October 27th

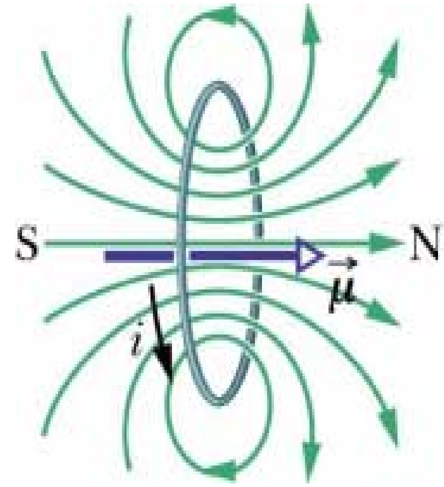
Chapter 32

Magnetism of Matter

Midterm-2

- Wednesday October 29 at 6pm
  - Section 1 – N100 BCC (Business College)
  - Section 2 – 158 NR (Natural Resources)
- Allowed one sheet of notes (both sides) and calculator
- Covers Chapters 27-31 and homework sets #5-8
- Send an email to your professor if you have a class conflict and need a make-up exam
- Review in class on Tuesday, October 28th

Magnetism



- Orbital motion of electrons around nucleus generates magnetic dipoles
- Electrons have 2 types of magnetic dipoles:
  - Spin magnetic dipole (intrinsic to electron)
  - Orbital magnetic dipole (due to motion of electron around the nucleus)
  - Full explanation needs quantum physics
- In some materials the magnetic dipoles all cancel so no net *B* field
- In permanent magnets the dipoles are oriented in same direction giving net *B* field

Magnetism

- 3 types of magnetism (from weakest to strongest):
- **Diamagnetism**
  - Exhibited by all common materials but masked if other two types of magnetism are present
- **Paramagnetism**
  - Exhibited by materials containing transition, rare earth or actinide elements
- **Ferromagnetism**
  - Property of iron, nickel and a few other elements
  - Strongest type of magnetism

Diamagnetism

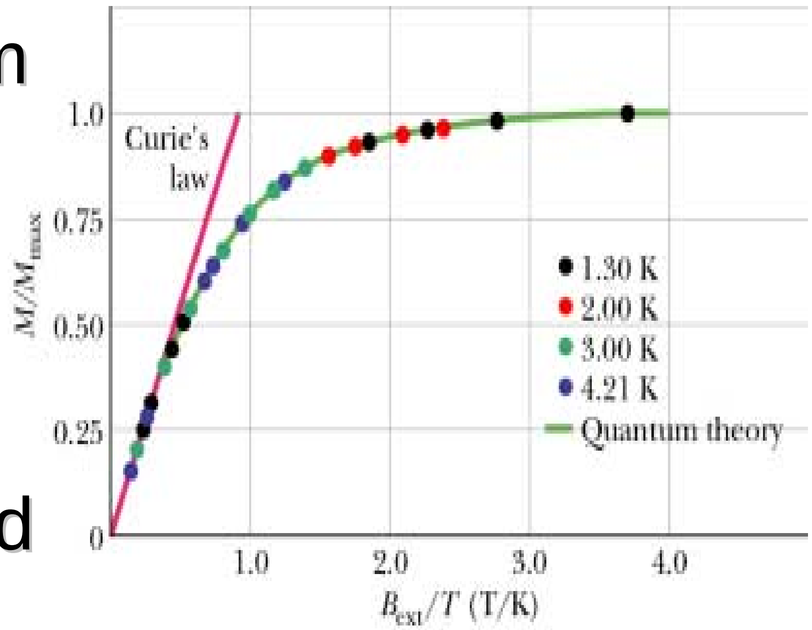
- Atoms in diamagnetic materials lack a net magnetic dipole moment
- If external B field present, induce a weak net B field in material directed opposite to B_{ext}
- Dipole moments and their net B field disappear when B_{ext} is removed
- Organic material (animals, humans) exhibit diamagnetism (picture in the book of a floating frog)

Paramagnetism

- Each atom has a permanent net magnetic dipole moment from spin and orbital dipole moments of its electrons
- Atomic dipole moments are randomly oriented so material has no net magnetic field
- If B_{ext} present, partially align the atomic dipole moments giving the material a net B_M field in the direction of B_{ext}
- The dipole alignment and their net B field disappear when B_{ext} is removed

