Magnetism and Spintronics: 1

11/22/2005

Definitions

B:

• magnetic induction (usually means by magnetic field).

• most physically significant quantity - what shows up in Lorentz force law, in determining NMR frequencies, etc.

• Unit is the Tesla. Earth's magnetic field = 6×10^{-5} T.

• More convenient cgs unit is the Gauss = 10^{-4} T.

• Important boundary condition: $\nabla \cdot \mathbf{B} = 0$

Definitions in SI

H:

- the magnetic field.
- Caused by currents of *free* charge.
- Unit is the Amp/m.
- Important relation: $\nabla \times \mathbf{H} = \mathbf{J}$
- With no magnetic materials around, $\mathbf{B} = \mu_0 \mathbf{H}$

"permeability of free space" = $4\pi \times 10^{-7}$ Tm/A

M:

- the magnetization.
- magnetic moment per unit volume of a material.
- Unit is the Amp/m.
- For a material with a permanent magnetization $\boldsymbol{M}_0$,

$$\mathbf{M} = \chi \mathbf{H} + \mathbf{M}_0$$

magnetic susceptibility

Susceptibility and permeability

Combining effects of external currents and material response,

$$\mathbf{B}=\mu_0(\mathbf{H}+\mathbf{M})$$

We define the *permeability* by: $\mathbf{B} = \mu\mathbf{H}$

So, for a material with a magnetic susceptibility χ,

$$\mathbf{B}=\mu\mathbf{H}=\mu_0(1+\chi)\mathbf{H}$$

$$\longrightarrow \quad \mu=\mu_0(1+\chi)$$

Note that for real materials χ and μ are tensorial.
Relative permeability is defined as $\mu_r = \mu/\mu_0$. $\longrightarrow$ $\mathbf{B}=\mu_0\mu_r\mathbf{H}$

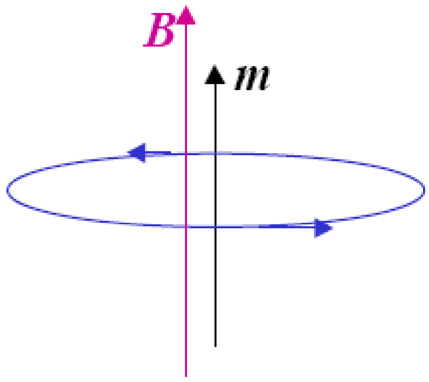
Susceptibility is most useful when discussing *diamagnetic* ($\chi < 0$) and *paramagnetic* ($\chi > 0$) materials, rather than systems with nonzero $\boldsymbol{M}_0$.

Diamagnetism

Some materials develop a magnetization that is *antialigned* with the applied external field ***H***.

Such materials are *diamagnetic*, and have $\chi < 0$.

Simple *classical* picture for diamagnetism: Lenz's Law



Try ramping up $\boldsymbol{B} = \mu_0 \boldsymbol{H}$.

Result is a circumferential electric field that *opposes* the direction of the current in the loop.

This would act to reduce the dipole moment along ***H***, and would be diamagnetic.

Correct quantum treatment involves 2nd order perturbation theory - can end up with either sign, depending on particulars of atoms. *Larmor* diamagnetism or *Van Vleck* paramagnetism.

Paramagnetism

Also common is paramagnetism, when $\chi > 0$.

Two common origins of paramagnetism:
- *Curie* paramagnetism - localized moments free to flip.
- *Pauli* paramagnetism - requires "free" electrons in a metal.

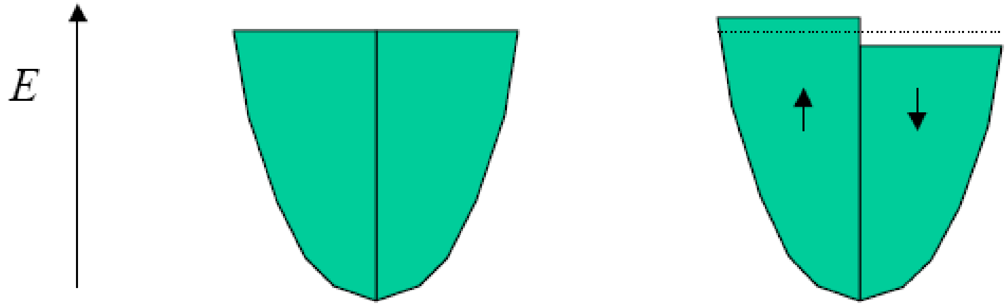
Curie paramagnetism

Alignment of spin with external field lowers spin energy.

