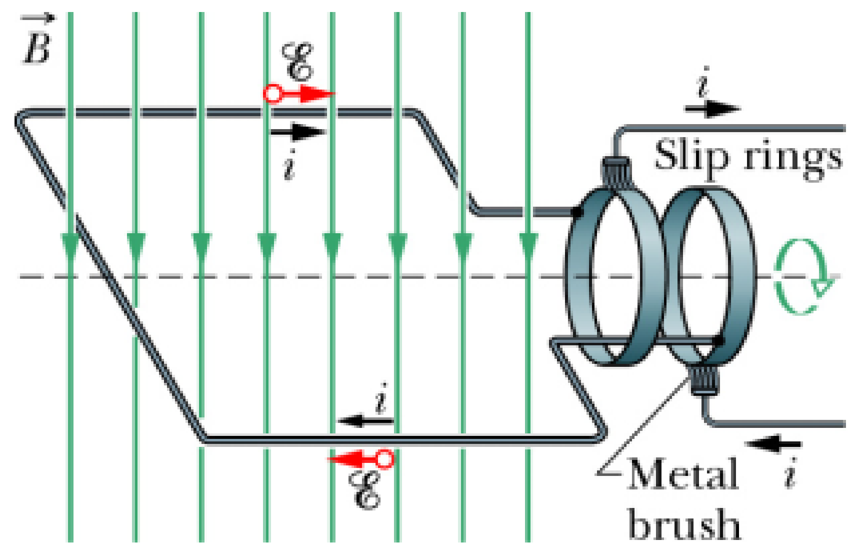
Lecture 26

Chapter 32

Magnetism of Matter

Review

- Generators and motors



- Maximum emf of an ac rotating at ω

$$E_{max} = NBA\omega$$

- Eddy currents occur in pieces of metal and act as a retarding force to the external *B* field

Review

- Generate *B* field from current
- Biot-Savart law

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{i d\vec{s} \times \vec{r}}{r^3}$$

- Ampere's Law

$$\oint \vec{B} \bullet d\vec{s} = \mu_0 i_{enc}$$

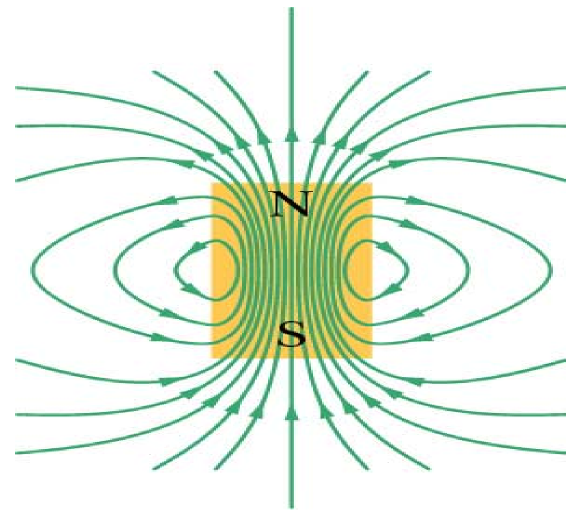
- What about permanent magnets?

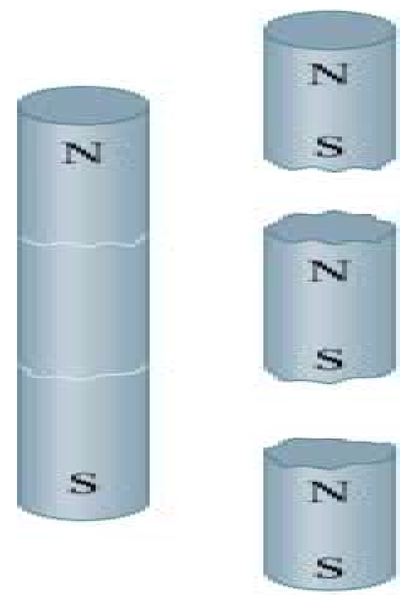
Magnetism (1)

- What makes some materials magnetic?

