Physics 202, Lecture 11

Today’s Topics

- Magnetic Fields and Forces (Ch. 27)
  - Magnetic materials
  - Magnetic forces on moving point charges
  - Magnetic forces on currents, current loops
  - Motion of charge in uniform B field

Thurs: applications (cyclotron, velocity selector, Hall effect)
Magnetism: Overview

Previously: electrostatics

- Forces and fields due to stationary charges
- Coulomb force $F_E$, Electrostatic field $E$:
  $$\vec{F}_E = q\vec{E}$$

Now: magnetism (magnetostatics)
(historically: magnetic materials, Oersted effect)

- Forces and field due to moving charges (currents)
- Magnetic Force $F_B$, magnetic field $B$:
  $$\vec{F}_B = qv \times \vec{B}$$ (charges: Lorentz force)
  $$\vec{F}_B = \int I d\vec{l} \times \vec{B}$$ (currents)
Magnetic Materials (1)

Focus first on bar magnets (permanent magnets):
Two types of poles: N and S

Magnetic forces: like poles repel, opposite poles attract

Magnetic field: $B$ (vector field).
Units: 1 Tesla (T) = 1 N/(A m)

Direction: as indicated by compass’s “north” pole

Field lines:
Outside magnet: N to S
Inside magnet: S to N
**Typical Magnetic Field Strengths**

**Some Approximate Magnetic Field Magnitudes**

<table>
<thead>
<tr>
<th>Source of Field</th>
<th>Field Magnitude (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong superconducting laboratory magnet</td>
<td>30</td>
</tr>
<tr>
<td>Strong conventional laboratory magnet</td>
<td>2</td>
</tr>
<tr>
<td>Medical MRI unit</td>
<td>1.5</td>
</tr>
<tr>
<td>Bar magnet</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Surface of the Sun</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Surface of the Earth</td>
<td>$0.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Inside human brain (due to nerve impulses)</td>
<td>$10^{-13}$</td>
</tr>
</tbody>
</table>

**1 Gauss = $10^{-4}$ Tesla**
Electrostatics analogy:

- Electric Field Lines of an Electric Dipole
- Magnetic Field Lines of a bar magnet

dipole field!
Magnetic Monopoles

Perhaps there exist magnetic charges, just like electric charges: magnetic monopole (+ or - magnetic charge).

How can you isolate this magnetic charge?

Try cutting a bar magnet in half:

Even an individual electron has a magnetic “dipole”!

Despite extensive searches, magnetic monopoles have never been found!

\[ \oint B \cdot d\vec{A} = 0 \quad \text{(compare Gauss’s Law)} \]
Bar Magnets and Compass

Recap: 2 magnetic poles, N and S
- like poles repel, opposite poles attract
- both poles attract iron (ferromagnetic material)
- Two poles not separable

Compass: a bar magnet
- Its “north” pole (conventionally defined) points towards the northern direction

Magnets | Modern compasses | An ancient Chinese compass (~220BC)
Earth’s Magnetic Field

South Magnetic Pole

Geographic North Pole

The Earth’s Magnetic Field

Geographic South Pole

South Magnetic Pole

North Magnetic Pole

Geographic North Pole

11.5°
Magnetic Force

We know about the existence of magnetic fields by the force they exert on moving charges.

What is the "magnetic force"?
How is it distinguished from the "electric" force?

Experimental observations about the magnetic force $F_B$:

a) magnitude: $\propto$ to velocity of $q$

b) direction: $\perp$ to direction of $q$’s velocity

c) direction: $\perp$ to direction of $B$

$B$ is the magnetic field vector
Magnetic Force

Force $F$ on charge $q$ moving with velocity $v$ through region of space with magnetic field $B$:

$$\vec{F} = q\vec{v} \times \vec{B}$$

If also electric field $E$: Lorentz Force Law

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$
Cross product review (board):
- direction: “right hand rule”
- magnitude: \[ F = q\vec{v} B \sin \theta \]
Exercise: Direction of Magnetic Force

Indicate the direction of $\mathbf{F}_B$ in the following situations:

(a) $\mathbf{B}$ out of page:

(b) $\mathbf{B}$ into page:
Question: Direction of Magnetic Force

Which fig has the correct direction of $\mathbf{F}_B$?
Question: Direction of Magnetic Force

Which fig has the correct direction of $\mathbf{F}_B$?
Now you know how a single charged particle moves in a magnetic field. What about a group?

