Magnetic Materials

Chapter 32:
- **Induced Electric Fields**
- **Maxwell's Equations**
- **Magnetic Materials**

Thursday: Exam #2
Electrodynamics: Chapters 26-32

Magnetic Materials

- **Three main classes of magnetic materials:**
  - **Ferromagnetic (includes permanent magnets)**
  - **Paramagnetic**
  - **Diamagnetic**
- **Key quantity is the** *magnetization*, **defined as the** *density of dipole moments*.

$$\vec{M} = \vec{\mu}/(Volume)$$

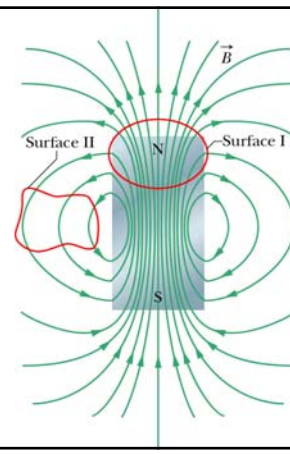
Gauss's Law for Magnetism

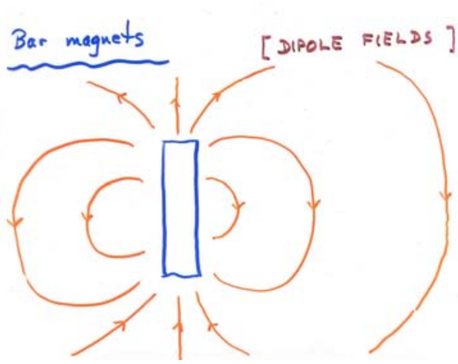
- **Given any *closed* surface**
- **Outward *electric* flux = enclosed charge**
- **Outward *magnetic* flux = *zero.***
- **"There are no magnetic monopoles."**
- **This is Maxwell Equation #2:**

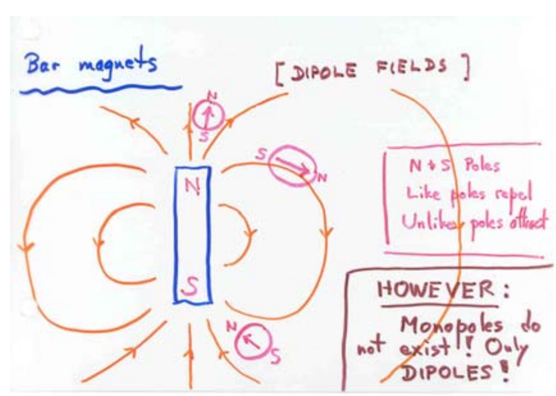
$$\oint \vec{B} \cdot d\vec{A} = 0$$

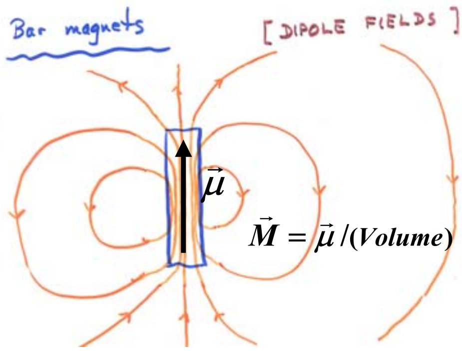
Bar magnet

Possible closed Gaussian surfaces shown in red. Zero net outward flux in both cases.

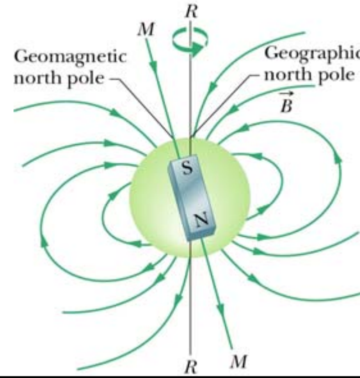








Magnetic Field of Earth



Approximately a dipole field.

Q.32-1

What can you say about the vertical component of the earth's magnetic field in North America?

(1) It is upward (2) It is downward (3) It is zero

Q.32-1

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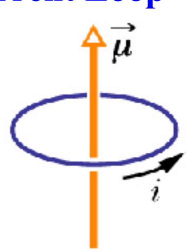
Review: Dipole Moment of Current Loop

Definition: ***Magnetic dipole moment vector:*** $\vec{\mu}$

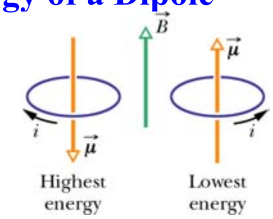


- Direction: ***RH rule***
- Magnitude: $\mu = iA$

Analogous to electric dipole moment vector $\vec{p}$

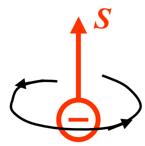
Review: Potential Energy of a Dipole

Work required to turn dipole moment ***against*** the field.



