76 $\frac{\lambda g}{I}\tan\theta$

P29.78 (a) $\alpha = 8.90°$; (b) -8.00×10^{-21} kg · m/s

P29.80 (a) 0.501 m; (b) 45.0°