Refresher lecture in Magnetism

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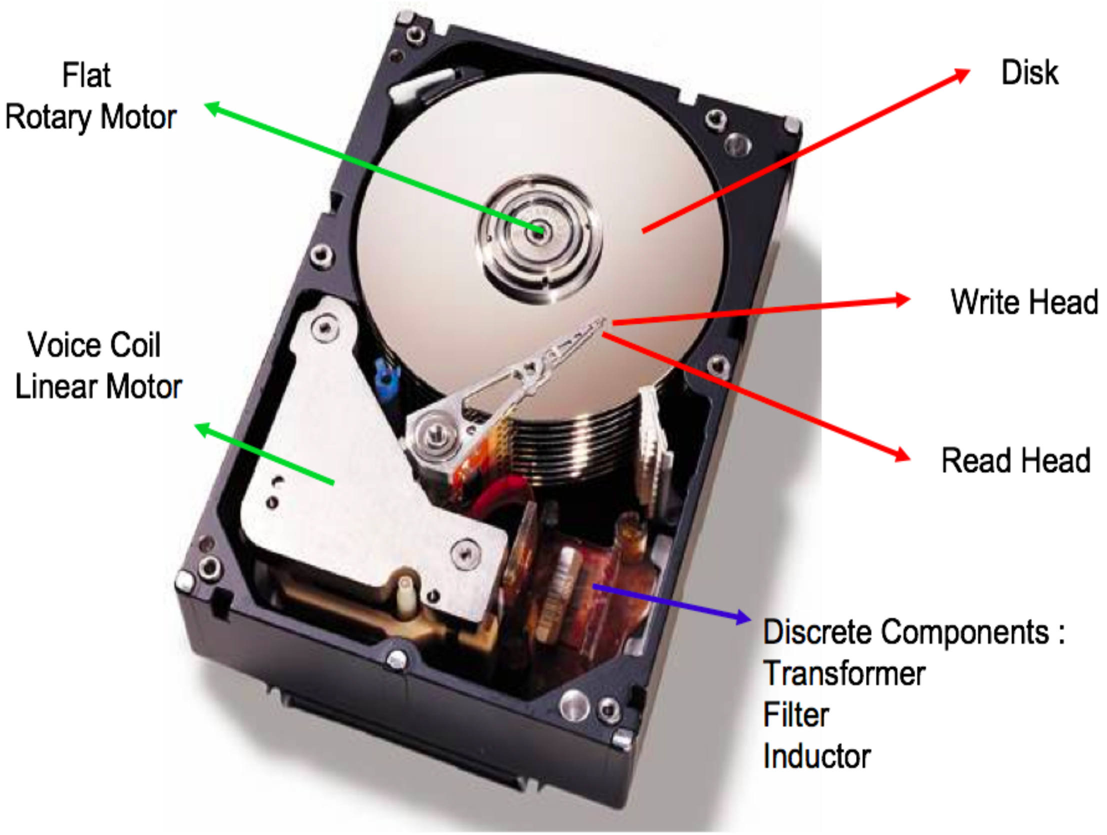
Introduction
Atomic magnetic moment
Assembly of non interacting moments
Magnetic moments in interaction
Localized versus itinerant electrons
From microscopic to macroscopic
Applications
Modern trends in research

Introduction

Magnetic materials all around us : the earth, cars, audio, video, telecommunication, electric motors, medical imaging, computer technology…

Hard Disk Drive



Introduction

Magnetism:
science of cooperative effects of orbital and spin moments in matter
➔Wide subject expanding over physics, chemistry, geophysics, life science.

Large variety of behaviors: dia/para/ferro/antiferro/ferrimagnetism, phase transitions, spin liquid, spin glass, spin ice, skyrmions, magnetostriction, magnetoresistivity, magnetocaloric, magnetoelectric effects, multiferroism, exchange bias…
in different materials: metals, insulators, semi-conductors, oxides, molecular magnets,.., films, nanoparticles, bulk...

Inspiring or verifying lots of model systems (ex. Ising model)

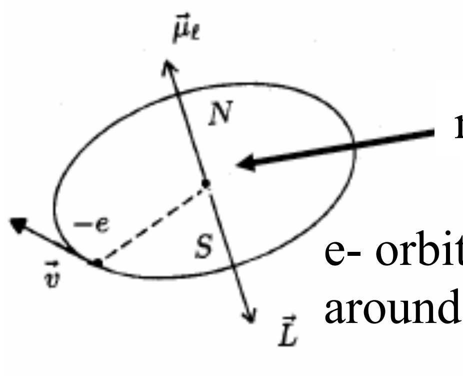
Magnetism is a quantum phenomenon but phenomenological models are commonly used to treat classically matter as a continuum

Atomic magnetic moment

✔An electric current is the source of a magnetic field B

✔A magnetic moment is equivalent to a current loop

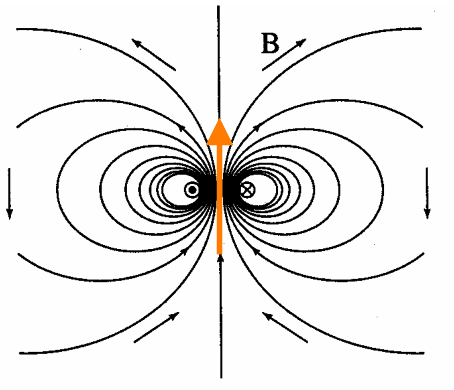
$$\vec{\mu}_\ell = \vec{I}.\vec{S} = \frac{-ev}{2\pi r}\pi r^2 \vec{n} = \frac{-evr}{2}\vec{n}$$



nucleus

e- orbiting around the nucleus

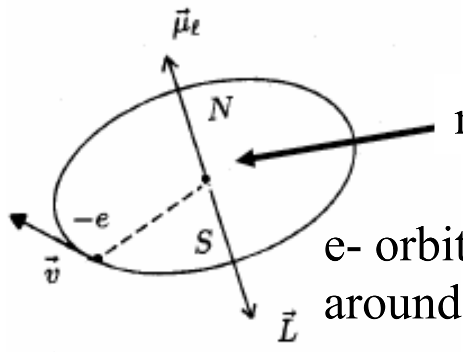
creating a dipolar magnetic field



Atomic magnetic moment

✔A magnetic moment is equivalent to a current loop

$$\vec{\mu}_\ell = \vec{I}.\vec{S} = \frac{-ev}{2\pi r}\pi r^2 \vec{n} = \frac{-evr}{2}\vec{n}$$



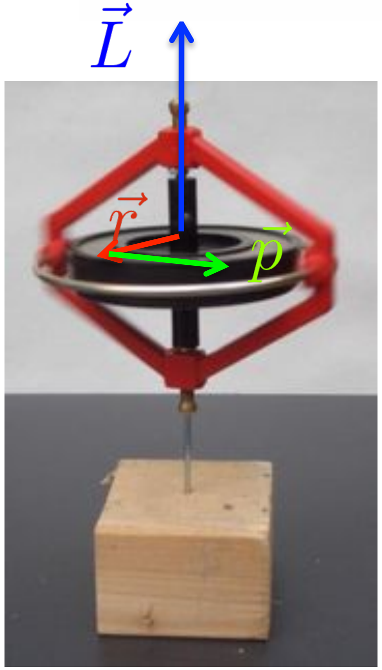
✔ The magnetic moment is related to the angular momentum

$$\vec{L} = \vec{r} \times \vec{p} = \vec{r} \times m\vec{v}$$

$$\vec{\mu}_\ell = \frac{-e}{2m}\vec{L} = \gamma\vec{L}$$

Orbital magnetic moment

Gyromagnetic ratio



gyroscope

Atomic magnetic moment

Consequences:

✔ Magnetic moment and angular momentum are antiparallel

✔ Calculations with magnetic moment using formalism of angular momentum

Atomic magnetic moment

Magnetism in quantum mechanics:

Distribution of electrons on atomic orbitals, which minimizes the energy:
Building of atomic magnetic moments

The electronic wavefunction $\Psi_{n\ell m_\ell}$ is characterized by 3 quantum numbers

n : electronic shell

ℓ : orbital angular momentum quantum number $0 < \ell < n-1$

ℓ	0	1	2	3
	s	p	d	f

m_ℓ : magnetic quantum number $-\ell < m_\ell < +\ell$

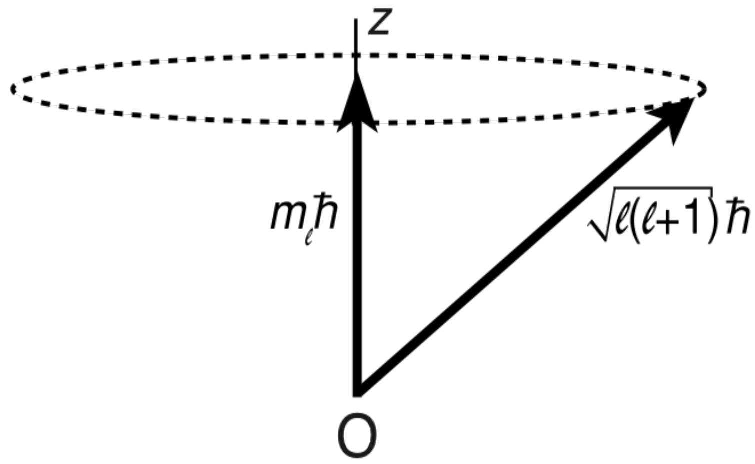
Atomic magnetic moment

Magnetism in quantum mechanics: quantized orbital angular momentum

$\hat{\ell}$ is the angular momentum operator

Electronic orbitals are eigenstates of $\hat{\ell}^2$ and $\hat{\ell}_Z$

$$\hat{\ell}^2 \Psi_{n\ell m_\ell} = \hbar^2 \ell(\ell+1) \Psi_{n\ell m_\ell}$$
$$\hat{\ell}_Z \Psi_{n\ell m_\ell} = \hbar m_\ell \Psi_{n\ell m_\ell}$$



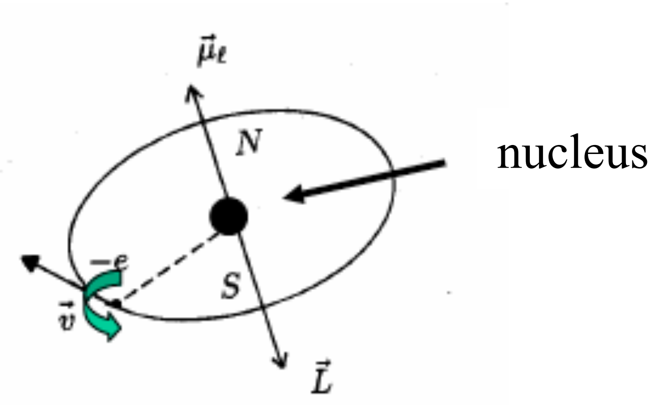
The magnitude of the orbital momentum is $\hbar\sqrt{\ell(\ell+1)}$

The component of the orbital angular momentum along the z axis is $\hbar m_\ell$

Atomic magnetic moment

Magnetism in quantum mechanics: spin angular momentum
of pure quantum origin

$$\hat{s}_Z \Psi_s = \hbar m_s \Psi_s$$
$$\hat{s}^2 \Psi_s = \hbar^2 s(s+1) \Psi_s$$



With the quantum numbers :

$$s = 1/2, m_s = -1/2, +1/2$$

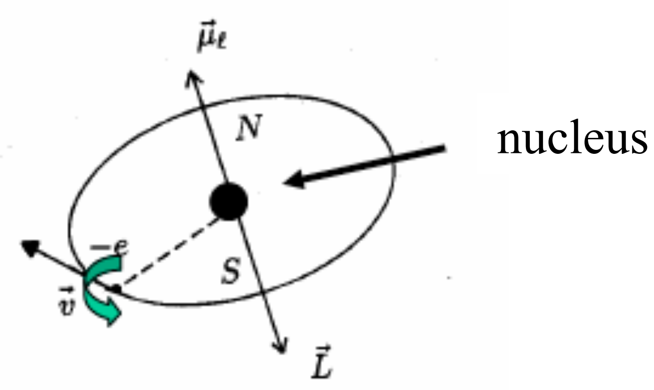
The magnitude of the spin angular momentum is $\hbar\sqrt{s(s+1)} = \hbar\sqrt{3/4}$

The component of the spin angular momentum along the z axis is $\hbar m_s$

Atomic magnetic moment

Magnetism in quantum mechanics:

Magnetic moment associated to 1 electron in the atom
Two contributions: spin and orbit



Magnetic moments

$$\hat{\mu}_\ell = -g_\ell \mu_B \hat{\ell}$$

$$\hat{\mu}_s = -g_s \mu_B \hat{s}$$

With $g_\ell = 1$ and $g_s = 2$

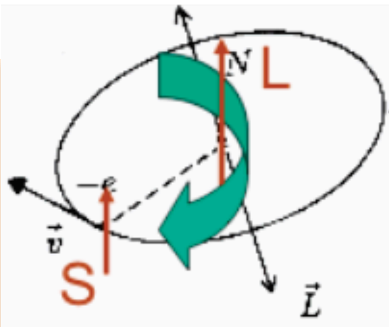
and the Bohr magneton $\mu_B = \dfrac{\hbar e}{2m_e}$

