8.10: The Magnetic Field (Summary)

Key Terms

cosmic rays	comprised of particles that originate mainly from outside the solar system and reach Earth
gauss	G, unit of the magnetic field strength; $1G = 10^{-4}T$
helical motion	superposition of circular motion with a straight-line motion that is followed by a charged particle moving in a region of magnetic field at an angle to the field
magnetic dipole	closed-current loop
magnetic dipole moment	term **IA** of the magnetic dipole, also called μ
magnetic field lines	continuous curves that show the direction of a magnetic field; these lines point in the same direction as a compass points, toward the magnetic south pole of a bar magnet
magnetic force	force applied to a charged particle moving through a magnetic field
north magnetic pole	currently where a compass points to north, near the geographic North Pole; this is the effective south pole of a bar magnet but has flipped between the effective north and south poles of a bar magnet multiple times over the age of Earth
right-hand rule	using your right hand to determine the direction of either the magnetic force, velocity of a charged particle, or magnetic field
south magnetic pole	currently where a compass points to the south, near the geographic South Pole; this is the effective north pole of a bar magnet but has flipped just like the north magnetic pole
tesla	SI unit for magnetic field: $1T = 1N/A-m$

Ampère’s law	physical law that states that the line integral of the magnetic field around an electric current is proportional to the current
Biot-Savart law	an equation giving the magnetic field at a point produced by a current-carrying wire
diamagnetic materials	their magnetic dipoles align oppositely to an applied magnetic field; when the field is removed, the material is unmagnetized
ferromagnetic materials	contain groups of dipoles, called domains, that align with the applied magnetic field; when this field is removed, the material is still magnetized
hysteresis	property of ferromagnets that is seen when a material’s magnetic field is examined versus the applied magnetic field; a loop is created resulting from sweeping the applied field forward and reverse
magnetic domains	groups of magnetic dipoles that are all aligned in the same direction and are coupled together quantum mechanically
magnetic susceptibility	ratio of the magnetic field in the material over the applied field at that time; positive susceptibilities are either paramagnetic or ferromagnetic (aligned with the field) and negative susceptibilities are diamagnetic (aligned oppositely with the field)
paramagnetic materials	their magnetic dipoles align partially in the same direction as the applied magnetic field; when this field is removed, the material is unmagnetized
permeability of free space	μ_0, measure of the ability of a material, in this case free space, to support a magnetic field

solenoid	thin wire wound into a coil that produces a magnetic field when an electric current is passed through it
toroid	donut-shaped coil closely wound around that is one continuous wire

Key Equations

Force on a charge in a magnetic field	$\vec{F} = q\vec{v} \times \vec{B}$
Magnitude of magnetic force	$F = qvBsin\theta$
Radius of a particle's path in a magnetic field	$r = \frac{mv}{qB}$
Period of a particle's motion in a magnetic field	$T = \frac{2\pi m}{qB}$
Force on a current-carrying wire in a uniform magnetic field	$\vec{F} = I\vec{l} \times \vec{B}$

Permeability of free space	$\mu_0 = 4\pi \times 10^{-7} T \cdot m/A$
Contribution to magnetic field from a current element	$dB = \frac{\mu_0}{4\pi} \frac{Idlsin\theta}{r^2}$
Biot–Savart law	$\vec{B} = \frac{\mu_0}{4\pi} \int_{wire} \frac{Id\vec{l} \times \hat{r}}{r^2}$
Magnetic field due to a long straight wire	$B = \frac{\mu_0 I}{2\pi R}$
Force between two parallel currents	$\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi r}$
Magnetic field of a current loop	$B = \frac{\mu_0 I}{2R}$ (at center of loop)
Magnetic field strength inside a solenoid	$B = \mu_0 nI$
Magnetic field strength inside a toroid	$B = \frac{\mu_o NI}{2\pi r}$
Magnetic permeability	$\mu = (1 + \chi)\mu_0$
Magnetic field of a solenoid filled with paramagnetic material	$B = \mu nI$

Summary

Magnetism and Its Historical Discoveries

- Magnets have two types of magnetic poles, called the north magnetic pole and the south magnetic pole. North magnetic poles are those that are attracted toward Earth's geographic North Pole.
- Like poles repel and unlike poles attract.
- Discoveries of how magnets respond to currents by Oersted and others created a framework that led to the invention of modern electronic devices, electric motors, and magnetic imaging technology.