Calculation from statistical physics.

$$\longrightarrow \quad \chi \propto 1/T$$

Pauli paramagnetism



Starting from unpolarized electrons, applying a field ***B*** shifts the Fermi level for spin-up and spin-down electrons oppositely!

$$N_{up} = V\int d\varepsilon \frac{\nu(\varepsilon)}{2} f(\varepsilon + \mu_B B) \qquad N_{down} = V\int d\varepsilon \frac{\nu(\varepsilon)}{2} f(\varepsilon - \mu_B B)$$

Taylor expanding to find the difference,

$$M = \frac{\mu_B}{V}(N_{up} - N_{down}) \approx \mu_B^2 \cdot \upsilon(E_F)\mu_0 H$$

Only good for metals - can't have gap at Fermi surface.

Ferromagnetism - toy model

Start from Curie paramagnetism picture - local moments (spins), but now allow them to respond to the *local* magnetic field at their position.

Assume $\boldsymbol{M} = \chi_0 (\boldsymbol{H} + \boldsymbol{H}_m)$ "molecular field", $= \eta \boldsymbol{M}$

$$M(1-\eta\chi_0) = \chi_0 H$$

At high temperatures, $\chi_{eff} = \dfrac{\chi_0}{(1-\eta\chi_0)}$

Recall that $\chi_0 \sim 1/T$, so we find at high temperatures

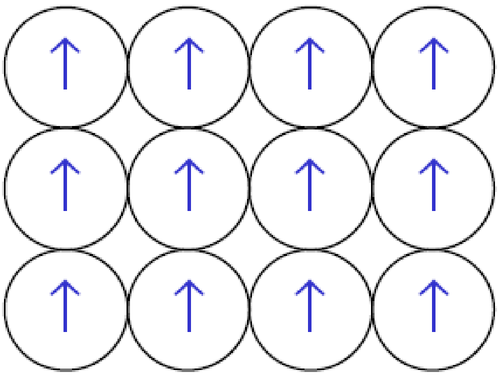
$$\chi_{eff} \sim \frac{1}{T - T_c}$$ Curie-Weiss law

At T_c, the Curie temperature, the susceptibility diverges! Spontaneous magnetization = ferromagnetism.

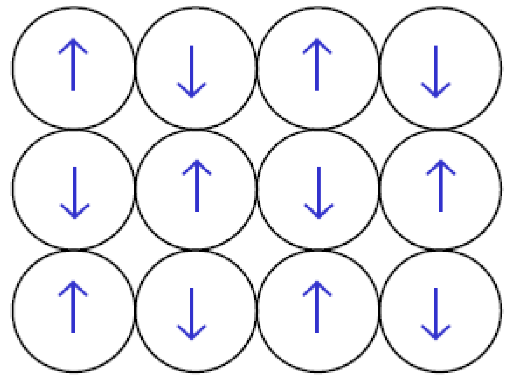
Ferromagnetism, microscopic picture

Exchange energy caused by interaction of charged Fermions

$$E_{ex} = -J\mathbf{S}_1 \cdot \mathbf{S}_2$$



Ferromagnetism J>0



Antiferromagnetism J<0

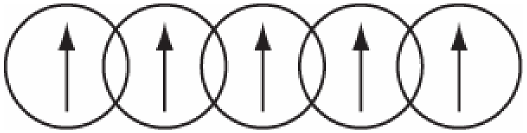
$$\psi(1,2) = \varphi(1,2)S(1,2)$$

orbital spin

S parallel -> φ antiparallel, lowers Coulomb enenergy

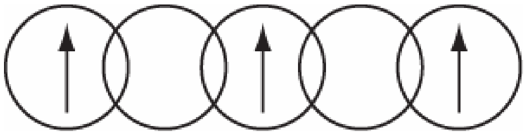
Exchange interactions

Direct exchange



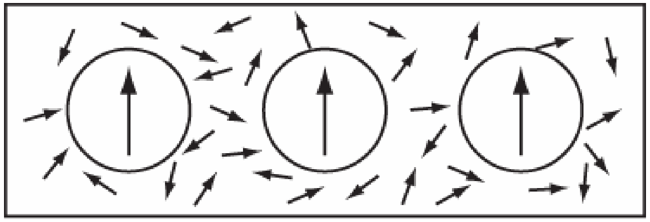
charge distribution of magnetic ions overlap