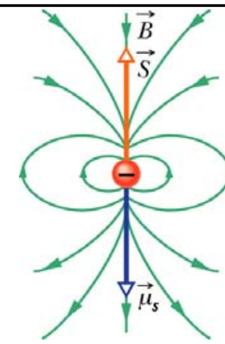
$$U = -\vec{\mu} \cdot \vec{B}$$

Electron spin



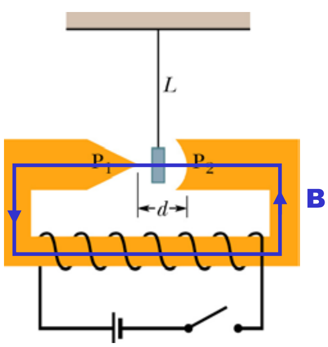
- Electrons have spin as an intrinsic quality. There are no non-spinning electrons.
- This gives an angular momentum vector $\vec{S}$
- This corresponds to right-hand rotation about S as shown.

Electron Magnetic Dipole



- **Electron spin creates a magnetic dipole just as if it were a tiny current loop.**
- **Negative charge means dipole momentum vector points opposite to the spin angular momentum vector.**
- **Text figure shows the resulting magnetic field.**

Materials in an External Field



Place sample in external magnetic field. Measure its magnetization.

Paramagnetism

$$\vec{M} = (C/T)\vec{B}_{ext}$$

1. The magnetization is ***parallel*** to an applied field. Interior field is ***strengthened***.
2. Curie Law: Thermal and magnetic forces compete. As temperature goes up, magnetization goes down.

Diamagnetism

$$\vec{M} \propto -\vec{B}_{ext}$$

Dipoles align themselves ***opposite*** to the applied field. Field inside is ***weakened.*** (Like a dielectric material.)

Text gives explanations in terms of electron currents inside atoms. We won't worry about that.

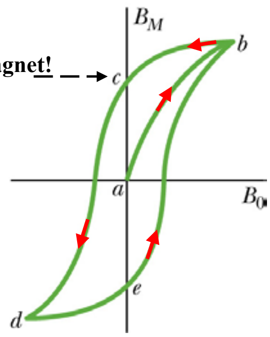
Ferromagnetism

$$\vec{M} \not\propto \vec{B}_{ext}$$

- The basic dipole moments responsible for ferromagnetism are the ***electron spins.***
- In a ***permanent magnet,*** dipoles align themselves ***spontaneously,*** due to their interactions with each other.
- In an ***applied field***, dipoles tend to line up ***with*** the applied field, but a ferromagnet shows the phenomenon of ***hysteresis:*** $\boldsymbol{M}$ is not determined just by the present value of $\boldsymbol{B}_{ext}$, but by the history of $\boldsymbol{B}_{ext}$.

Hysteresis Loop

Permanent magnet!



Q.32-2

- In techniques such as MRI and NMR, the magnetic properties of spinning *protons* may be detected.
- How should the proton's magnetic dipole moment vector be related to its angular momentum vector?

(1) Parallel (2) Anti-parallel (3) Perpendicular

Q.32-2

How should the proton's magnetic dipole moment vector be related to its angular momentum vector?

Because the proton has a positive charge, its spin angular momentum and magnetic dipole moment are parallel.

(1) Parallel (2) Anti-parallel (3) Perpendicular

Example: Problem 32-45

The saturation magnetization M_{max} of nickel is 4.7×10^5 A/m. Calculate the magnetic moment of a single nickel atom.

Remember the definition of M:

$$M = \frac{dipole}{volume} = \frac{atoms}{volume}\frac{dipole}{atom}$$

First find the number of atoms per unit volume.

Example (cont'd)

$$\frac{atoms}{volume} = \frac{mass/volume}{mass/atom}$$

$$\frac{mass}{volume} = (density) = 8.90\ g/cm^3$$

$$\frac{mass}{atom} = \frac{mass}{nucleon}\frac{nucleons}{atom} = \left(1g/6\times10^{23}\right)(59) = 9.8\times10^{-23}\ g$$

So:

$$\frac{atoms}{volume} = \frac{8.9\ g/cm^3}{9.8\times10^{-23}\ g/atom} = 0.91\times10^{23}\ atoms/cm^3$$

$$= 0.91\times10^{23}\frac{atoms}{cm^3}10^6\frac{cm^3}{m^3} = 0.91\times10^{29}\frac{atoms}{m^3}$$

Example (cont'd)

The saturation magnetization M_{max} of nickel is 4.7×10^5 A/m. Calculate the magnetic moment of a nickel atom.

$$\mu = \frac{dipole}{atom} = \frac{dipole/volume}{atoms/volume}$$

$$\mu = \frac{4.7\times10^5\ A/m}{0.91\times10^{29}\ /m^3} = \underline{5.2\times10^{-24}\ Am^2}$$

Summary: 3 kinds of materials

- **Paramagnetic:** $\vec{M} = +(const)\,\vec{B}_{ext}$
- **Diamagnetic:** $\vec{M} = -(const)\,\vec{B}_{ext}$
- **Ferromagnetic:** $\vec{M} \neq (const)\,\vec{B}_{ext}$

$\vec{M}$ {
Depends on history.
Spins align with each other.
May be very strong.