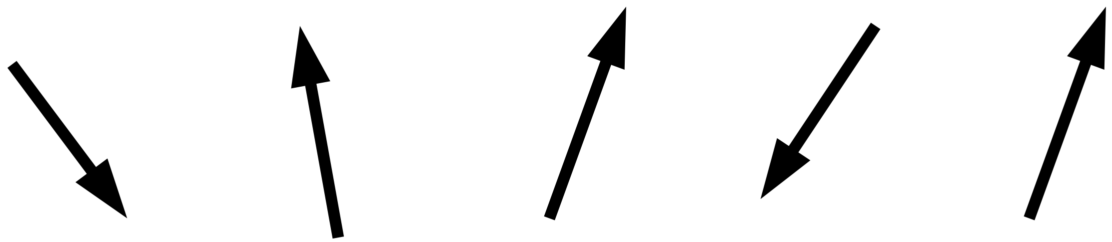
Magnetic Structure of Solids

Magnetic properties of a solid are determined by magnetic dipole moments of particles constituting the solid and their interaction with each other and the external magnetic field.

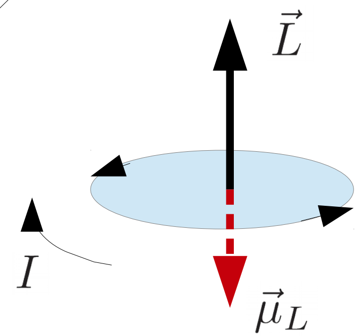


→ magnetic dipole moments **may interact with each other** (they may be correlated)

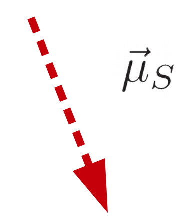
→ they also **respond to an external magnetic field**

important contribution is due to electrons

orbital motion

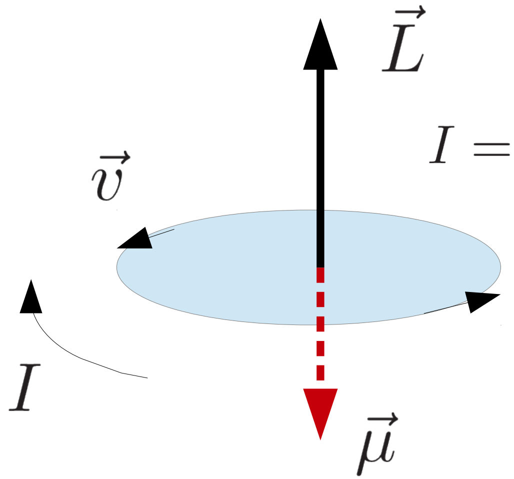


intrinsic degree of freedom (electron's spin)



(I) Orbital Magnetic Dipole Moment of the Electron

semi-classical picture: classical laws of dynamics + quantization of physical quantities



$$I = \frac{e}{T} = \frac{e\omega}{2\pi} = \frac{ev}{2\pi r}$$

$$\mu_L = \text{area} \times \text{current}$$

$$\mu_L = \pi r^2 \frac{ev}{2\pi r} = \frac{evr}{2}$$

$$\vec{L} = \vec{r} \times m\vec{v} \quad \xRightarrow{\vec{r} \perp \vec{v}} \quad L = mrv$$

$$\mu_L = \frac{e}{2m} L$$

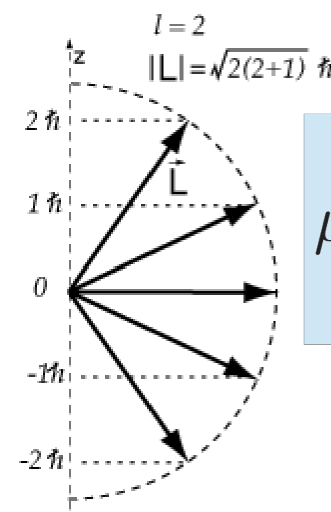
QUANTUM MECHANICS

Projection of the angular momentum onto a specific direction (e.g. that of the magnetic field) is **quantized**