Atomic magnetic moment

Magnetism in quantum mechanics: several e- in an atom

$$\hat{L} = \sum_{ne-} \hat{\ell} \qquad \hat{S} = \sum_{ne-} \hat{s}$$

Combination of the orbital and spin angular momenta of the different electrons: related to the filling of the electronic shells in order to minimize the electrostatic energy and fulfill the Pauli exclusion principle



Spin-orbit coupling: $\lambda \hat{L}.\hat{S}$

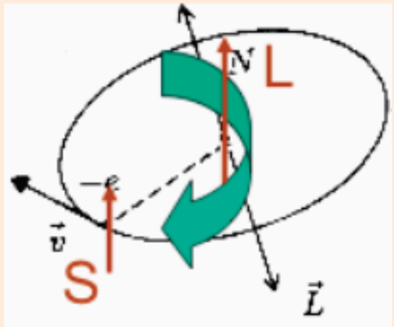
Total angular momentum $\hat{J} = \hat{L} + \hat{S}$

A given atomic shell (multiplet) is defined by 4 quantum numbers :
L, S, J, M_J with $-J < M_J < J$

Atomic magnetic moment

Magnetism in quantum mechanics: several e- in an atom

Hund's rules for the ground state



1st rule $S = M_S = \sum_{ne^-} m_s$ maximum

2nd rule $L = M_L = \sum_{ne^-} m_\ell$ maximum in agreement with the 1st rule

3rd rule from spin-orbit coupling

$$J = |L - S| \qquad J = |L + S|$$

for less than ½ filled shell for more than ½ filled shell

Atomic magnetic moment

Application of Hund's rule : L and S are zero for filled shells

Example of unfilled shell
Tb^{3+} is $4f^8$, 8 electrons to put in 14 boxes ($\ell = 3$)

m_ℓ	-3	-2	-1	0	1	2	3
$m_s = \frac{1}{2}$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
$m_s = -\frac{1}{2}$	$\downarrow$						

so L=3 and S=3

The spin-orbit coupling applies for more than ½ filled shell
so J=6 and $-6 < M_J < 6$

The ground state is 13-fold degenerate

Atomic magnetic moment

Total magnetic moment of the unfilled shell

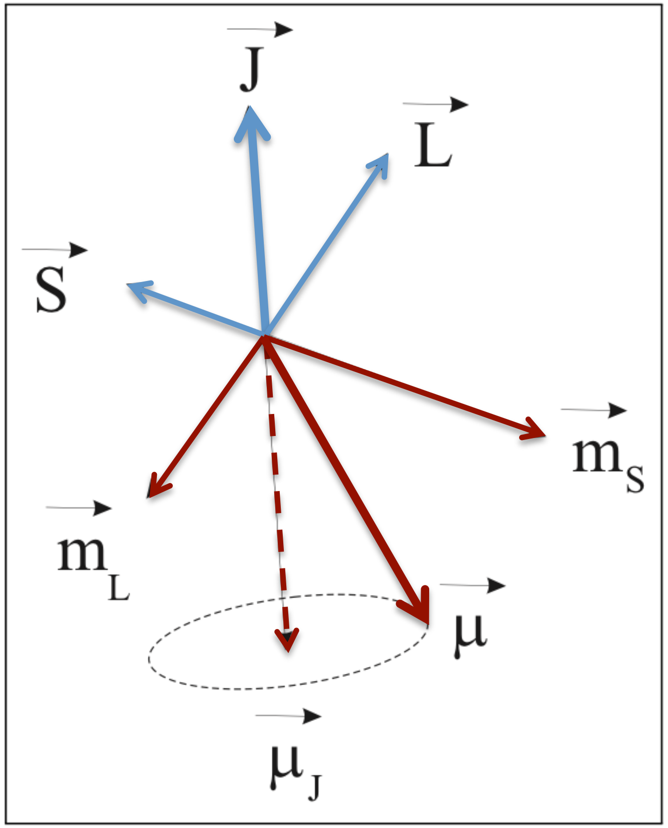
$$\hat{\mu} = -\mu_B(\hat{L} + 2\hat{S})$$

$$\mu = g_J \mu_B \sqrt{J(J+1)}$$

$$\mu_J = -g_J \mu_B J$$

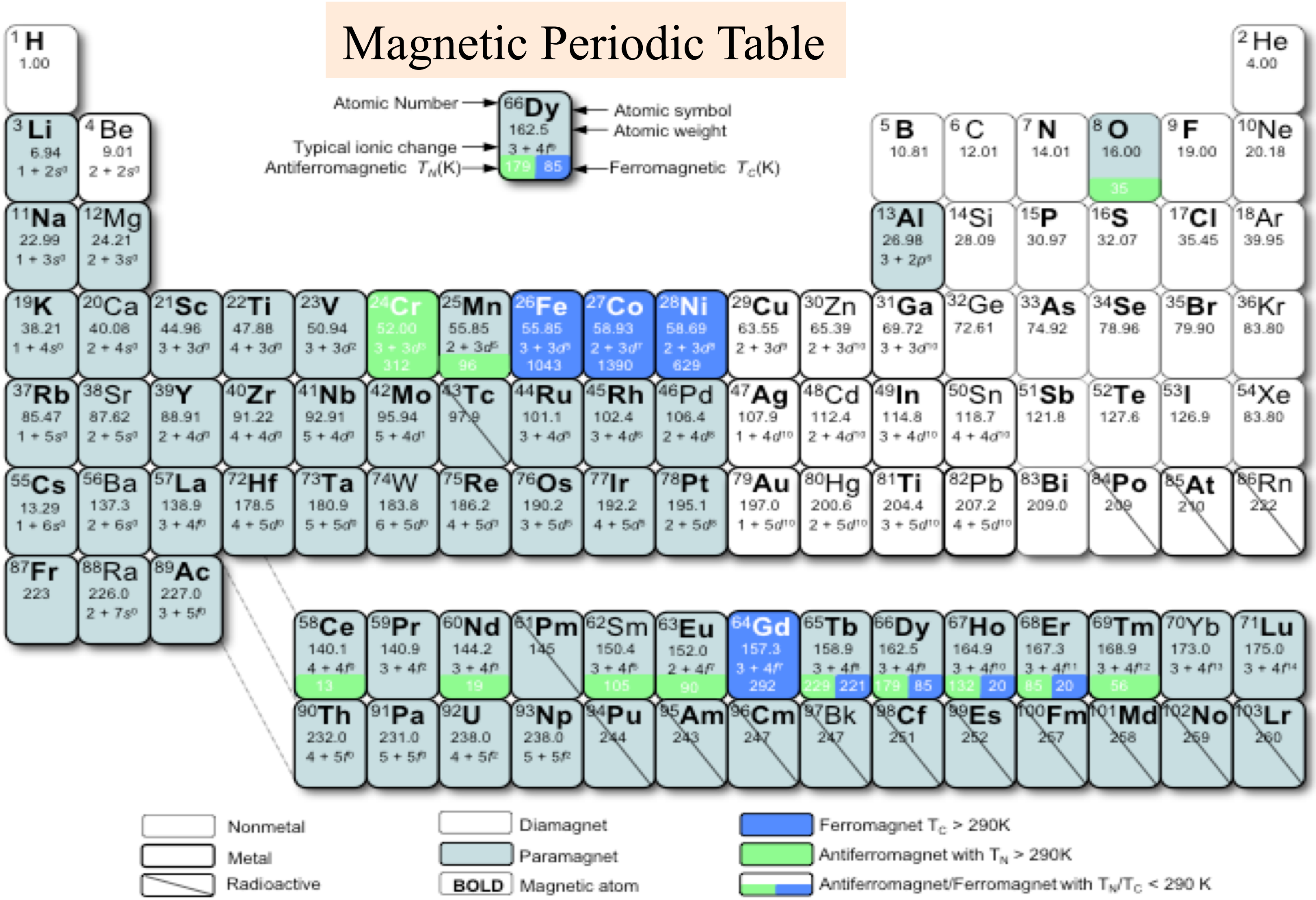
With the Landé g_J-factor

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$



Atomic magnetic moment

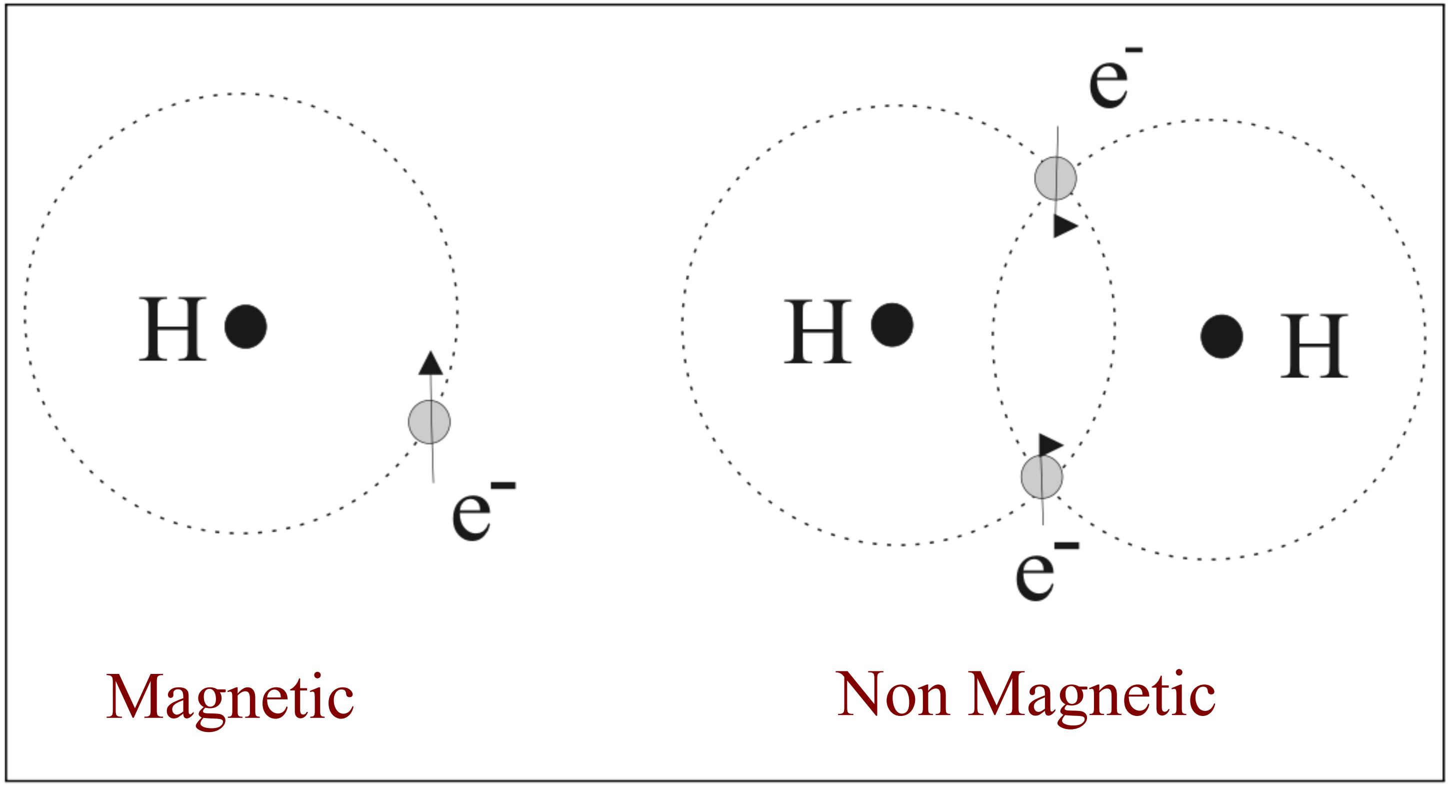
Magnetism is a property of unfilled electronic shells:
Most atoms (bold) are concerned but 22 are magnetic in condensed matter



Atomic magnetic moment

Atom in matter:

✔ Chemical bonding ➔ filled e- shells : no magnetic moments



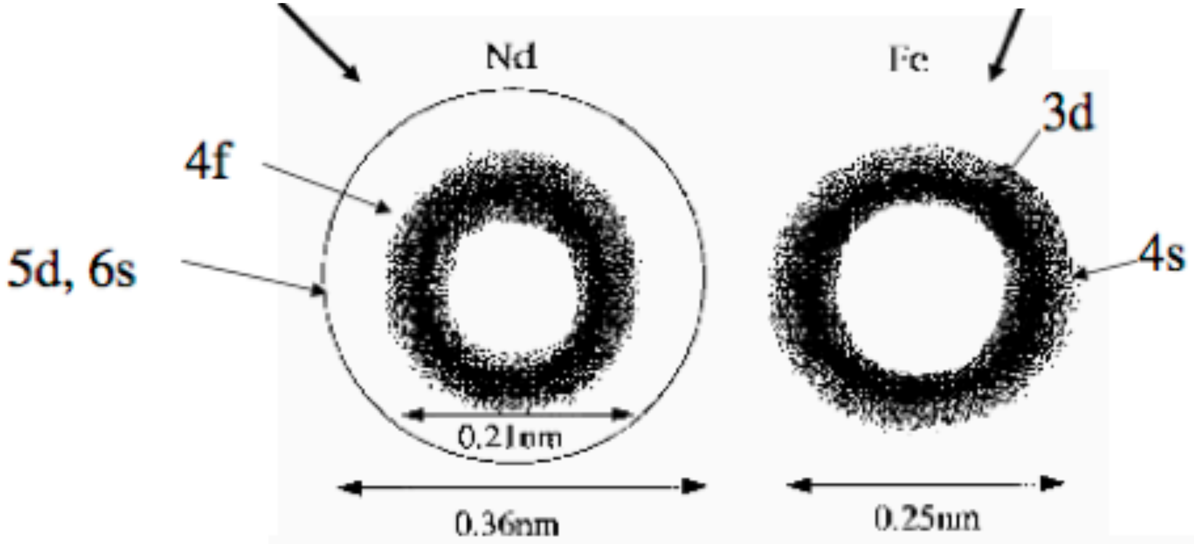
Atomic magnetic moment

Atom in matter:

✔ Chemical bonding ➔ filled e- shells : no magnetic moments, except for:

Rare-earth element

Transition-metal element



4f electrons: inner shell

3d electrons: outer shell (more delocalized)

Atomic magnetic moment

Atom in matter:

✔ Influence of surrounding charges ➔ crystal field (CEF)

3d electrons

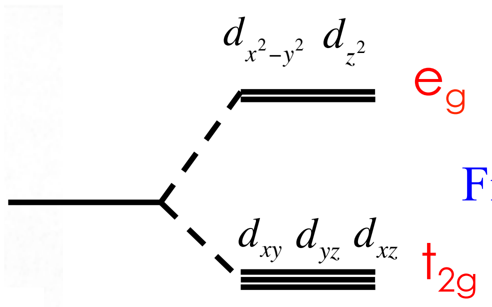
Large CEF >> spin-orbit coupling

angular distribution of 5 orbitals

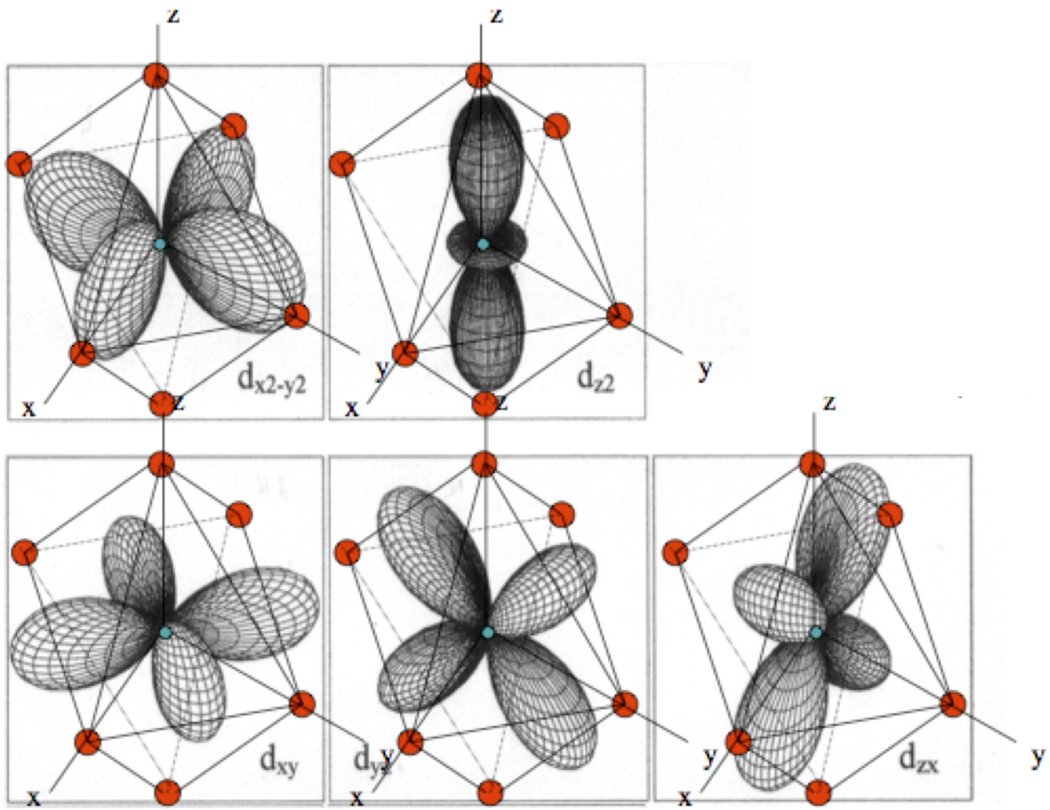
➔ some favored by the CEF

➔ quenching of the orbital momentum

spin-orbit ➔ g anisotropy



Five 3d orbitals



Atomic magnetic moment

Atom in matter:

✔ Influence of surrounding charges ➔ crystal field (CEF)

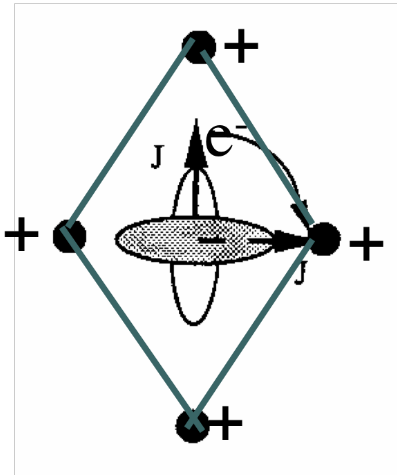
4f electrons

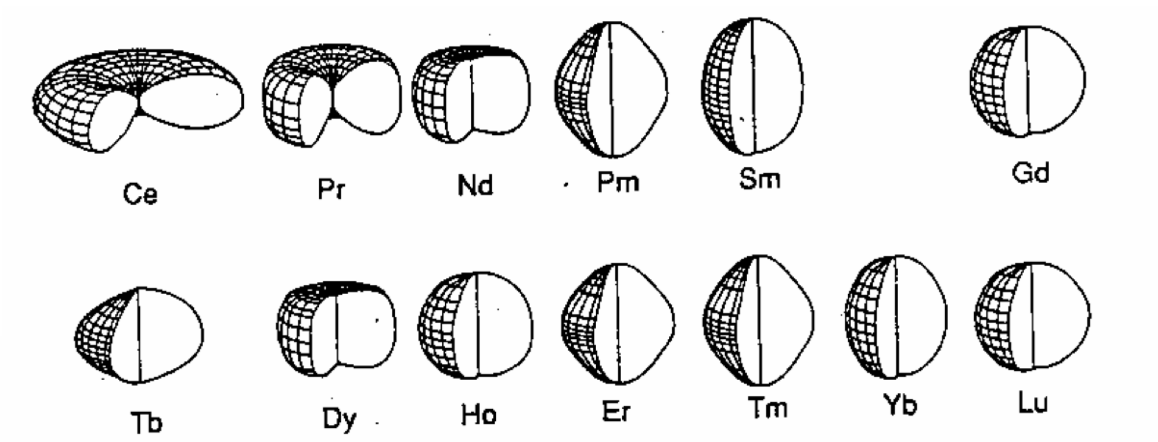
spin-orbit >> CEF

Partially filled electronic shells : non-spherical 4f charge distribution

+ CEF ➔ selects some orbitals (lift degeneracy)

+ spin-orbit ➔ anisotropy J: alignment of magnetic moments along some directions





Atomic magnetic moment

Summary

Magnetism is a quantum phenomenon

Magnetic moments are associated to angular momenta

Orbital magnetic moment and spin magnetic moment

Localized magnetic moment in 3d and 4f atoms with different behaviors

Orbital and spin moments can be coupled (spin-orbit coupling)

Importance of environment, crystal field:

- quenching of orbital moment in 3d
- magnetocrystalline anisotropy in 4f atoms

Assembly of non-interacting magnetic moments

Measurable quantities:

Magnetization : magnetic moment per unit volume
derivative of the energy w. r. t. the magnetic field

$$M = -\frac{\partial F}{\partial B}$$

Susceptibility: derivative of magnetization w. r. t. magnetic field,
alternatively, ratio of the magnetization on the field in the linear regime

$$\chi = \mu_0 \frac{\partial M}{\partial B} \approx \mu_0 \left(\frac{M}{B}\right)_{lin}$$

Assembly of non-interacting magnetic moments

One atomic moment in a magnetic field B

position of the i^{th} e-

Energy: $$\hat{W}_B = \boxed{\mu_B(\vec{\hat{L}} + 2\vec{\hat{S}}).\vec{B}} + \boxed{\frac{e^2}{8m_e}\sum_{ie-}(\vec{\hat{R}}_i \times \vec{B})^2}$$

Zeeman energy: coupling of total magnetic moment with the magnetic field

Diamagnetic term: induced orbital moment by the external magnetic field

Assembly of non-interacting magnetic moments

N atomic moments in a magnetic field B

Calculation of magnetization and susceptibility

Thermal average (Boltzmann statistics) + perturbation theory

$$M_\alpha = \frac{N}{V} \sum_j -\frac{\partial E_j}{\partial B_\alpha} \frac{\exp(-\beta E_j)}{\sum_j \exp(-\beta E_j)} \qquad \text{with} \qquad \beta = k_B T$$

Assembly of non-interacting magnetic moments

Energy: $\hat{W}_B = \boxed{\mu_B(\vec{\hat{L}} + 2\vec{\hat{S}}).\vec{B}} + \boxed{\frac{e^2}{8m_e}\sum_{ie-}(\vec{\hat{R}}_i \times \vec{B})^2}$

Diamagnetic term for N atoms:

$$\chi = -\frac{N}{V}\mu_0 \frac{e^2}{4m_e} < R_\perp^2 >$$

perpendicular to the field

due to the induced moment by the magnetic field

➔ negative weak susceptibility, concerns all e- of the atom, T-independent

Assembly of non-interacting magnetic moments

Energy: $$\hat{W}_B = \boxed{\mu_B(\vec{\hat{L}} + 2\vec{\hat{S}}).\vec{B}} + \boxed{\frac{e^2}{8m_e}\sum_{ie-}(\vec{\hat{R}}_i \times \vec{B})^2}$$

Paramagnetic term for N atoms:

$$M = \frac{N}{V} g_J J \mu_B B_J(x) \qquad \text{with} \qquad x = \frac{g_J J \mu_B B}{k_B T}$$

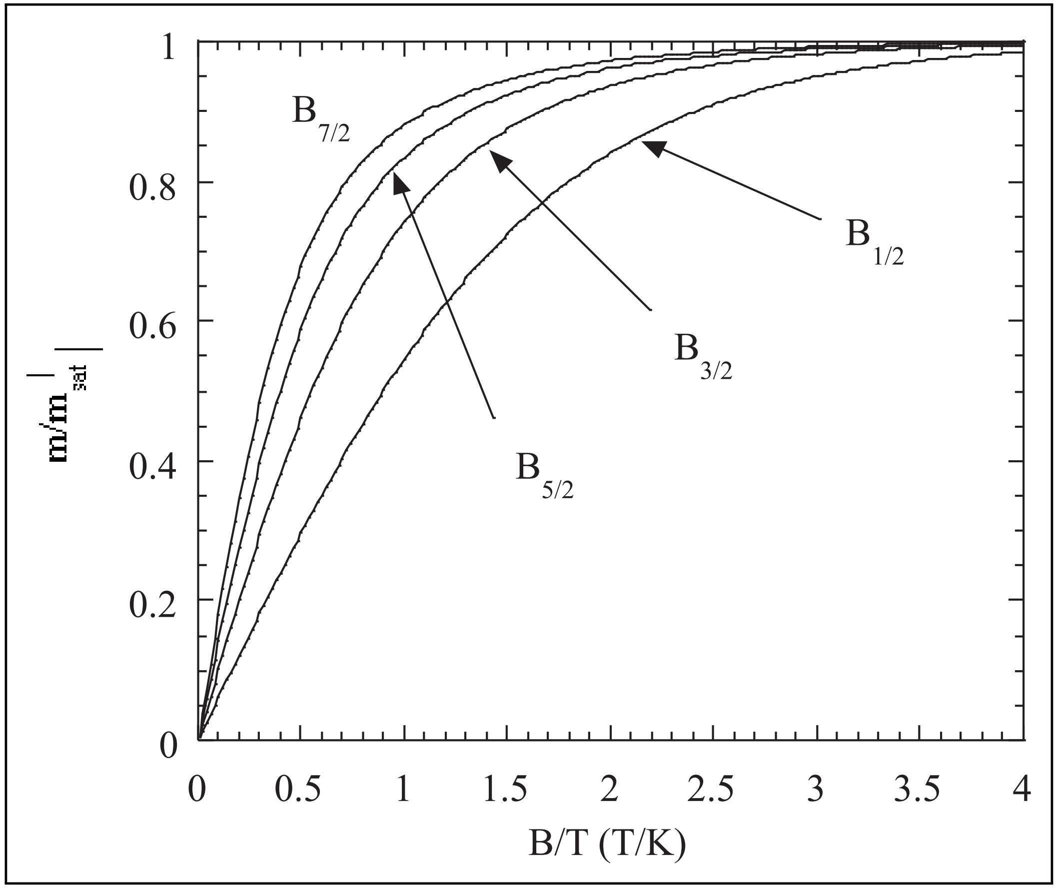
and the Brillouin function:

$$B_J(x) = \frac{2J+1}{2J}\coth\left(\frac{2J+1}{2J}x\right) - \frac{1}{2J}\coth\left(\frac{x}{2J}\right)$$