Paramagnetism

- Stronger than diamagnetism
- Random collisions of atoms due to thermal agitation prevent total alignment of atomic dipoles thus weakening material's *B* field
- Curie's law relates magnetization, *M*, of sample to B_{ext} and temperature, *T*
  - Only valid when ratio B_{ext}/T is not too large



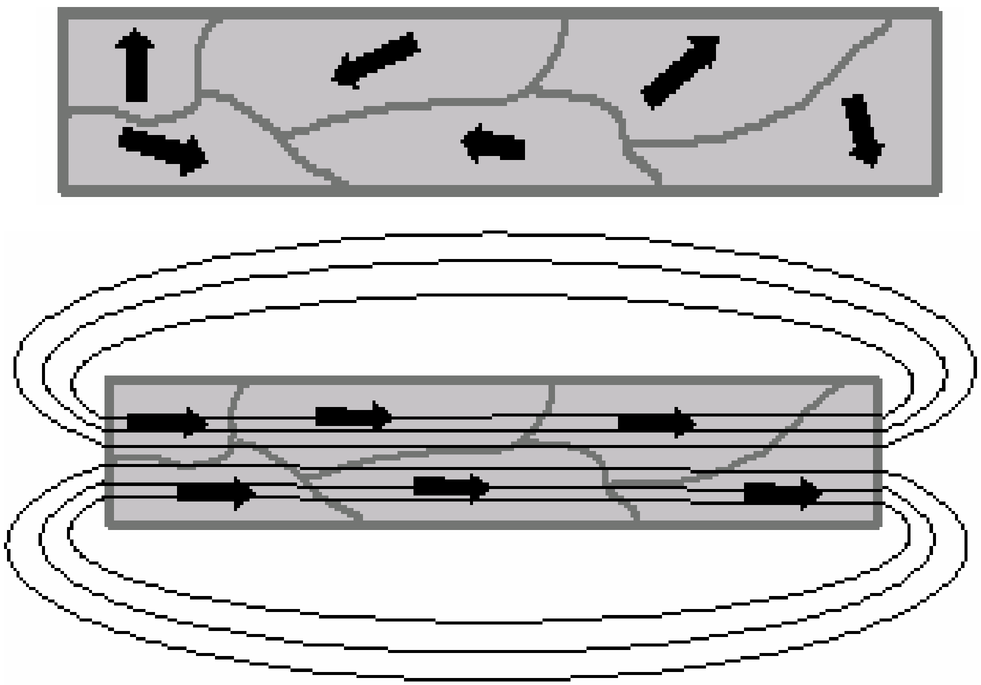
$$M = C\frac{B_{ext}}{T}$$

Ferromagnetism

- Electron spins of one atom in the material interact with those of neighboring atoms
- Process of exchange coupling causes alignment of magnetic dipole moments of the atoms despite thermal agitations
- Persistent alignment gives material its permanent magnetism
- If coupling produces strong alignment of adjacent atomic dipoles, why aren't all pieces of iron strong magnets?

Ferromagnets

- Generally material's magnetic domains are oriented randomly and effectively cancel each other out



- If B_{ext} applied, domains align giving a strong net B field in same direction as B_{ext}
- Net B field partially exists even when B_{ext} is removed
- Above a critical temp, the Curie temp, exchange coupling no longer works and the magnetic properties go away
  - For iron this is 1043 K (770 C)

Ferromagnets

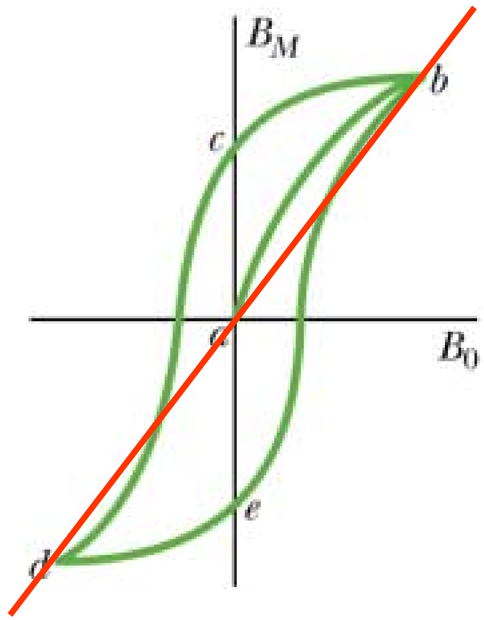
- If we place ferromagnetic material (e.g. iron) inside a solenoid with field B_0, increase the total B field inside coil to