$$L_z = l_z \hbar, \qquad l_z = \underbrace{-l, -l+1, \ldots, l-1, l}_{2l+1 \text{ values}}$$

$$\hbar = \frac{h}{2\pi} \qquad\qquad l = 0, 1, 2 \ldots$$

Planck's constant h = 6.62 x 10^{-34} J s



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$$\mu_{L,z} = \underbrace{\frac{e\hbar}{2m}}_{\mu_B} l_z$$

Bohr magneton
9.27 x 10^{-34} J/T

(II) Spin Magnetic Dipole Moment of the Electron

No classical analogue, needs to be treated entirely within the formalism of quantum mechanics.

In quantum mechanical description, electron's spin has the same properties as the angular momentum, but only two possible values of the projection on a specific direction

$$S_z = \pm\frac{\hbar}{2}$$

This intrinsic degree of freedom gives rise to another magnetic dipole moment (*spin magnetic dipole moment*)

$$\boxed{\mu_{S,z} = \pm\frac{1}{2}\,g\mu_B}$$

$g \approx 2$ – Lande factor

Both the orbital and the spin magnetic dipole moment combine to produce the total magnetic dipole moment.

Caution: Spin and orbital momentum do not add like classical vectors! See quantum mechanics for details.

Magnetization

The net magnetic dipole moment of a solid per unit volume
(may be non-zero even if external magnetic field is zero)

$$\vec{M} = \frac{\vec{\mu}_{\mathrm{tot}}}{\mathrm{volume}}$$

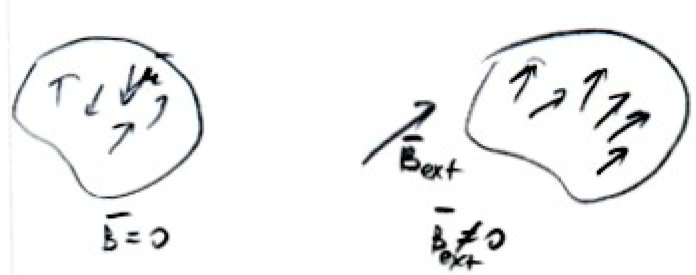
Different materials respond differently to an external magnetic field

$$\vec{B}_{\mathrm{tot}} = \vec{B}_{\mathrm{ext}} + \mu_0 \vec{M} = \mu_0(\vec{H} + \vec{M})$$

auxiliary magnetic field
(magnetic field strength)

$$\vec{B}_{\mathrm{tot}} = (\chi_{\mathrm{m}} + 1)\mu_0 \vec{H} = \mu\mu_0 \vec{H}$$