Assembly of non-interacting magnetic moments

Paramagnetic term

Brillouin functions for different J values,



Limit x >> 1 i.e. H >> k_BT

Saturation magnetization $M_s = \frac{N}{V} g_J J \mu_B$

Assembly of non-interacting magnetic moments

Paramagnetic term

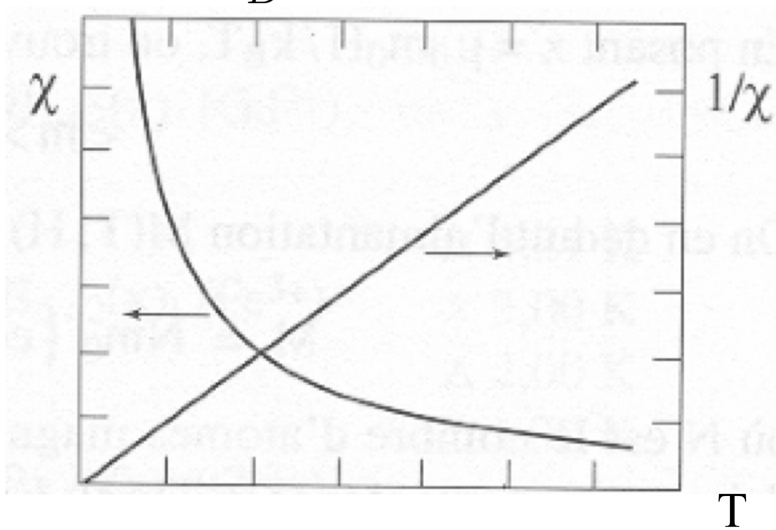
Limit x << 1 i.e. $k_B T >> H$

Curie law:

$$\chi = \frac{N}{V}\frac{(\mu_B g_J)^2 J(J+1)}{3k_B T} = \frac{C}{T} = \frac{N}{V}\frac{p_{eff}^2}{3k_B T}$$

with the effective moment

$$p_{eff} = g_J\sqrt{J(J+1)}\mu_B$$

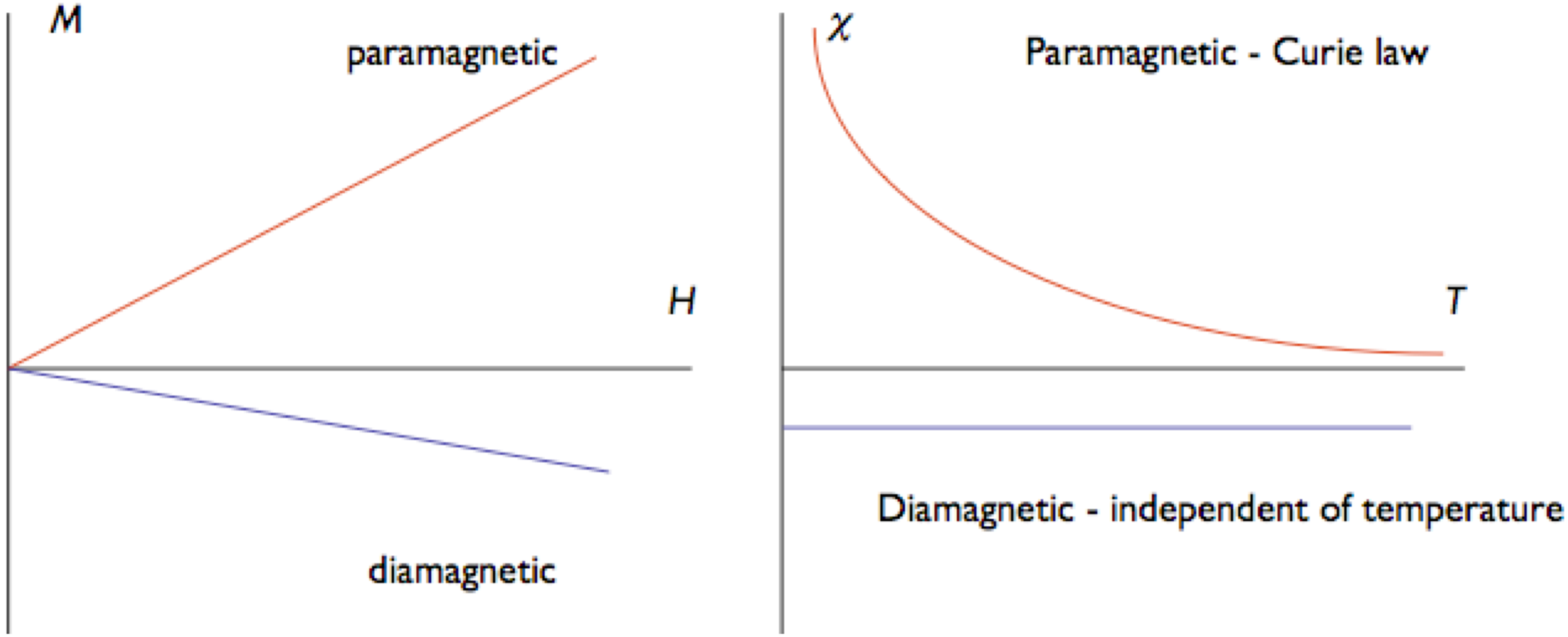


It works well for magnetic moments without interactions and negligible CEF: ex. Gd^{3+}, Fe^{3+}, Mn^{2+} (L=0)

Assembly of non-interacting magnetic moments

Summary of magnetic field response of non-interacting atomic moments

At small H/k_BT: linear regime



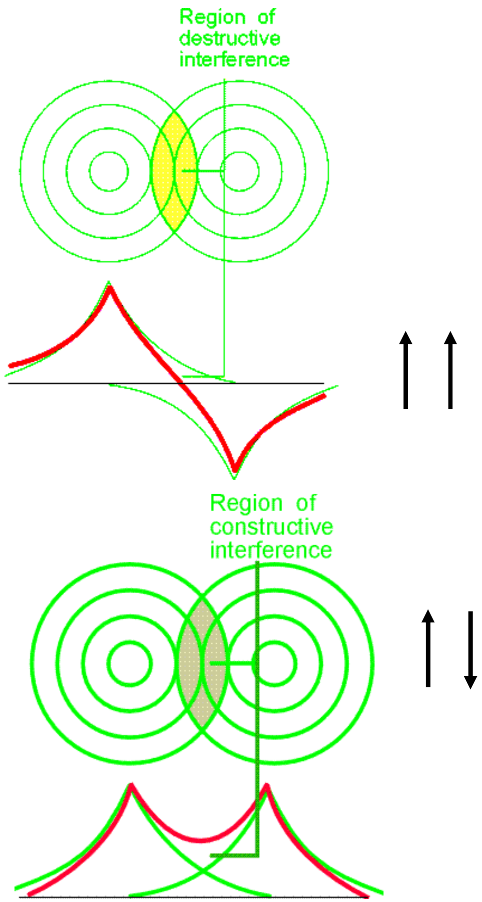
Magnetic moments in interaction

Dipolar interaction: $$E = \frac{\mu_0}{4\pi r^3}[\vec{\mu}_1.\vec{\mu}_2 - \frac{3}{r^2}(\vec{\mu}_1.\vec{r})(\vec{\mu}_2.\vec{r})]$$

Much too weak to account for the ordering of most magnetic materials

Exchange interaction:

Origin: electrostatic and Pauli exclusion principle
Many-electron wavefunctions must be antisymmetric through the exchange of two electrons



Heisenberg Hamiltonian $$\mathcal{H} = -\sum_{ij} \mathrm{J}_{\mathrm{ij}} \vec{S}_i.\vec{S}_j$$

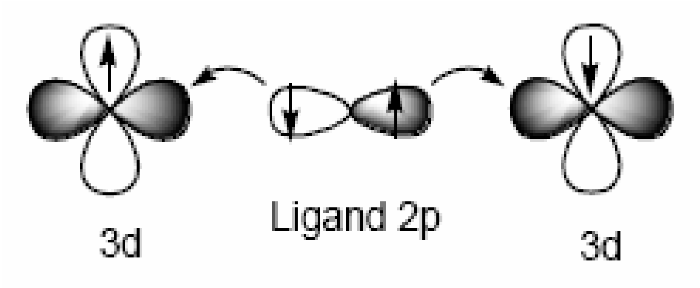
J: exchange coupling constant
J > 0 ferromagnetic
J < 0 antiferromagnetic

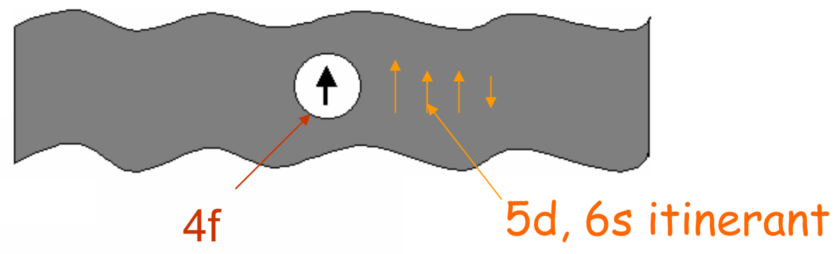
Magnetic moments in interaction

Exchange interaction

•Direct exchange: usually weak ➔ overlap between magnetic orbitals

•Superexchange: in insulators, indirect mediated by non-magnetic atoms
Depends on geometry of the bonds. Most often antiferromagnetic.
Explains the magnetism in transition metal oxides.





- RKKY (*Ruderman-Kittel-Kasuya-Yosida*) in metals

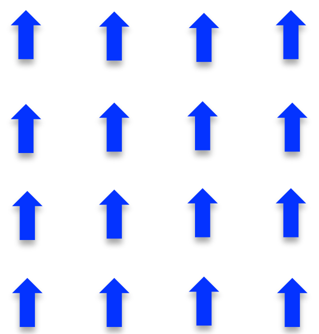
coupling localized spins on rare-earth via itinerant electrons.

$$J_{RKKY} \propto \frac{\cos(2k_F)}{r^3}$$

Magnetic moments in interaction

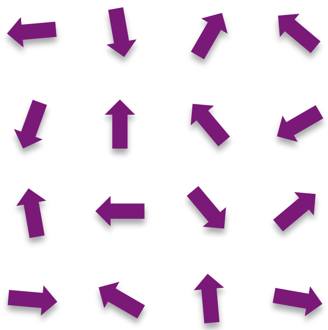
From paramagnetic state at high temperature to ordered state at low temperature: phase transition

All magnetic moments //



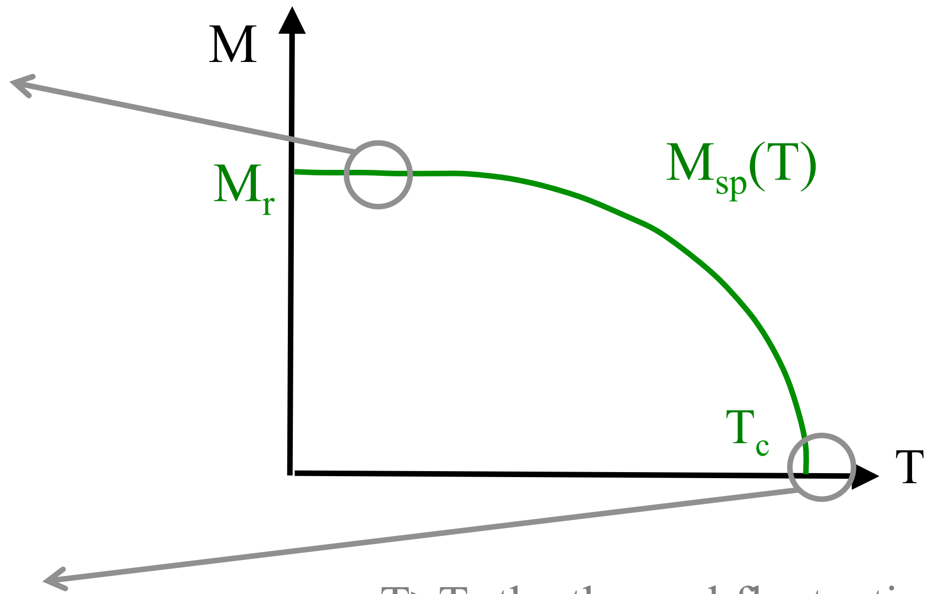
Ferromagnetic

Fluctuating moment



Paramagnetic

$T \ll T_c$ exchange interactions dominate

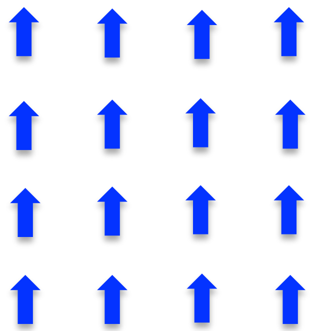


$T > T_c$ the thermal fluctuations dominate over exchange interactions in zero field

