Physics 1214 — Chapter 20: Magnetic Field and Magnetic Forces — 02/06

1 Magnetism

permanent magnets: a magnet which remains a magnet over time; has a **north pole** or N pole and a **south pole** or **S pole**; opposite poles attract; like poles repel.
magnetic monopoles: an isolated magnetic pole; not observed to date.
magnetic declination: the compass variation from the earth's geographic axis (the axis of rotation) the the magnetic axis.
angle of dip: the inclination up or down due to the earth's magnetic field not being horizontal at most points on the surface of the planet.
electromagnets: a magnet created by an electric current.

Electric and magnetic interactions are intimately intertwined!

2 Magnetic Field and Magnetic Force

A permanent magnet, a moving charge, or a current creates a ***magnetic field*** at all points in the surrounding space.

The magnetic field exerts a force $\vec{F}$ on any other moving charge or current that is present in the field.

A magnetic field is a vector field, $\vec{B}$.

magnetic field lines: a representation of the magnetic field by vectors. The lines are drawn so that the line through any point is tangent to the magnetic-field vector $\vec{B}$ at that point.

Magnitude of the magnetic force

When a charge particle moves with velocity $\vec{v}$ in a magnetic field $\vec{B}$, the magnitude F of the force exerted on it is

$$F = |q|v_{\perp}B = |q|vB\sin\phi,$$

where $|q|$ is the magnitude of the charge and ϕ is the angle measured from the direction of $\vec{v}$ to the direction of $\vec{B}$.

Right-hand rule for magnetic force

The right-hand rule for finding the direction of magnetic force on a *positive charge* is as follows:

1. Draw the vector $\vec{v}$ and $\vec{B}$ with their tails together.
2. Imagine turning $\vec{v}$ in the plane containing $\vec{v}$ and $\vec{B}$ until it points in the direction of $\vec{B}$. Turn it through the smaller of the two possible angles.
3. The force then acts along a line perpendicular to the plane containing $\vec{v}$ and $\vec{B}$. Using your right hand, curl your fingers around this line in the same direction (clockwise or counterclockwise) that you turned $\vec{v}$. Your thumb now points in the direction of the force $\vec{F}$ on a *positive charge*.

Definition of the tesla

1 tesla = 1 T = 1 N/(A · m). The cgs unit of B, the gauss (1 G = 10^{-4}), is also in common use. Instruments for measuring magnetic field are sometimes called gaussmeters or teslameters.

velocity selector: a device that uses electric and magnetic fields to select particles of a particular velocity.
Thompson's e/m ***experiment***

- speeds of electrons in a beam were determined from the V_{ab} used to accelerate them
- from the measurements of the $\vec{E}$ and $\vec{B}$, the ratio of electric charge magnitude (e) to mass (m) of the electrons were determined
- all particles in the beam had the same value

Current value for the mass of an electron from NIST: $m_e = 9.10938291x10^{-31}kg$

3 Motion of Charged Particles in a Magnetic Field

The path of a charged particle in a magnetic field with *force* given by $F = |q|v_{\perp}B$ is a circle with constant speed v. Where m is the *mass* of the particle, R is the *radius* of the circular path, *radial acceleration* is $a_R = v^2/R$ and $F = ma$ (*Newton's Second Law*), then

$$F = |q|vB = m\frac{v^2}{R}.$$

And the radius of the circular path is

$$R = \frac{mv}{|q|B}.$$

The angular velocity $\omega = v/R$, then with the above equation

$$\omega = \frac{v}{R} = v\frac{|q|B}{mv} = \frac{|q|B}{m}.$$

cyclotron frequency: the frequency of revolution (the number of revolutions per unit time) of a charged particle in a magnetic field is given by $f = \omega/2\pi$ and is independent of R.

4 Mass Spectrometers

mass spectrometers: used to measure masses of positive ions and measure atomic and molecular masses.
isotopes: atoms that are very similar in chemical behavior but different in mass resulting from different numbers of neutrons in the nuclei; most elements have several isotopes.

$$\boxed{{}^{Protons+Neutrons}Element}$$

5 Magnetic Force on a Current-Carrying Conductor

Magnetic force on a current-carrying conductor

The magnetic-field force on a segment of conductor with length l, carrying a current I in a uniform magnetic field $\vec{B}$, is

$$F = IlB_{\perp} = IlB\sin\phi.$$

The force is always perpendicular to both the conductor and the field with the direction determined by the same right-hand rule that we used for a moving positive charge.