In a portion of current-carrying conducting wire:

\[ F_B = nA dl (q \vec{v}_d \times \vec{B}) = I d\vec{l} \times \vec{B} \]

\[ \Rightarrow I \int d\vec{l} \times \vec{B} = I \vec{L} \times \vec{B} \]

(for uniform field)

Text: 27.7
Magnetic Force On A Current Carrying Wire (2)

Top View

(a) 

(b) $I = 0$

(c) $I$

(d) $I$

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Magnetic Force On Current Carrying Wire (3)

For a **uniform** magnetic field:

To get the sum of a number of vectors - put them all head to tail and connect the initial \((a)\) and final point \((b)\):

\[
\int_{a}^{b} d\vec{l} = \vec{L}_{ba}
\]

If the initial and final points are the same, the integral is **zero**!

There is **no net magnetic force** on a **closed current loop** in a uniform magnetic field.

Text example: 27.9
Suppose charge $q$ enters a uniform $B$-field with velocity $v$. What will be the path that $q$ follows?

Force perpendicular to velocity: uniform circular motion

Note: magnetic force does no work on the charge!
Kinetic energy constant
Trajectory in Constant B Field (2)

- **Force:**
  \[ F = qvB \]

- **centripetal acc:**
  \[ a = \frac{v^2}{R} \]

- **Newton's 2nd Law:**
  \[ F = ma \quad \Rightarrow \quad qvB = m \frac{v^2}{R} \]

  \[ \Rightarrow \quad R = \frac{mv}{qB} = \frac{p}{qB} \]

  **“Cyclotron” frequency:**
  \[ \omega = \frac{v}{R} = \frac{qB}{m} \]
Motion Of Charged Particle in a Uniform $\mathbf{B}$ Field – General 3D Case

- In the plane perpendicular to $\mathbf{B}$:
  - $r = \frac{mv_{\perp}}{qB}$
  - $T = \frac{2\pi m}{qB}$

- Parallel to $\mathbf{B}$, spacing between helix
  - $d = \frac{v_{\parallel}T}{2\pi m/qB}$
The drawing shows the top view of two interconnected chambers. Each chamber has a unique magnetic field. A positively charged particle fired into chamber 1 follows the dashed path shown in the figure.

What is the direction of the magnetic field in chamber 1?

a) Up  
b) Down  
c) Left  
d) Right  
e) Into page  
f) Out of page
Question 4

What is the direction of the magnetic field in chamber 2?

a) Up  

b) Down  
c) Left  
d) Right  
e) Into page  
f) Out of page

Which field is larger, $B_1$ or $B_2$?

Text examples: 27.19, 26, 30
Forces on a Current Loop

For current loops in a uniform magnetic field as shown, what is the direction of the force on each side?

Case 1

recall: $\Sigma F_B = 0$

Case 2

$F_B = 0$
Torque on Current Loop in Uniform B Field

Though the net magnetic force on a closed current loop in a uniform B field is zero, there can be a net torque.

Loop has length dimension $a$ (normal to $B$), width $b$.

Case 1:

$$\tau = 2F \frac{b}{2} \sin \theta = I ab B \sin \theta$$

$$\vec{\tau} = I \vec{A} \times \vec{B}$$

Define the magnetic moment $\bar{\mu} \equiv I \vec{A}$

$$\vec{\tau} = \bar{\mu} \times \vec{B}$$

More general:

Define the magnetic moment $\bar{\mu} = NI \vec{A}$ (N turns)
Magnetic Dipole Moments

Magnetic dipole moment $\mu$.

Macroscopic
$\mu = IA$

Microscopic
$\mu \propto L$

angular momentum of orbiting or spin

definition of magnetic moment

$\sum F = 0$

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

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

$\mu$ in B Field