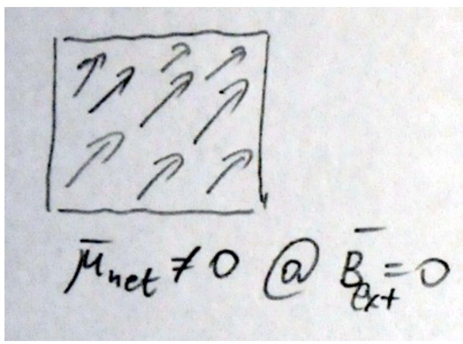
magnetic susceptibility

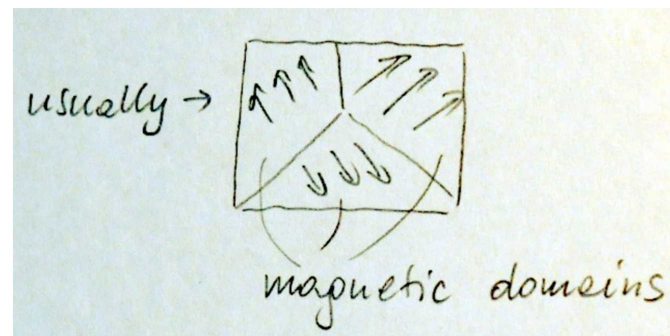


Magnetic Order in Solids

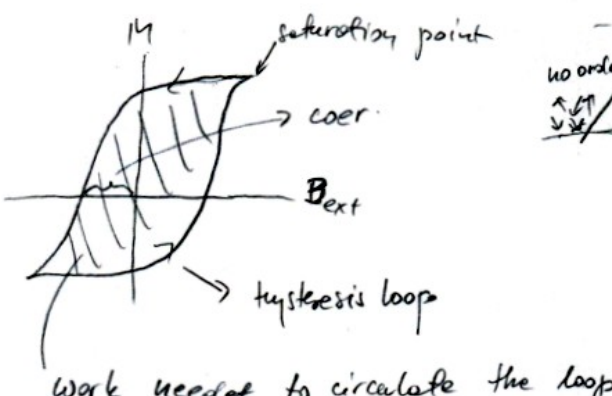
(A) materials with spontaneous magnetic ordering

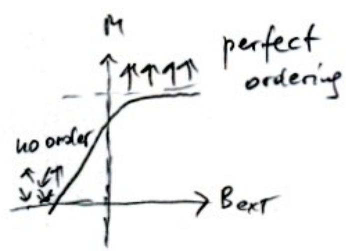
FERROMAGNETS non-zero net magnetic moment in zero external magnetic field; magnetic dipole moments aligned parallel to each other;
high temperature destroys the order (Curie temp.)

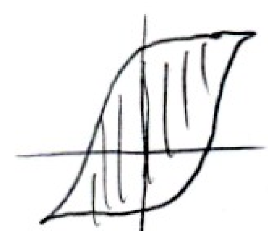




Magnetic Hysteresis







difficult to magnetize
(hard)

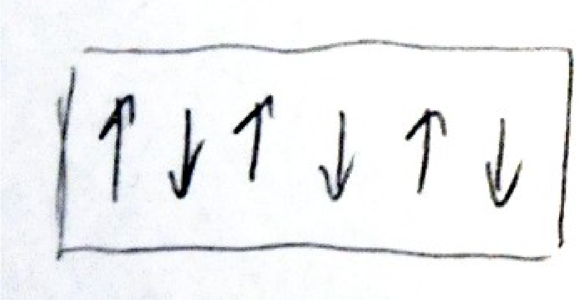
vs.

easy to magnetize
(soft)

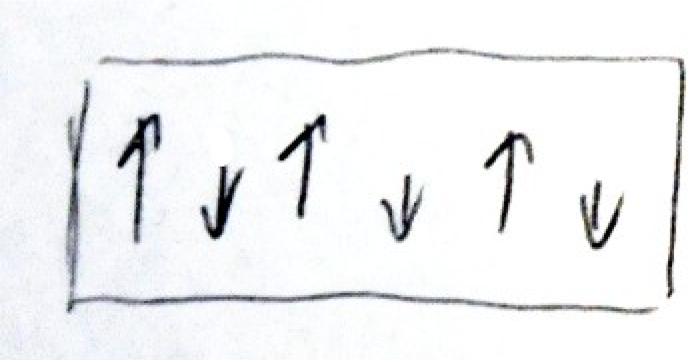
Magnetic Order in Solids

(A) materials with spontaneous magnetic order

ANTIFERROMAGNETS → no net magnetic moment in zero external field, but still microscopically ordered;
→ magnetic dipole moments aligned anti-parallel to each other;
→ high temperature destroys the order (Neel temperature)



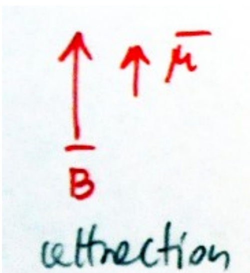
FERRIMAGNETS → net magnetic moment is non-zero in the absence of an external field
→ microscopically ordered – magnetic dipole moments aligned anti-parallel to each other, but do not cancel;
→ high temperature destroys the order