Magnetic Fields and Lines

- Charges moving across a magnetic field experience a force determined by $\vec{F} = q\vec{v} \times \vec{B}$. The force is perpendicular to the plane formed by $\vec{v}$ and $\vec{B}$.
- The direction of the force on a moving charge is given by the right hand rule 1 (RHR-1): Sweep your fingers in a velocity, magnetic field plane. Start by pointing them in the direction of velocity and sweep towards the magnetic field. Your thumb points in the direction of the magnetic force for positive charges.
- Magnetic fields can be pictorially represented by magnetic field lines, which have the following properties:

    1. The field is tangent to the magnetic field line.
    2. Field strength is proportional to the line density.
    3. Field lines cannot cross.

4. Field lines form continuous, closed loops.

- Magnetic poles always occur in pairs of north and south—it is not possible to isolate north and south poles.

Motion of a Charged Particle in a Magnetic Field

- A magnetic force can supply centripetal force and cause a charged particle to move in a circular path of radius $r=\frac{mv}{qB}$.
- The period of circular motion for a charged particle moving in a magnetic field perpendicular to the plane of motion is $T=\frac{2\pi m}{qB}$.
- Helical motion results if the velocity of the charged particle has a component parallel to the magnetic field as well as a component perpendicular to the magnetic field.

Magnetic Force on a Current-Carrying Conductor

- An electrical current produces a magnetic field around the wire.
- The directionality of the magnetic field produced is determined by the right hand rule-2, where your thumb points in the direction of the current and your fingers wrap around the wire in the direction of the magnetic field.
- The magnetic force on current-carrying conductors is given by $\vec{F}=I\vec{l}\times\vec{B}$ where I is the current and l is the length of a wire in a uniform magnetic field B.
- The force between two parallel currents I_1 and I_2, separated by a distance r, has a magnitude per unit length given by $\frac{F}{l}=\frac{\mu_0 I_1 I_2}{2\pi r}$.
- The force is attractive if the currents are in the same direction, repulsive if they are in opposite directions.

The Biot-Savart Law

- The magnetic field created by a current-carrying wire is found by the Biot-Savart law.
- The current element $Id\vec{l}$ produces a magnetic field a distance r away.

Common Magnetic Field Models

- The strength of the magnetic field created by current in a long straight wire is given by $B=\frac{\mu_0 I}{2\pi R}$ (long straight wire) where **I** is the current, **R** is the shortest distance to the wire, and the constant $\mu_0=4\pi\times 10^{-7} T\cdot m/s$ is the permeability of free space.
- The direction of the magnetic field created by a long straight wire is given by right-hand rule 2 (RHR-2): Point the thumb of the right hand in the direction of current, and the fingers curl in the direction of the magnetic field loops created by it.
- The magnetic field strength at the center of a circular loop is given by $B=\frac{\mu_0 I}{2R}$ **(at center of loop),**, where R is the radius of the loop. RHR-2 gives the direction of the field about the loop.
- The magnetic field strength inside a solenoid is $B=\mu_0 nI$ (inside a solenoid) where n is the number of loops per unit length of the solenoid. The field inside is very uniform in magnitude and direction.
- The magnetic field strength inside a toroid is $B=\frac{\mu_o NI}{2\pi r}$ (within the toroid) where N is the number of windings. The field inside a toroid is not uniform and varies with the distance as $1/r$.

Magnetism in Matter

- Materials are classified as paramagnetic, diamagnetic, or ferromagnetic, depending on how they behave in an applied magnetic field.
- Paramagnetic materials have partial alignment of their magnetic dipoles with an applied magnetic field. This is a positive magnetic susceptibility. Only a surface current remains, creating a solenoid-like magnetic field.
- Diamagnetic materials exhibit induced dipoles opposite to an applied magnetic field. This is a negative magnetic susceptibility.
- Ferromagnetic materials have groups of dipoles, called domains, which align with the applied magnetic field. However, when the field is removed, the ferromagnetic material remains magnetized, unlike paramagnetic materials. This magnetization of the material versus the applied field effect is called hysteresis.

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