# Magnetism in Solids

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# Outline

- Diamagnetism
- Paramagnetism
- Ferromagnetism/Antiferromagnetism
- Exchange Interactions
- Curie-Weiss Law
- Spin Hamiltonians
- More Magnetic Structure
- Conduction Electrons

# Diamagnetism

Magnetic field induces anti-parallel moment in substance

Every material has a diamagnetic response

Causes of diamagnetism

- Larmor diamagnetism
- Conduction electron diamagnetism

www.laputanlogic.com

# Larmor Diamagnetism

Isolated atom or ion

Perturbation:

$$\delta E_n = \mu_0 H \cdot \langle n | L + g_0 S | n \rangle + \frac{\sum_{n \neq n'} \left| \mu_0 H \cdot \langle n | \mu_0 H \cdot (L + g_0 S) | n' \rangle^2 \right|}{E_n - E_n'} + \frac{e^2}{8mc^2} H^2 \langle n | r^2 | n \rangle$$

If shells of ions (or atoms) are filled so the ground state has zero angular and spin momentum, only the third term survives

Used to describe the response in the condensed state as well

# Paramagnetism

Magnetic field creates a parallel moment

$$\delta E_n = \mu_0 H \cdot \langle n | L + g_0 S | n \rangle + \frac{\sum_{n \neq n'} \left| \mu_0 H \cdot \langle n | \mu_0 H \cdot (L + g_0 S) | n' \rangle^2 \right|}{E_n - E_n'} + \frac{e^2}{8\mathrm{mc}^2} H^2 \langle n | r^2 | n \rangle$$

Second term called Van-Vleck paramagnetism

- Same order as Larmor diamagnetism

If J is non-zero, first term dominates

- Due to incomplete shells
- Moment ~ 1000 times larger than Larmor

Still applicable to isolated ions in insulators

# Hund's Rules

1. The lowest energy level of an unfilled shell is that of highest total spin S (minding exclusion principle)
2. After rule 1, the lowest energy level has the largest angular momentum
3. After other rules, the lowest energy state has highest J if the shell is over half full or the lowest J if the shell is less than half full

# Ordering
# (In Absence of Magnetic Field)

- Due to inter-ion interactions (exchange)
- Ferromagnets
  - Neighboring spins align parallel
  - Show hysteresis (memory of magnetic field)
- Antiferromagnets
  - Neighboring spins align anti-parallel
  - Respond as paramagnets to magnetic field, but with reduced susceptibility
- Both behave as paramagnets above ordering temperature

# Exchange Interactions

Interaction of electron spins with each other

- Due to Pauli exclusion principle
- "Exchange" interactions since the responsible terms for the energy splitting come from antisymmetry of wavefunction
- Source of ferromagnetism, antiferromagnetism, ferrimagnetism, ... magnetic ordering.
- Super-exchange, Itinerant electron exchange
- Dipole-dipole interactions exist but will be ignored, since they are of much smaller magnitude

# Magnetization

$$M(H) = \frac{-1}{V} \frac{\partial E(H)}{\partial H}$$

Above: Hysterisis of a ferromagnet

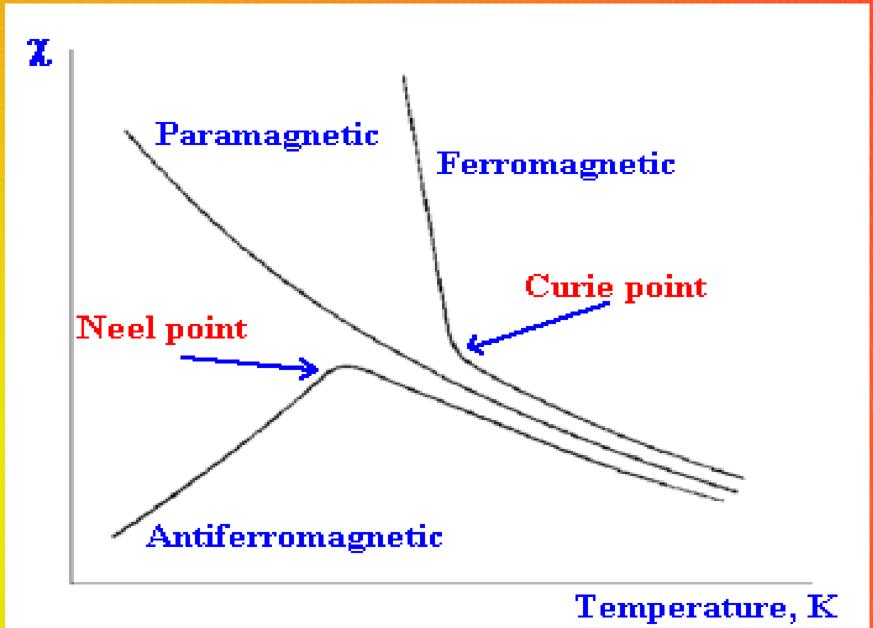
Left: Magnetization and saturation of a paramagnet or antiferromagnet at low temperature

# Susceptibility

$$\chi = \frac{\partial M}{\partial H}$$

Curie's Law for paramagnets

$$\chi \sim \frac{1}{T}$$




Curie-Weiss Law

$$\chi \sim \frac{1}{T-\theta}$$

# Spin Hamiltonians

J characterizes exchange

Heisenberg Model:

$$H = \frac{-1}{2} \sum_{RR'} J_{RR'} S_R \cdot S_{R'} - g \mu_B B \sum_R S_z$$

Ising Model:

Exactly solvable in 2-D (several lattices)

$$H = \frac{-1}{2} \sum_{RR'} J_{RR'} S_{zR} S_{zR'} - g \mu_B B \sum_R S_z$$

# Magnetic Structure

- Magnetic anisotropy -easy/hard axis
  - Caused by spin orbit coupling
  - Or shape anisotropy
- Spin glass
  - Frustration makes it difficult to reach ground state
  - Frequency dependent susceptibility

# Conduction Electrons

- Diamagnetism
  - Field couples to orbital motion of conductors
  - – Same order of magnitude as Larmor Diamagnetism
  - Superconductors are perfect diamagnets
- Pauli Paramagnetism
  - Alignment of spins in conduction band
  - Same order as conduction electron diamagnetism
- Itinerant electron exchange interactions
- Hubbard Model
  - Treats magnetism including first band and localization

# Questions?