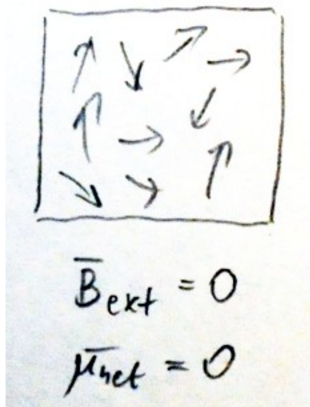


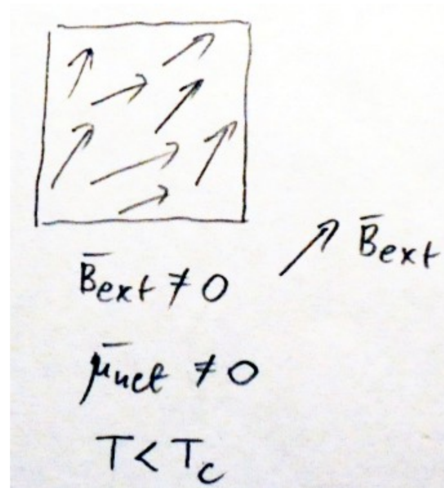
Magnetic Order in Solids

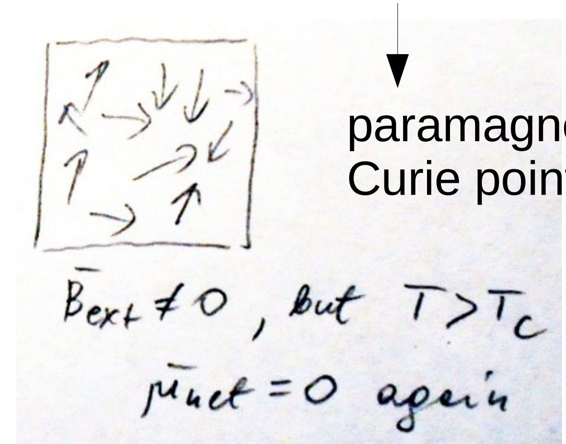
(B) materials without spontaneous magnetic order

PARAMAGNETS no net magnetic moment in zero external field, but non-zero moment in non-zero field (below T_c)



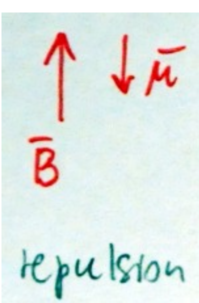


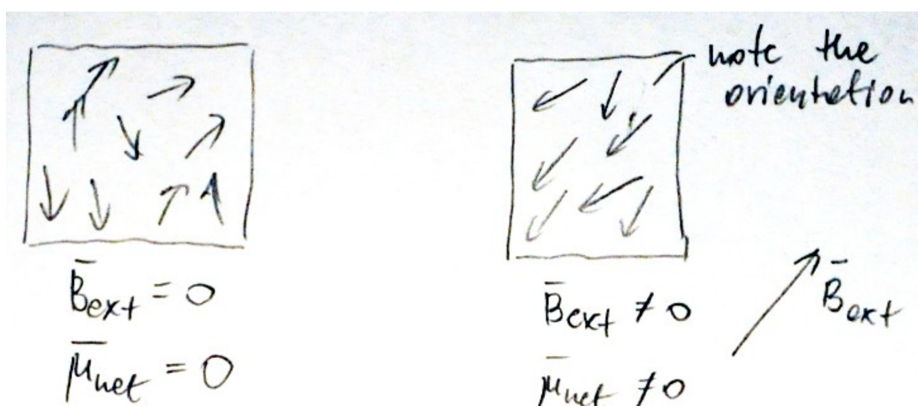




paramagnetic Curie point

DIAMAGNETS no net magnetic moment in zero external field, but non-zero moment in non-zero field (opposite to the field)