Super-exchange



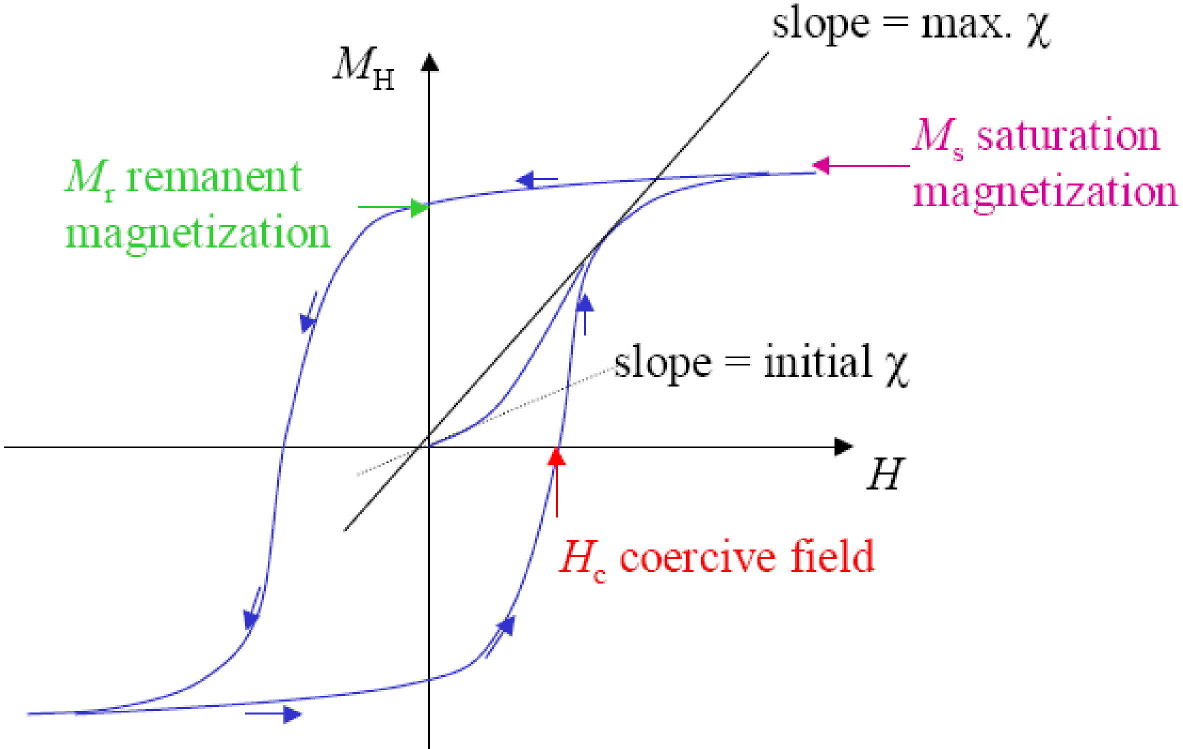
Magnetic ions interact by charge overlap with same non-magnetic ions

Indirect exchange



Magnetic ions interaction mediated by interaction with conduction elections. RKKY interaction

Ferromagnetism: ***M*** vs ***H*** hysteresis



"Hard" ferromagnetic materials: large values of H_c, large M_r.

"Soft" ferromagnetic materials: small values of H_c, small M_r.

Summary

- Most insulators are weakly diamagnetic.

- Metals can be either.

- Ferromagnetism caused by exchange effects.

- Susceptibilities are usually quoted *per molar volume* rather than in their dimensionless form, for experimental reasons.

- Strictly speaking, susceptibilities and permeabilities are defined as derivatives.