- Magnets are magnetic dipoles - have north and south pole
- Break magnet still have magnetic dipoles

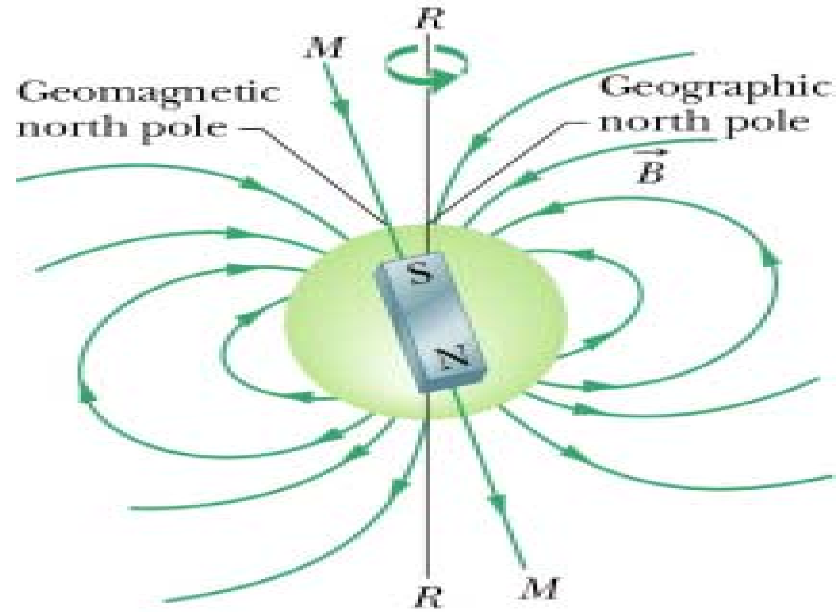
- Magnetic monopoles do not exist

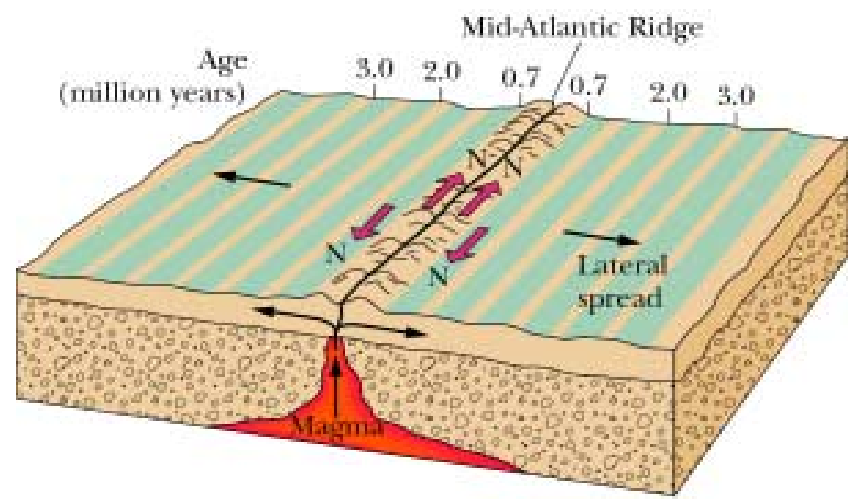




Magnetism (2)

- Earth acts as huge bar magnet
- Geomagnetic pole at angle of 11.5 degrees from rotational axis
- North pole is actually south pole of Earth’s magnetic dipole
- Polarity has reversed about every million years





Magnetism (3)

- Electrons moving (a current) set up *B* fields
- Electrons also responsible for *B* fields of magnetic materials

- Electrons have 2 types of magnetic dipoles:
  - Spin magnetic dipole
  - Orbital magnetic dipole

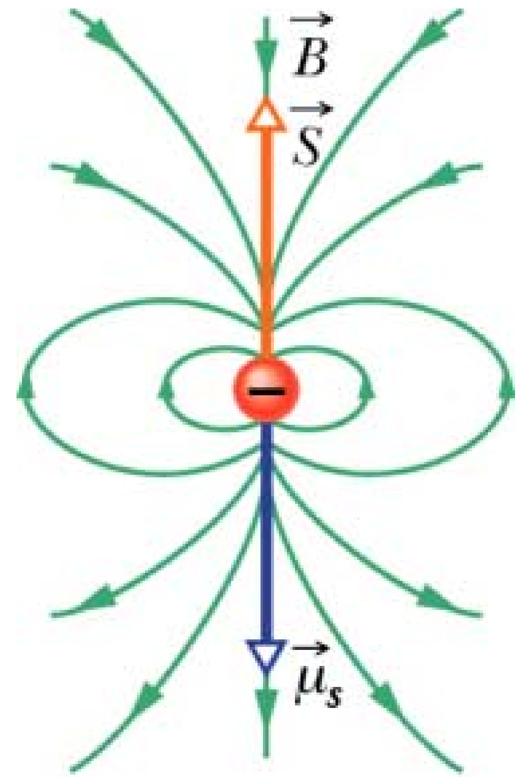
- Full explanation needs quantum physics