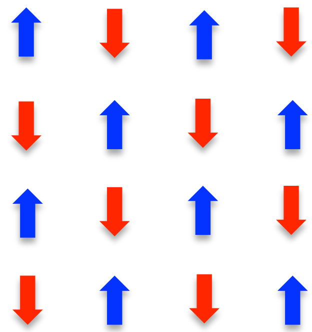
Magnetic moments in interaction

Collinear ordered states

All magnetic moments //

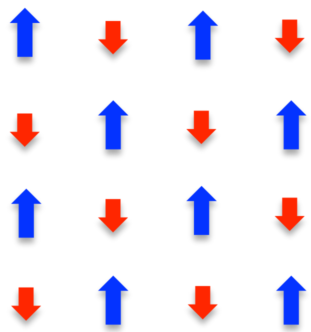


Ferromagnetic



Antiferromagnetic

Several sublattices: ≠ direction of magnetic moments ➔ compensate



Ferrimagnetism

Several sublattices do not compensate

➔spontaneous magnetization

Ex. ferrites, garnets…

Magnetic moments in interaction

Molecular field model

Calculation of magnetization and susceptibility for interacting magnetic moments

The interactions are represented by a fictitious field from neighboring moments

$$\mathcal{H} = -\sum_{ij} \mathrm{J}_{ij} \vec{S}_i . \vec{S}_j + g\mu_B \sum_j \vec{S}_j . \vec{B}$$

$$\mathcal{H} = g\mu_B \sum_i \vec{S}_i . (\vec{B} + \vec{B}_{mf}) \quad \text{with} \quad \vec{B}_{mf} = -\frac{2}{g\mu_B} \sum_j \mathrm{J}_{ij} \vec{S}_j$$

Magnetic moments in interaction

Molecular field model

Ferromagnetic case:

Calculation of the susceptibility in the low field, high temperature limit

$$\vec{B}_{mf} = \lambda \vec{M}$$

$$M = \frac{(g_J \mu_B)^2 J(J+1)}{3 k_B T}(B + \lambda M) = \frac{C}{T}(B + \lambda M)$$

$$\chi = \frac{C}{T - \lambda C} = \frac{C}{T - T_C}$$

$T_C = \lambda C$ the Curie temperature

- At T_C, χ becomes infinite : the system becomes spontaneously magnetized
- Below T_C, the moments can be aligned by the internal molecular field without *B*

Magnetic moments in interaction

Molecular field model

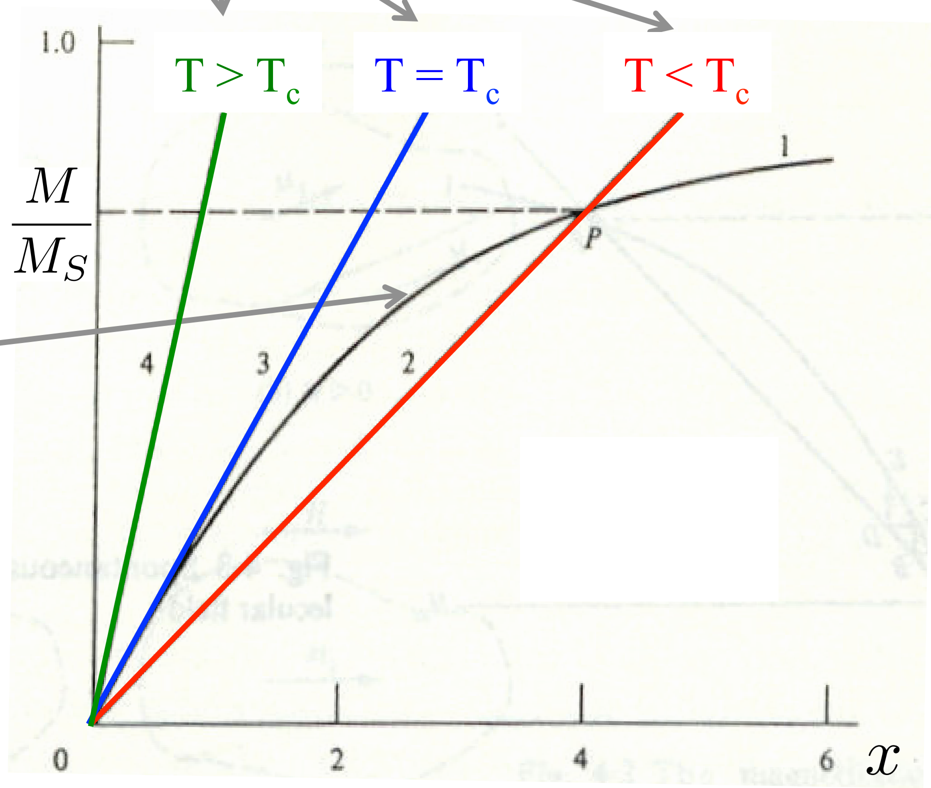
$$x = \frac{g_J \mu_B J(B + \lambda M)}{k_B T}$$

Ferromagnetic case:

Calculation of the magnetization below Tc

➔ Solve simultaneously 2 equations for B=0

$$M = g_J \mu_B J B_J(x)$$

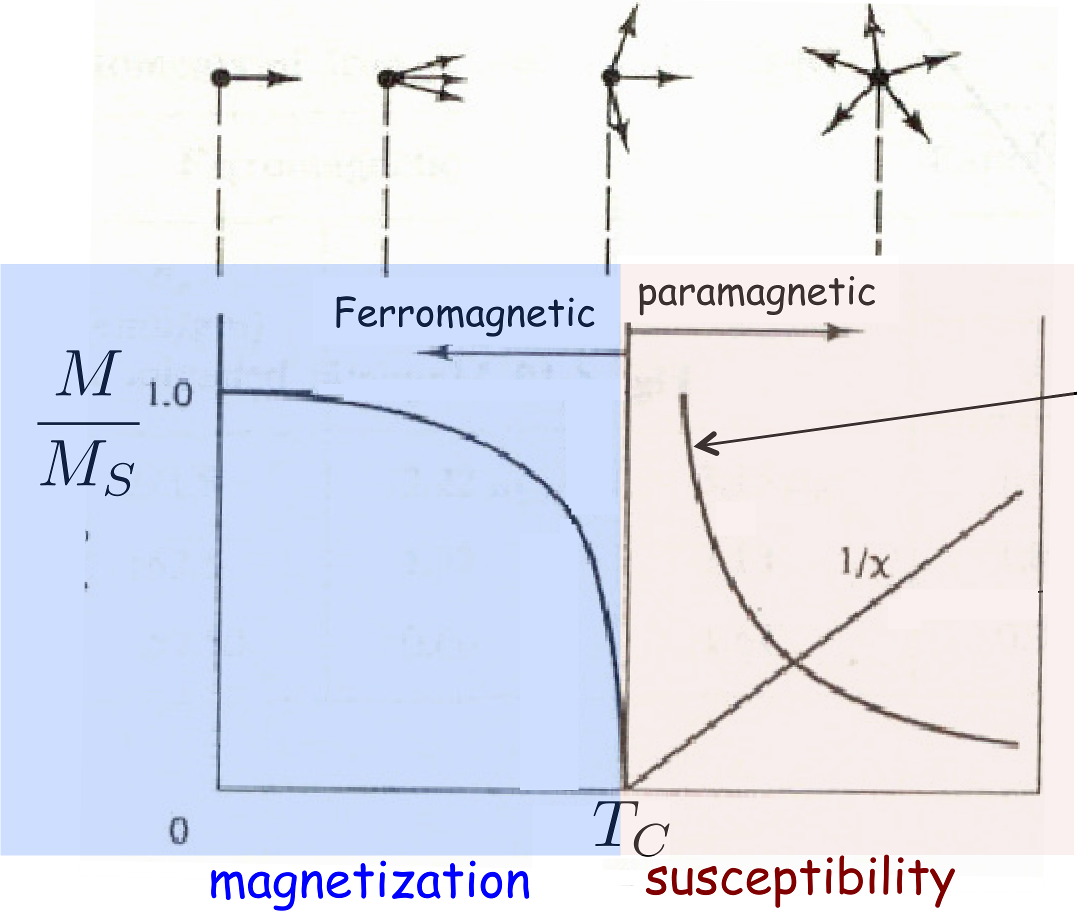


No solution for T > T$_C$
One solution for T < T$_C$
Spontaneous magnetization
2nd order phase transition at T$_C$

Magnetic moments in interaction

Molecular field model

Ferromagnetic case: summary



$$\chi = \frac{C}{T - T_C}$$

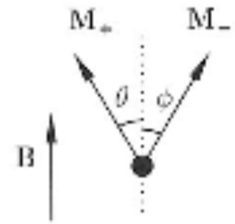
Magnetic moments in interaction

Molecular field model

Antiferromagnetic case: same analysis but for each of the 2 sublattices

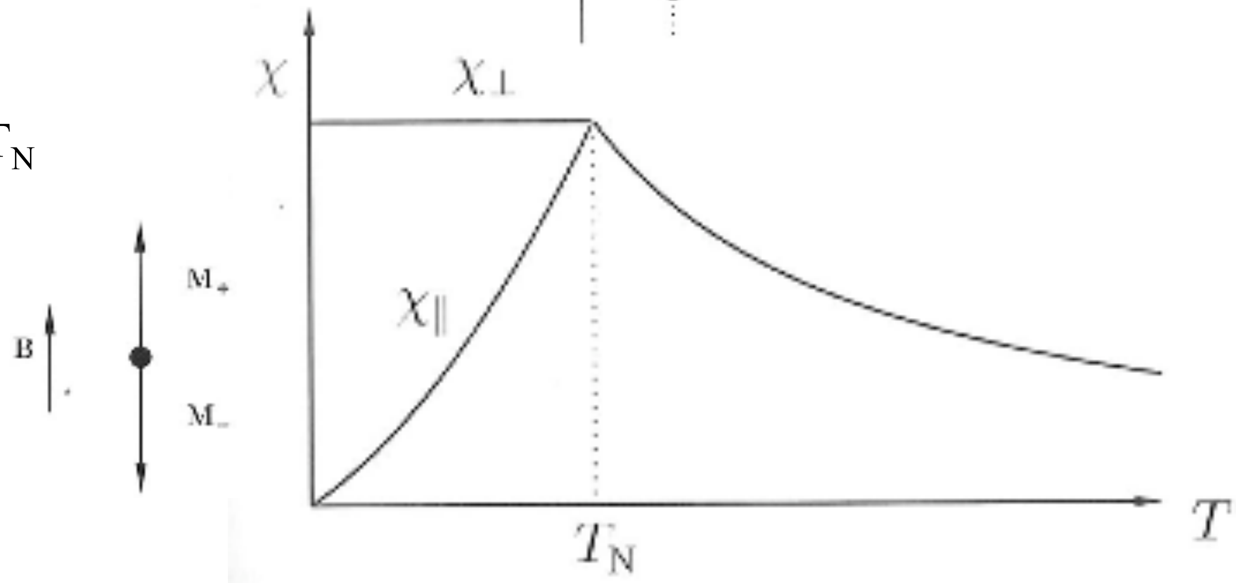
Spontaneous magnetization below the Néel temperature T_N

Susceptibility above T_N :
$$\chi = \frac{C}{T + T_N}$$



$$T_N = |\lambda| C$$

More complicated behavior below T_N
depends on the field orientation
for a single crystal