superconductors are ideal diamagnets: **B** inside is always zero

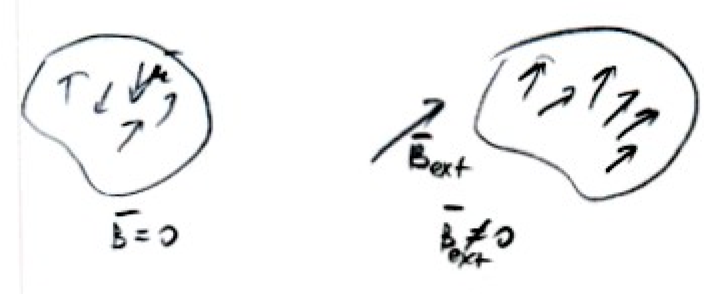
Magnetic Susceptibility

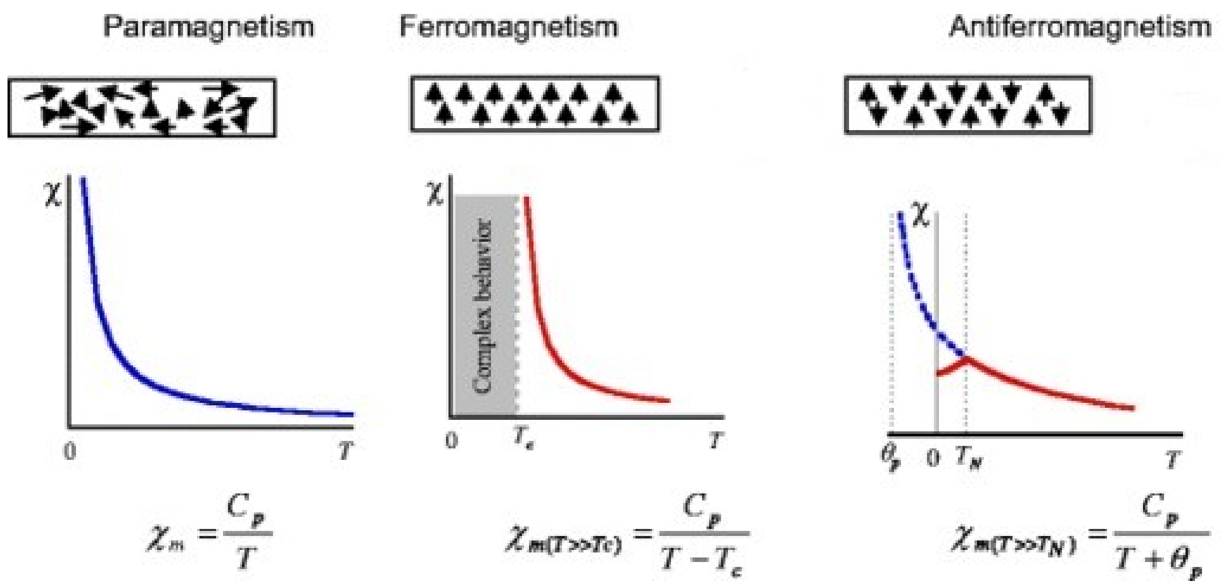
$$\vec{B}_{\mathrm{tot}} = (\chi_{\mathrm{m}} + 1)\mu_0 \vec{H} = \mu\mu_0 \vec{H}$$

magnetic susceptibility

Behaviour	Typical χ value
Diamagnetism	-8×10^{-6} for Cu
Paramagnetism	
Pauli paramagnetism	8.3×10^{-4} for Mn
Ferromagnetism	5×10^{3} for Fe
Antiferromagnetism	0 to 10^{-2}

Source: C. Kittel, *Introduction to Solid State Physics*





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