Magnetism (4)

- Electron has intrinsic spin, *S*, angular momentum
- *S* is quantized – has only a few discrete values
- Its component along any direction is given by

$$S_z = m_s \frac{h}{2\pi}$$

$$m_s = \pm\frac{1}{2}$$



- m_S is spin magnetic quantum number
- $+m_S$ called spin up
- $-m_S$ called spin down

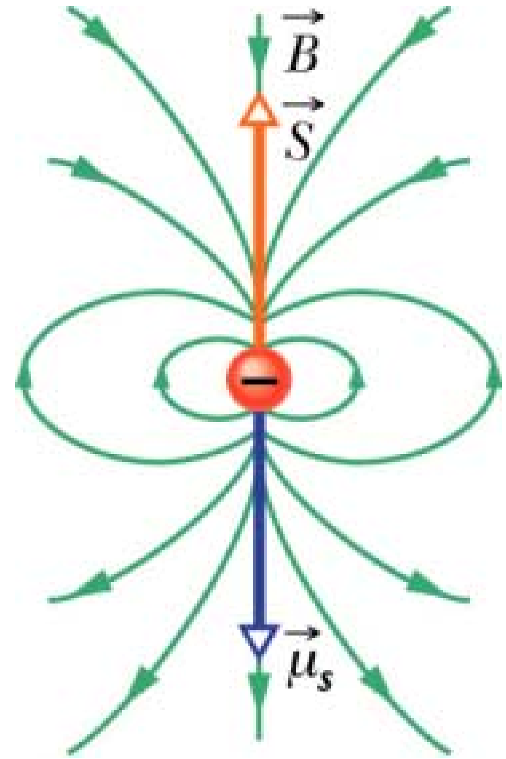
Magnetism (5)

- spin magnetic dipole moment, μ_S is associated with spin by

$$\mu_{s,z} = -\frac{e}{m} S_z$$

- Minus sign means opposite direction of spin
- Potential energy of an electron in external *B* field is associated with spin magnetic dipole moment

$$U = -\vec{\mu}_S \bullet \vec{B}_{ext}$$



Magnetism (6)

- Inside an atom, an electron has orbital angular momentum, L_{orb}
- L_{orb} is quantized
- Its component along any direction is given by

$$L_{orb,Z} = m_l \frac{h}{2\pi}$$

$$m_l = 0, \pm 1, \pm 2, \ldots, \pm(\text{limit})$$

- m_l is orbital magnetic quantum number

Magnetism (7)

- orbital magnetic dipole moment, μ_{orb} is associated with orbital angular momentum

$$\mu_{orb,Z} = -\frac{e}{2m} L_{orb,Z}$$

- Minus sign means opposite direction of Lorb
- Potential energy of an atom in external *B* field is associated with orientation of the orbital magnetic dipole moment of each electron in the atom

$$U = -\vec{\mu}_{orb} \bullet \vec{B}_{ext}$$

Magnetism (9)

- 3 types of magnetism:
- 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

Magnetism (10)