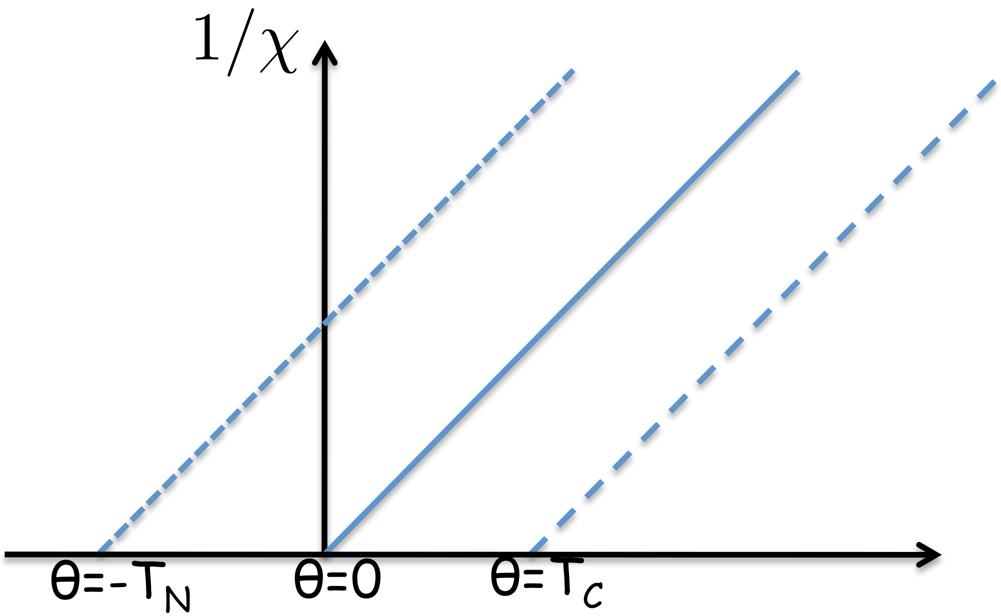


Magnetic moments in interaction

Molecular field model

Generalization: **Curie-Weiss law**

$$\chi = \frac{C}{T-\theta}$$



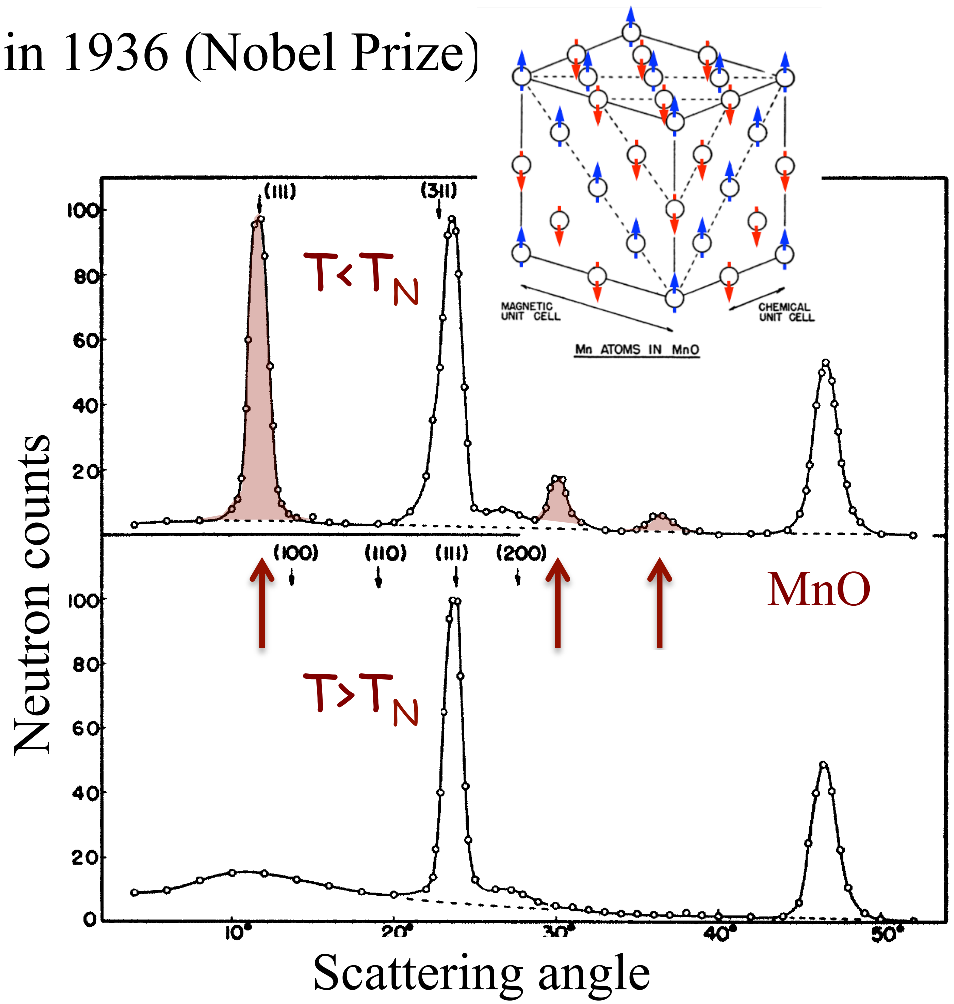
Antiferromagnets	Ferromagnets
T_N	T_C
CoO 293 K	Co 1394 K
NiO 523 K	Ni 631 K
MnO 116 K	Fe 1043 K
	Gd 293 K

Magnetic moments in interaction

Antiferromagnets

predicted by Louis Néel in 1936 (Nobel Prize)

MnO T_N=116 K



Shull 1951

Neutron diffraction

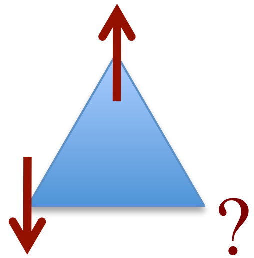
Magnetic moments in interaction

Other types of magnetic states (non collinear, disordered)

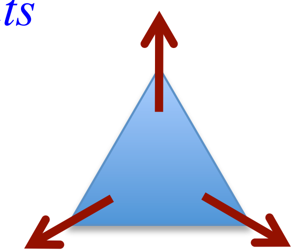
Complex magnetic structures or disordered ground states due to magnetic frustration

- Lattice geometry: ex. triangle of magnetic moments antiferromagnetically interacting

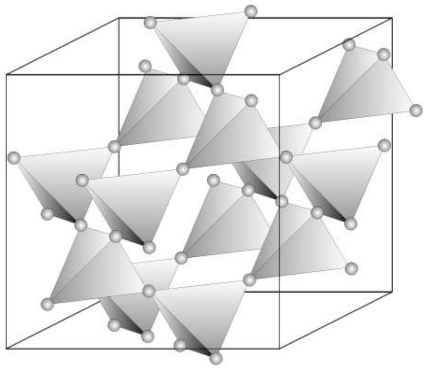
Ising moments

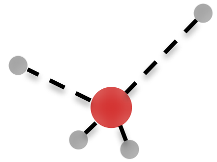


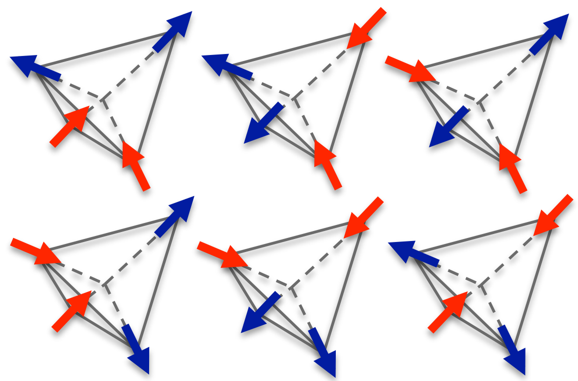
Heisenberg moments



ex. Spin ice in a pyrochlore lattice







Magnetic moments in interaction

Other types of magnetic states (non collinear, disordered)

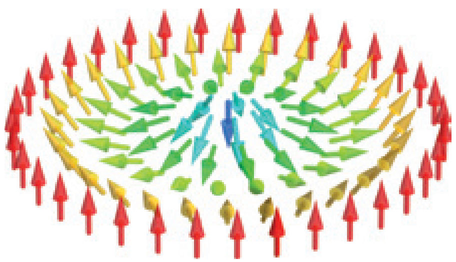
• Competition of interactions:

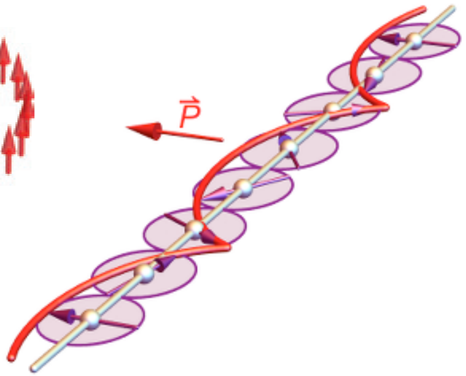
Several exchange interactions,

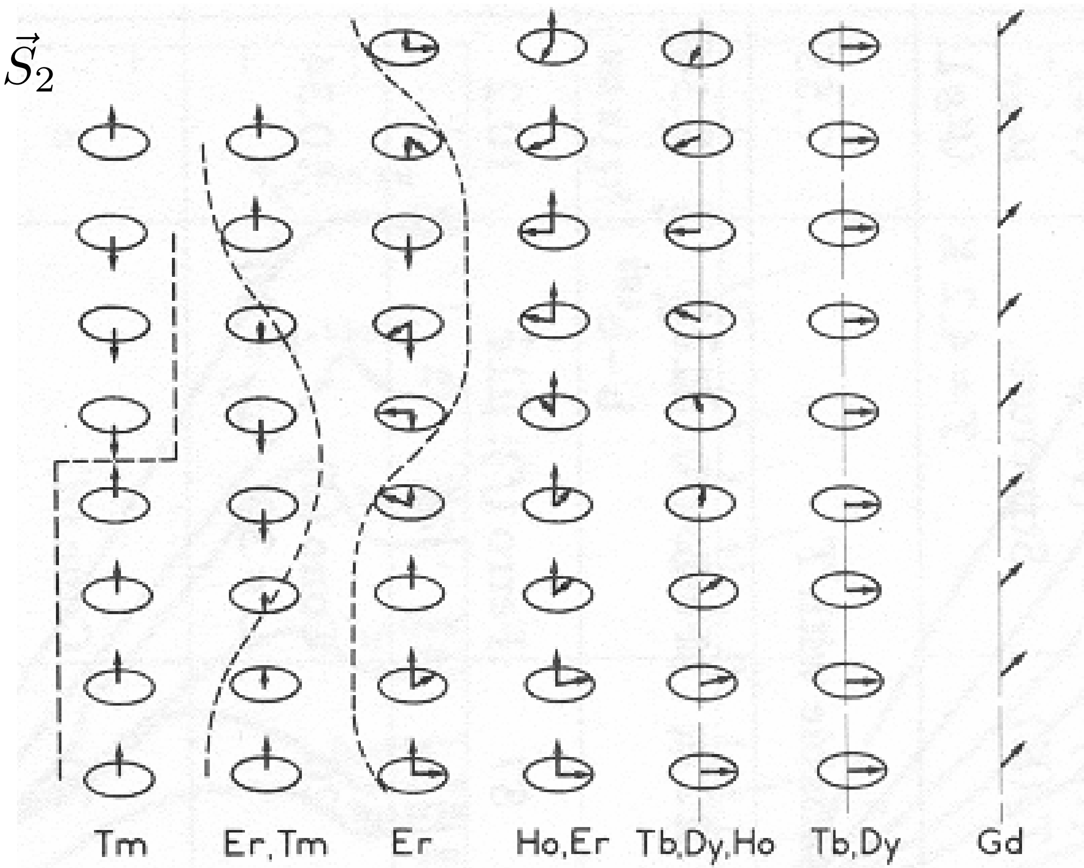
Dzyaloshinsky-Moriya interaction $\vec{D}.\vec{S}_1 \times \vec{S}_2$

Ex. Rare earth metals

➔ ex. spin density wave, helix, conical order, cycloids, spin textures like skyrmions



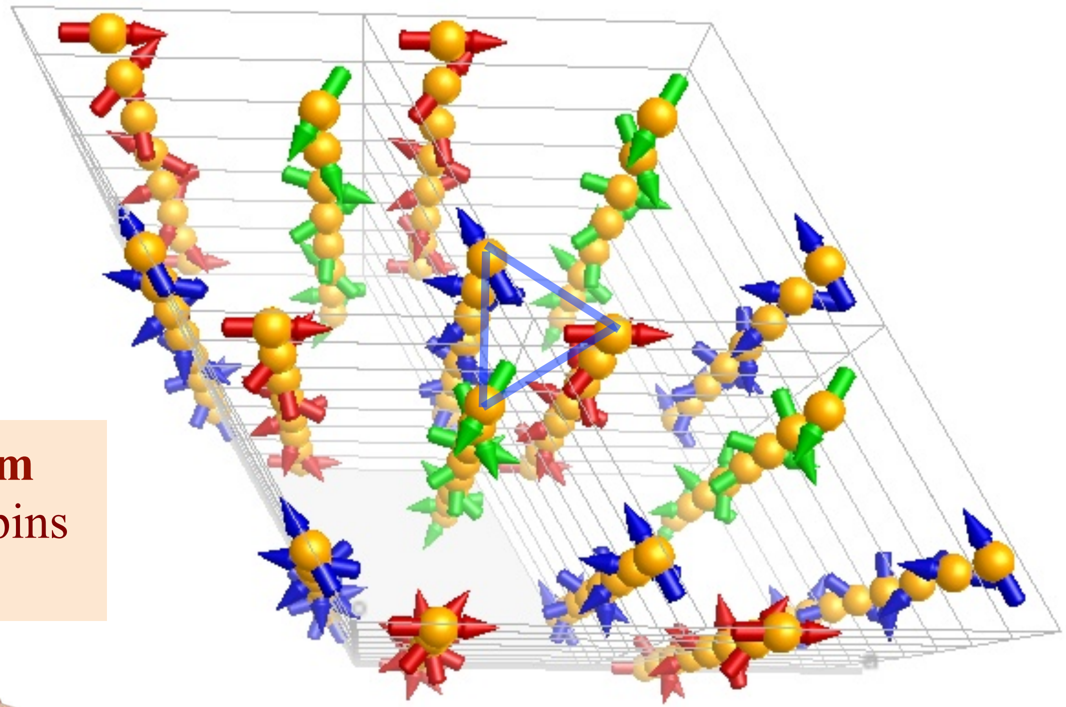




Magnetic moments in interaction

Other types of magnetic states (non collinear, disordered)

- Example of $Ba_3NbFe_3Si_2O_{14}$ insulator, helix + 120° arrangement, chiral compound



- **Definition of chirality in Magnetism**

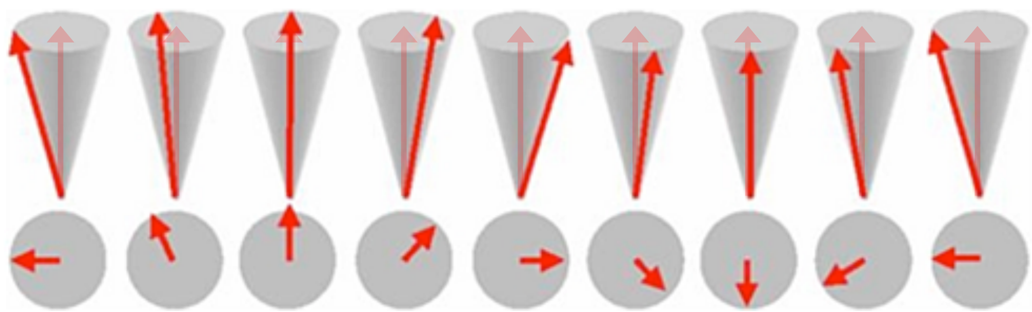
➔Sense of rotation of non collinear spins along an orientated line