$$B = B_0 + B_M \qquad B_0 = \mu_0 i n$$

- B_M is magnitude of B field contributed by iron core
  - Result of alignment of atomic dipoles within iron due to exchange coupling and external B_0 field
- B_M increases total B by large amount
  - Iron core inside solenoid increases B by typically about 5000 times
- For the electromagnetic core we use "soft" iron where the magnetism is not permanent (goes away when the external field is turned off).

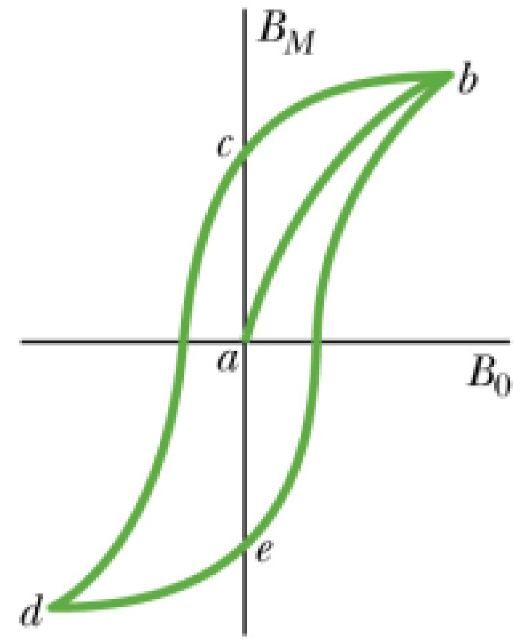
Ferromagnets

- If we increase and then decrease external field, B_0, the magnetization curves for "permanent" magnets are not the same
- Lack of retraceability is called hysteresis
- Change of magnetic domains orientations are not totally reversible, retain some memory of their alignment
- This is the origin of the permanent magnet
- Red line represents how "soft" iron behaves
  - Magnetism is not permanent – it goes away when the external field B_0 is turned off).