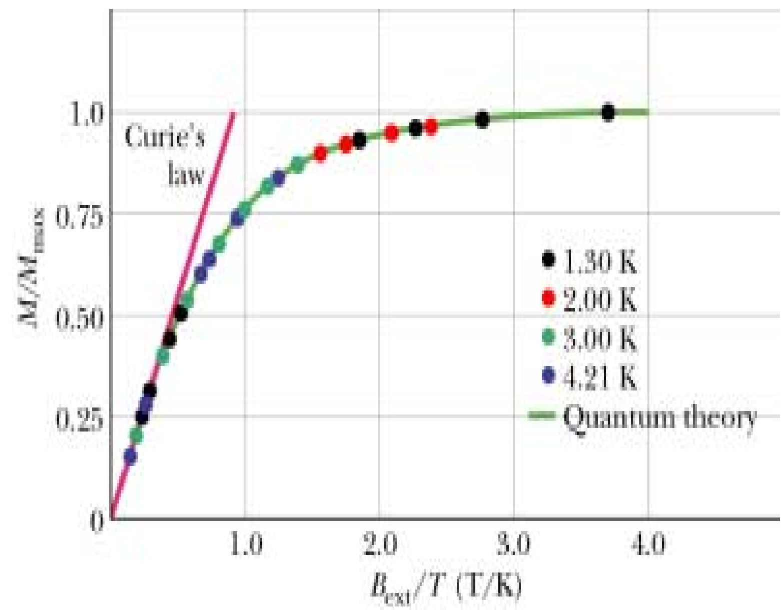
- Diamagnetism
  - Atoms in material lack net magnetic dipole moment
  - If external *B* field present, induce a weak net *B* field in material directed opposite B_{ext}
  - Dipole moments and their net *B* field disappear when B_{ext} is removed
  - Organic material (animals, humans) exhibit diamagnetism

Magnetism (11)

- 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 field in the direction of B_{ext}
  - The dipole alignment and their net B field disappear when B_{ext} is removed

Magnetism (12)

- 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 not too large



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

Magnetism (13)

- 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
  - Above a critical temperature, the Curie temperature, exchange coupling no longer works and material becomes only paramagnetic

Magnetism (14)

- Ferromagnetism
  - If exchange coupling produces strong alignment of adjacent atomic dipoles, why aren't all pieces of iron strong magnets?
  - Material made up of several magnetic domains, each domain has atomic dipoles aligned
  - As a whole the 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

Magnetism (15)

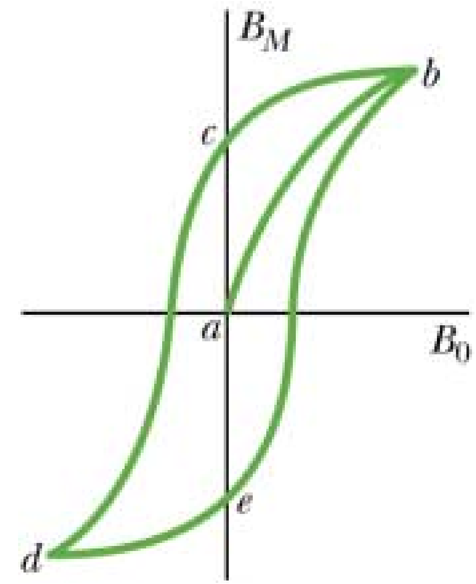
- Ferromagnetism
  - If place ferromagnetic material (e.g. iron) inside a solenoid, increase the *B* field inside coil

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

  - B_M is magnitude of *B* field contributed by iron core
  - B_M result of alignment of atomic dipole moments within the 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 5000 times

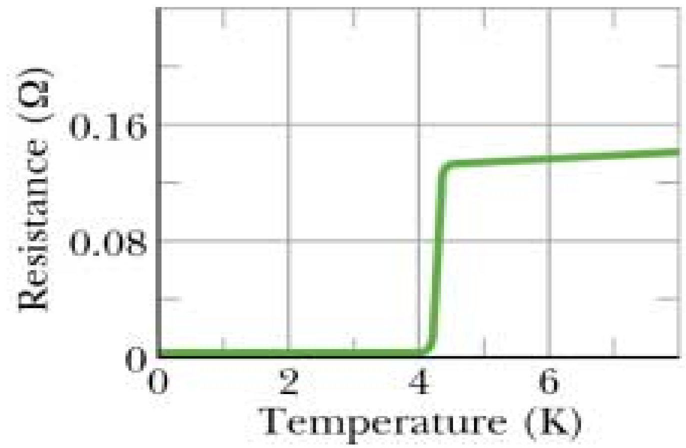
Magnetism (16)

- Ferromagnetism
  - If increase and then decrease external *B* field, B_0, the magnetization curves for iron 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
  - Used for magnetic storage of information on tapes, cds, etc



Magnetism (17)

- Superconductor – a material whose resistance disappears at very low temperatures
- Collisions of electrons in material are suppressed
- Explain effect using Cooper pairs (pairs of electrons)
- Doesn't explain high-temp superconductors
- Purely quantum effect



- Meissner effect – in a small B_{ext} field, a superconductor will exclude all B fields from within its bulk