Magnetic moments in interaction

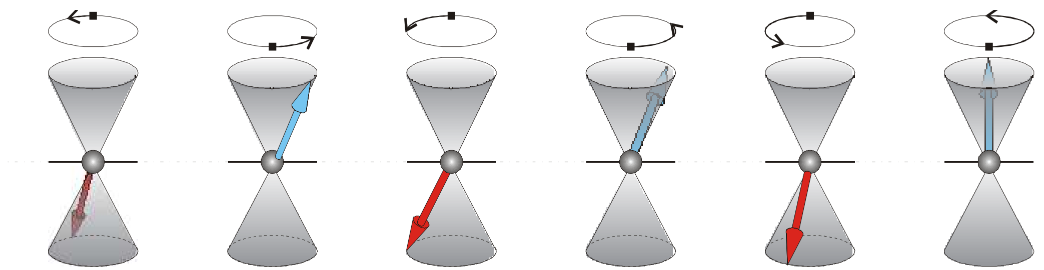
Magnetic excitations

Perfect order at T=0
At T≠0, order disrupted by spin waves
Allow entropy gain without losing too much in exchange energy

Ferromagnet



Antiferromagnet



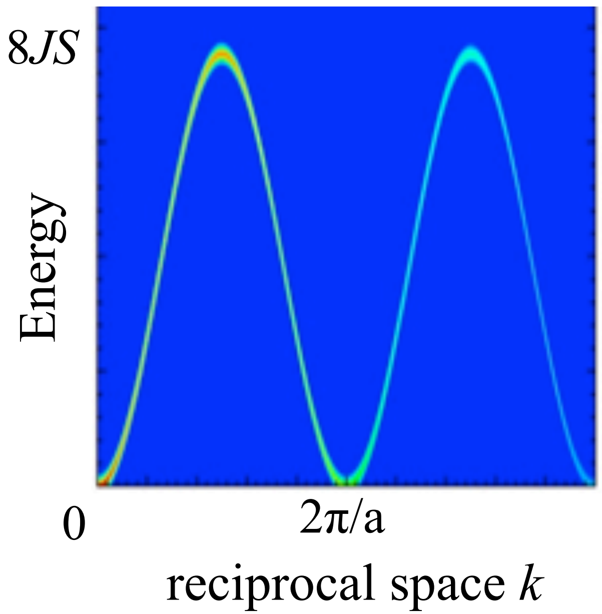
Magnetic moments in interaction

Magnetic excitations

Dispersion relation for a cubic crystal
Probed by inelastic neutron or resonant X-ray scattering: information on the ground state Hamiltonian

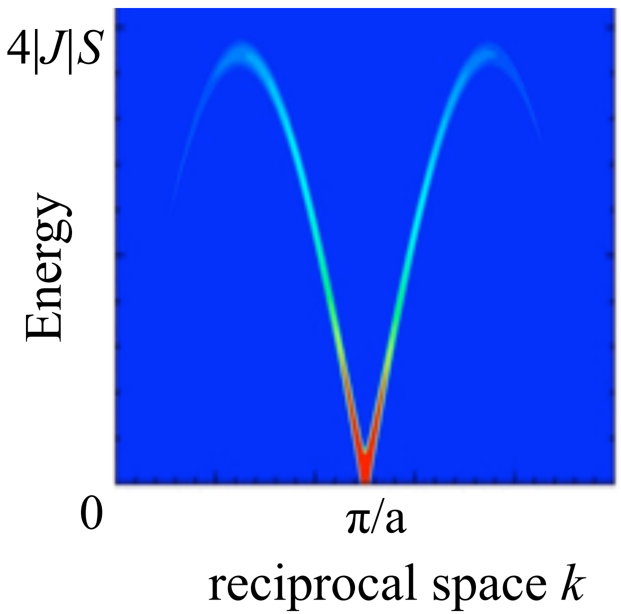
Ferromagnet J>0

$$E(k) = 4JS(1 - \cos(ka))$$



Antiferromagnet J<0

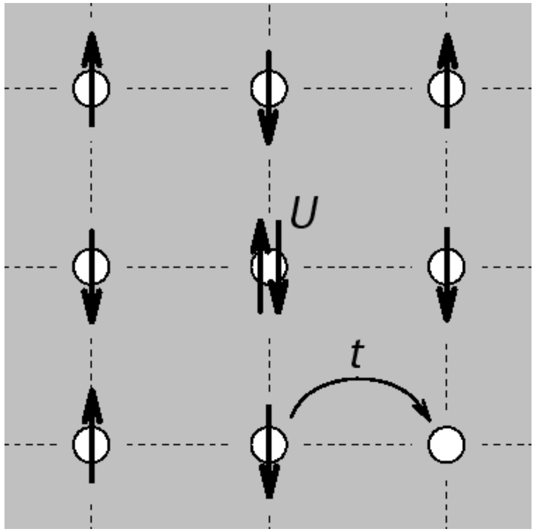
$$E(k) = -4JS|\sin(ka)|$$



Localized versus itinerant electrons

Hubbard model

$$H_{\text{Hubbard}} = -\sum_{i,j} t_{i,j,\sigma} c^{\dagger}_{i,\sigma} c_{j,\sigma} + \sum_{i} U n_{i,\uparrow} n_{j,\downarrow}$$



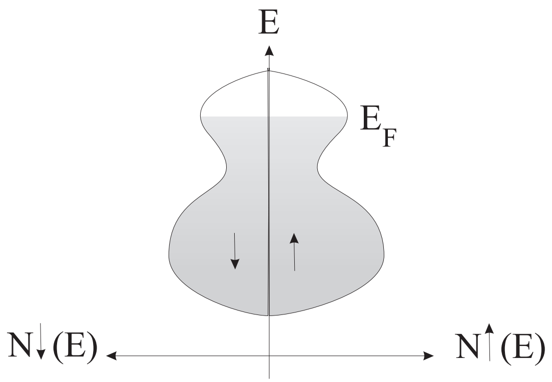
- Metal state due to hopping term t (gain in kinetic energy from Heisenberg uncertainty principle)➔ measure of band width
- Coulomb energy U: cost of putting 2 e^- on the same lattice site (Pauli exclusion principle) ➔measure of electron correlations

➔ Half filling, 1 e^- per site and $U=\infty$: insulator
➔ Half filling, U large and >> t: antiferromagnetic Mott insulator
Heisenberg Hamiltonian with $-J = 4t^2/U$
➔ $U \approx t$ metal-insulator transition
➔ $t >> U$ metallic ferromagnetic

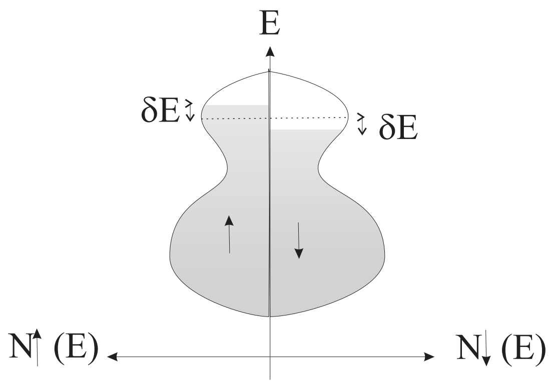
Localized versus itinerant electrons

Magnetism in metals

Starting point: the free electron model, properties of Fermi surface, electronic band structure, then add correlations



For a non-magnetic metal: same number of spin ↑ and ↓ electrons at Fermi level



Spin-split bands by magnetic field
➔ magnetization

$$\Delta M = 2\mu_B N(E_F)\delta E$$

Pauli paramagnetism
Bands split by magnetic field
Temperature independent > 0
Enhanced by e⁻ correlations

$$\chi_P = \mu_0 \mu_B^2 N(E_F)$$

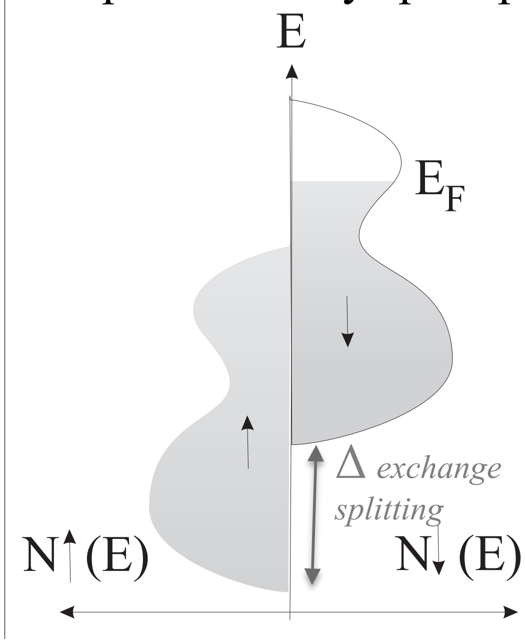
Landau diamagnetism
Orbital response of e⁻ gas to magnetic field
Temperature independent < 0

$$\chi_L = -\frac{m_e}{m^*}^2 \frac{\chi_P}{3}$$

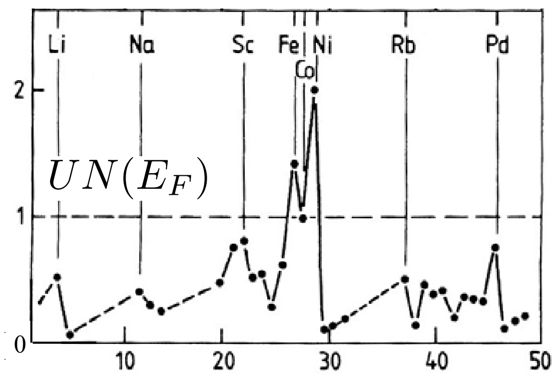
Localized versus itinerant electrons

Magnetism in metals

A spin-dependent electron interaction
Spontaneously spin-split bands: Stoner criterion



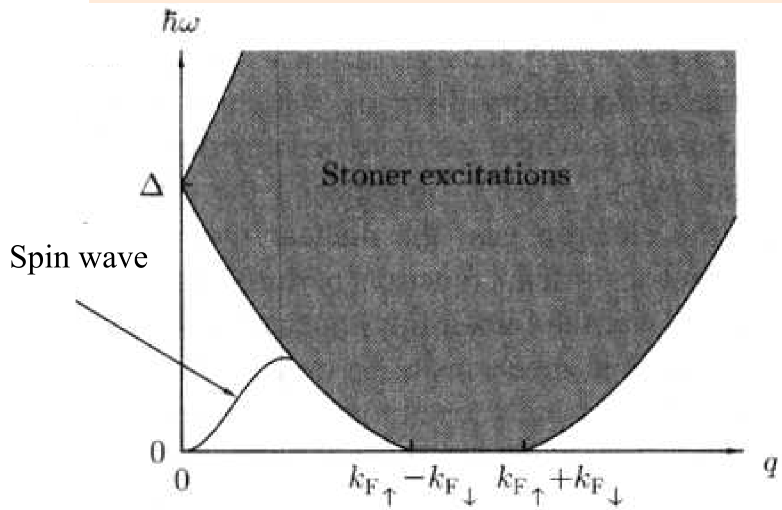
$$UN(E_F) \geq 1$$



➔band ferromagnetism
➔non-integer magnetic moment

Excitation in the e- gas:
Stoner continuum:
e^- hole excitations from to bands

$$\hbar\omega = E_{k+q} - E_k + \Delta$$



and more: generalized susceptibility, spin-density wave instabilities, Kondo effect…

From microscopic to macroscopic

Macroscopic behavior of magnetization, a compromise between 4 mechanisms:

✔Exchange interaction: favors uniform magnetization. Very strong but short-ranged

✔Dipolar interaction:
tends to avoid the formation of magnetic poles. Weak but long-ranged

✔Magnetocrystalline anisotropy:
orients the magnetic moments along privileged directions

✔Zeeman energy:
interaction with an external magnetic field
➔ alignment of the magnetic moments along the field

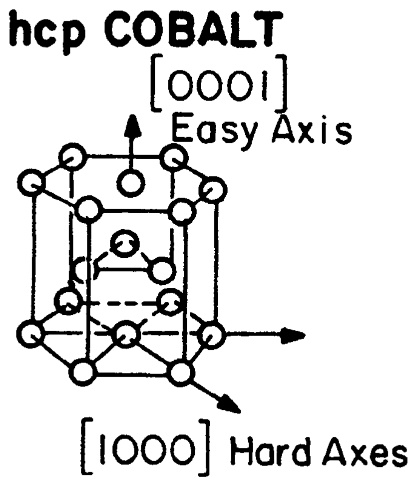
for a homogeneous ferromagnetic material, minimization of the energy:

$$F_T = F_{ex} + F_{dip} + F_{an} + F_H$$

From microscopic to macroscopic

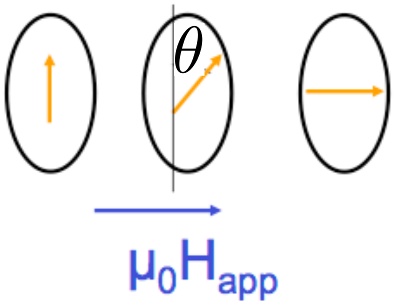
Magnetocrystalline anisotropy

➔Magnetic moments prefer to align along certain crystallographic directions (stronger for 4f than for 3d atoms)