6 Force and Torque on a Current Loop

Torque on a current-carrying loop

When a conducting loop with area A carries a current I in a uniform magnetic field of magnitude B, the torque exerted on the loop by the field is

$$\tau = IAB\sin\phi,$$

where ϕ is the angle between the normal to the loop and $\vec{B}$.

The torque τ tends to rotate the loop in the direction of decreasing ϕ–that is, toward its stable equilibrium position, in which $\phi = 0$ and the loop lies in the $x-y$ plane, perpendicular to the direction of the field $\vec{B}$. The product IA is called the ***magnetic moment*** of the loop, denoted by μ:

$$\mu = IA.$$

solenoid: helical winding of wire, such as a coil wound on a circular cylinder.

7 Magnetic Field of a Long, Straight Conductor

Magnetic field of a long, straight wire

The magnetic field $\vec{B}$ produced by a long, straight conductor carrying a current I, at a distance r from the axis of the conductor, has magnitude B given by

$$B = \frac{\mu_0 I}{2\pi r}.$$

In this equation, μ_0 is a constant called the ***permeability of vacuum***. Its numerical value depends on the system of units we use. In SI units, the units of μ_0 are (T · m/A). Its numerical value, which is related to the definition of the unit of current is defined to be exactly $4\pi \times 10^{-7}$:

$$\mu_0 \times 10^{-7}\mathrm{T \cdot m/A}.$$

A useful relationship for checks of unit consistency is 1 T · m/A = 1 N/A^2.

This μ is NOT the magnetic moment encountered earlier that was also denoted with μ.

8 Force between Parallel Conductors

Definition of the ampere

The forces that two straight, parallel conductors exert on one another form the basis for the official SI definition of the **ampere**, as follows: One ampere is that unvarying current which, if present in each of two parallel conductors of infinite length and 1 meter apart in empty space, causes a force of exactly 2×10^{-7} newtons per meter of length on each conductor. The definition is consistent with the definition of the constant μ_0 as exactly $4\pi \times 10^{-7}\mathrm{N/A^2}$.

9 Current Loops and Solenoids

solenoid: a helical winding of wire, usually wound around the surface of a cylindrical form.

Magnetic field at center of circular loop

$$B = \frac{\mu_0 I}{2R} \text{ center of circular loop.}$$

If we have a coil of N loops instead of a single loop, and if the loops are closely spaced and all have the same radius, then each loop contributes equally to the field, and the field at the center is just N times the previous equation:

$$B = \frac{\mu_0 N I}{2R} \text{ center of } N\text{circular loops.}$$

10 Magnetic Field Calculations

source point: the source of the field.
field point: the point where we wish to measure the field.

Law of Biot and Savart

The magnitude ΔB of the magnetic field $\Delta\vec{B}$ due to a segment of conductor with length Δl, carrying a current I is given by

$$\Delta B = \frac{\mu_0}{4\pi}\frac{I\Delta l\sin\theta}{r^2}.$$

Ampère's law

When a path is made up of a series of segments Δs, and when that path links conductors carrying total current $I_{enclosed}$,

$$\sum B_{||}\Delta s = \mu_0 I_{enclosed}.$$

11 Magnetic Materials

paramagnetic: materials that in the presence of an external magnetic field, the current loops in the material become oriented preferentially with the field so that their magnetic fields add to the external field; thus the material is *magnetized*.
relative permeability: denoted K_m; the additional magnetic field in a paramagnetic material than would be measured in a vacuum; for a given material, K_m depends on temperature.
permeability of a material: $\mu = K_m\mu_0$
diamagnetic: materials that have *no net* atomic current loops, but in an external field the loops are distorted in the *opposite* direction to the field.
susceptibility: defined as $K_m - 1$ (the permeability minus one)
ferromagnetic: strong interactions between microscopic current loops cause the loops to line up parallel to each other in regions called ***magnetic domains***, even when no external field is present.
saturation magnetization: in ferromagnetic materials, as the external field increases, a point is reached at which nearly all the microscopic current loops have their axes parallel to that field.
permanent magnets: materials that retain their magnetization in the absence of an external magnetic field.

12 Links

National High Magnetic Field Laboratory
Mathematica Demonstrations: A Simple Model of Magnetization Mathematica Demonstrations: Magnetic Field of a Bar Magnet
Mathematica Demonstrations: Magnetic Field of a Current Loop
Mathematica Demonstrations: The earth's Magnetosphere
Mathematica Demonstrations: Magnet Types in Particle Accelerators