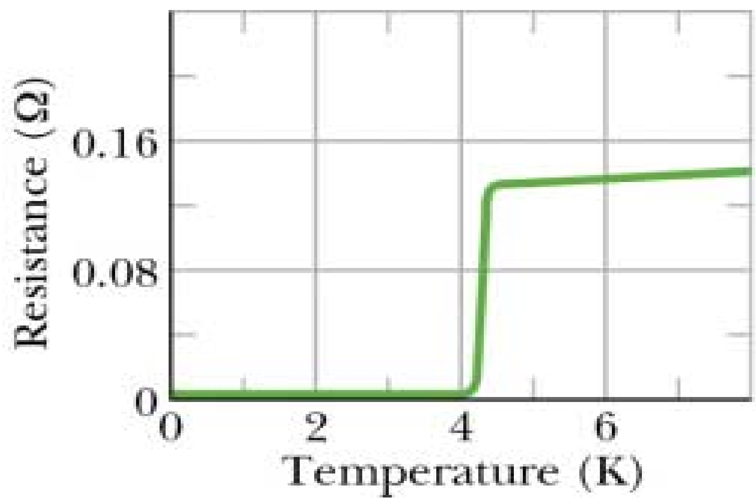
Ferromagnets

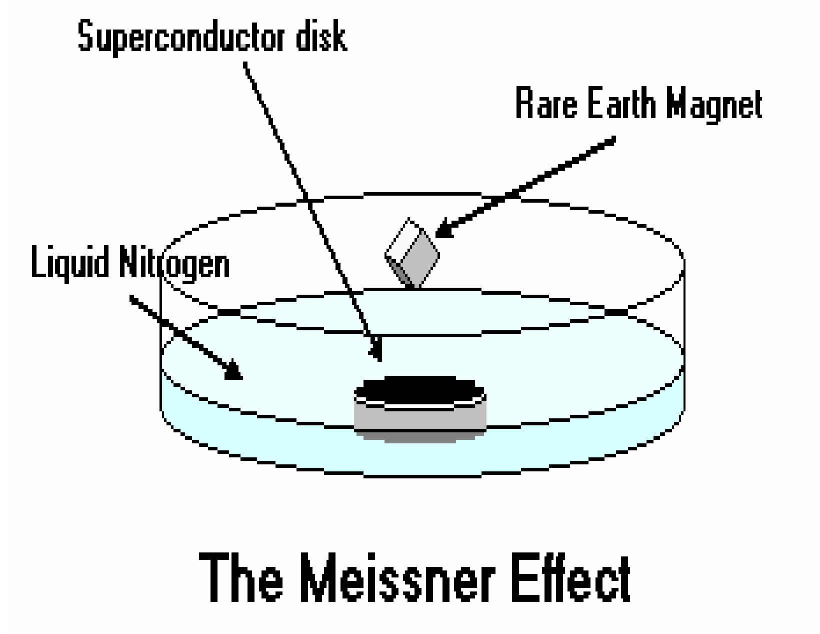
- We can destroy a magnet by putting it in an oscillating external field – decreases the hysteresis loop until $B_M = 0$
- We can change the direction of a “permanent” magnet
- Natural magnets or lodestones – are made by the magnetic fields set up when lightening strikes the ground



Magnetism

- Superconductor – a material whose resistance disappears at very low temperatures
- Collisions of electrons in material are suppressed
- Meissner effect – superconducting materials repel all magnetic fields (extreme diamagnetism) and will cause a magnet to float





Review

- 3 types of magnetism (weakest to strongest):
  - Diamagnetism
  - Paramagnetism
  - Ferromagnetism
- Explain how materials exhibit different types of magnetism using electron's spin and orbital magnetic dipole moments
- Placing material in an external B field causes dipole moments to align creating an induced B field
- Degree of alignment determines type of magnetism and amount of magnetization

Maxwell’s Equations

- Basis of all electrical and magnetic phenomena can be described by 4 equations called Maxwell’s equations
- As fundamental to electromagnetism as Newton’s law are to mechanics
- Einstein showed that Maxwell’s equations work with special relativity
- Maxwell’s equations basis for almost everything studied in PHY184

Gauss's Law

- Gauss's law for *E* fields

$$\Phi_E = \oint \vec{E} \bullet d\vec{A} = \frac{q_{enc}}{\varepsilon_0}$$

- Gauss's law for *B* fields

$$\Phi_B = \oint \vec{B} \bullet d\vec{A} = 0$$

- Both cases integrate over closed Gaussian surface

Faraday's Law

- Faraday's law of induction
  E field is induced along a closed loop by a changing magnetic flux encircled by that loop

$$\oint \vec{E} \bullet d\vec{s} = -\frac{d\Phi_B}{dt}$$

- Is the reverse true?
- Maxwell's law of induction
  B field is induced along a closed loop by a changing electric flux in region encircled by loop

$$\oint \vec{B} \bullet d\vec{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$$

Ampere-Maxwell Law

- Ampere's law $$\oint \vec{B} \bullet d\vec{s} = \mu_0 i_{enc}$$
- Combine Ampere's and Maxwell's law
$$\oint \vec{B} \bullet d\vec{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i_{enc}$$
- *B* field can be produced by a current and/or a changing *E* field
  - Wire carrying constant current, $d\Phi_E/dt = 0$
  - Charging a capacitor, no current so $i_{enc} = 0$

Maxwell's Equations

- Gauss' Law $$\oint \vec{E} \bullet d\vec{A} = \frac{q_{enc}}{\varepsilon_0}$$
- Gauss' Law for magnetism $$\oint \vec{B} \bullet d\vec{A} = 0$$
- Faraday's Law $$\oint \vec{E} \bullet d\vec{s} = -\frac{d\Phi_B}{dt}$$
- Ampere-Maxwell Law $$\oint \vec{B} \bullet d\vec{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i_{enc}$$