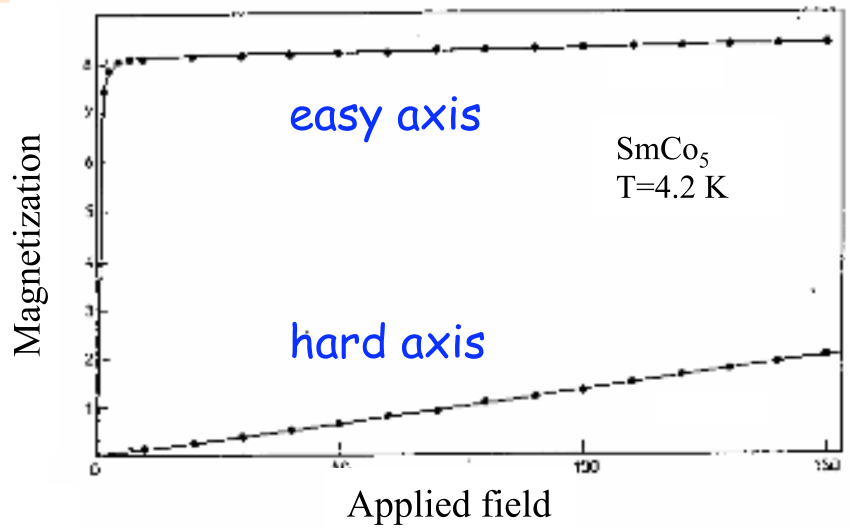


Magnetization variation against anisotropy in ferromagnets

Uniaxial anisotropy

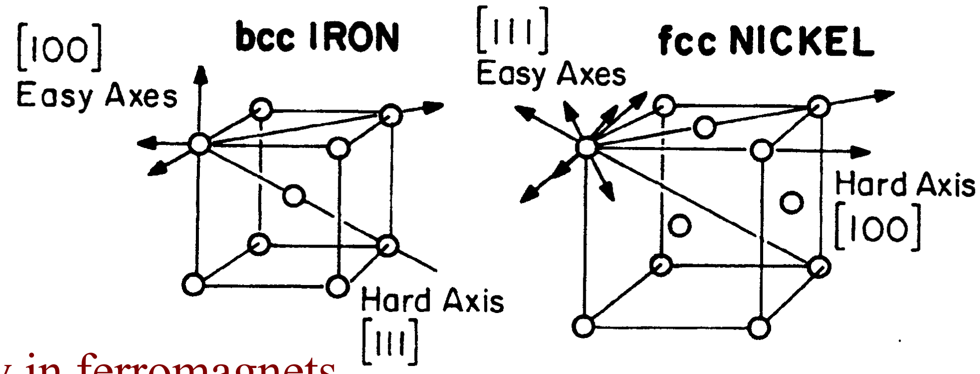


$$E = K \sin^2 \theta$$



From microscopic to macroscopic

Magnetocrystalline anisotropy

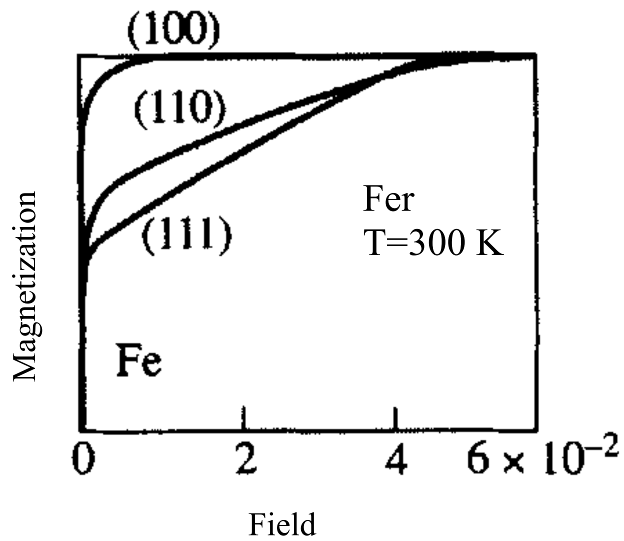


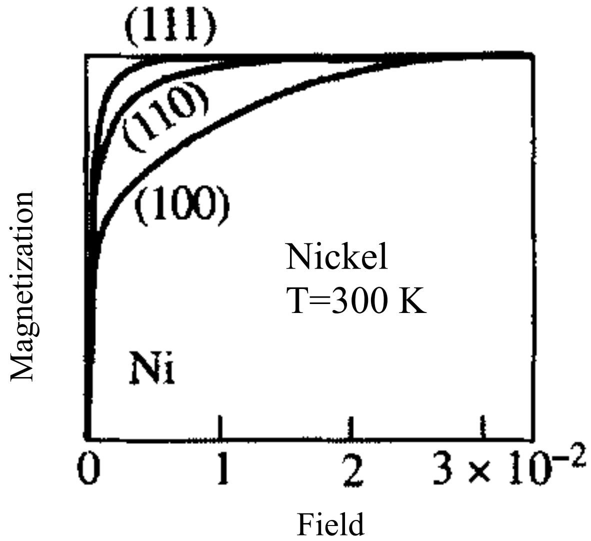
Magnetization variation against anisotropy in ferromagnets

Easy axis <100>

Cubic symmetry

Easy axis <111>





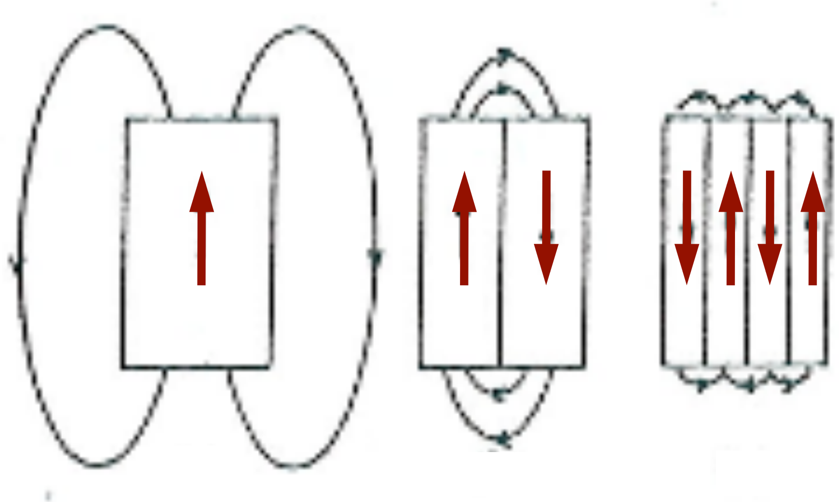
From microscopic to macroscopic

Dipolar energy $$E = \frac{\mu_0}{4\pi r^3}[\vec{\mu}_1.\vec{\mu}_2 - \frac{3}{r^2}(\vec{\mu}_1.\vec{r})(\vec{\mu}_2.\vec{r})]$$

Minimizing the demagnetizing field produced by the material

➔ shape anisotropy

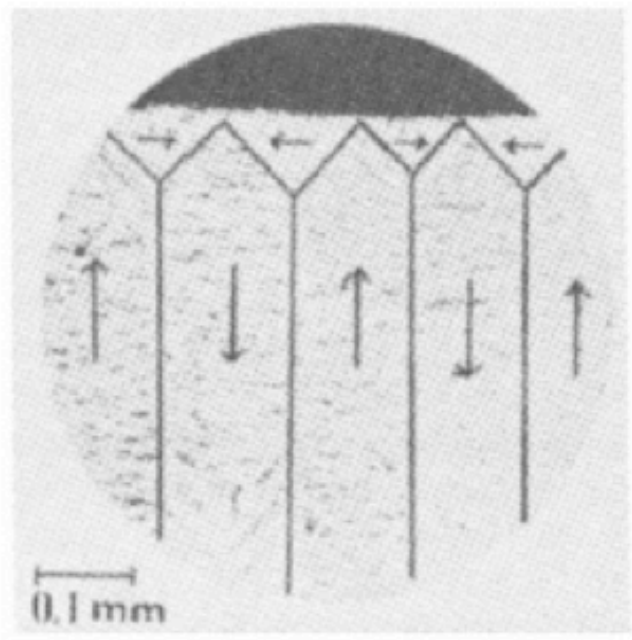
➔ formation of magnetic domains with magnetization // anisotropy directions



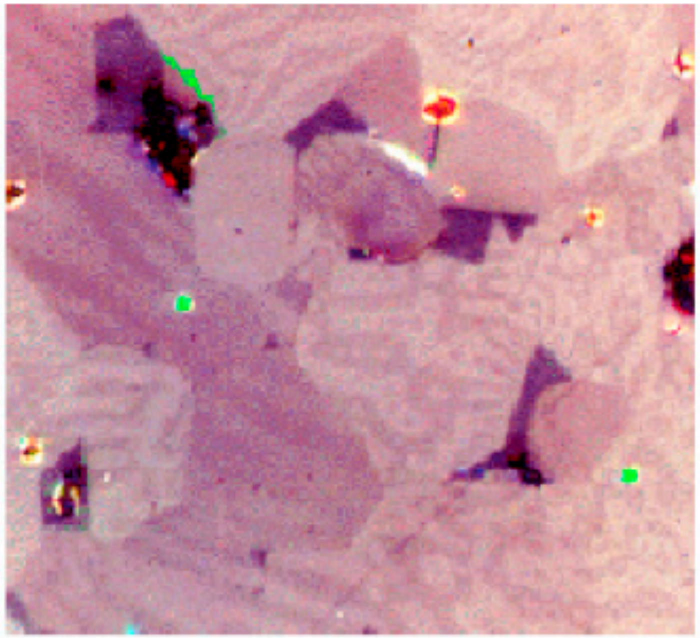
➔Explains zero macroscopic magnetization in ferromagnetic materials below T_C if they have not been submitted to a magnetic field

From microscopic to macroscopic

Magnetic domains



Fe-Si



NdFeB

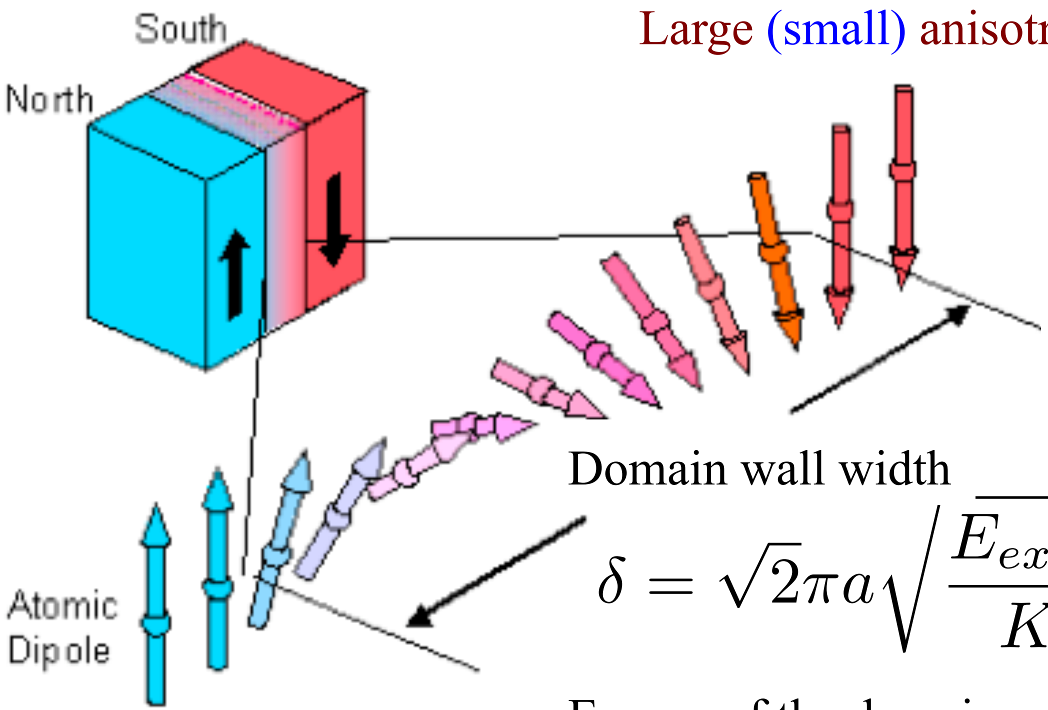
Cost in exchange and anisotropy energies
at the boundaries between domains: domain walls

From microscopic to macroscopic

Width of the wall: balance between exchange and anisotropy energy

Bloch walls

Large (small) anisotropy ➔ narrow (wide) domain walls



Domain wall width

$$\delta = \sqrt{2}\pi a \sqrt{\frac{E_{exch}}{K}}$$ ≈5-10 nm

Energy of the domain wall: $\gamma = \pi\sqrt{2}\sqrt{K E_{exch}}$

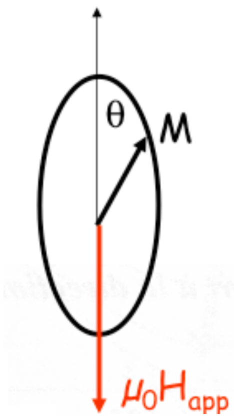
From microscopic to macroscopic

Coercitivity represents the magnetization ability to resist reversal against applied magnetic field

Coercive field for coherent rotation ➔
Stoner-Wolfarth model:

$$E = K \sin^2\theta + \mu_0 M_s H \cos\theta$$

Uniaxial anisotropy Zeeman term



From microscopic to macroscopic

Coercitivity represents the magnetization ability to resist reversal against applied magnetic field

Coercive field for coherent rotation➔
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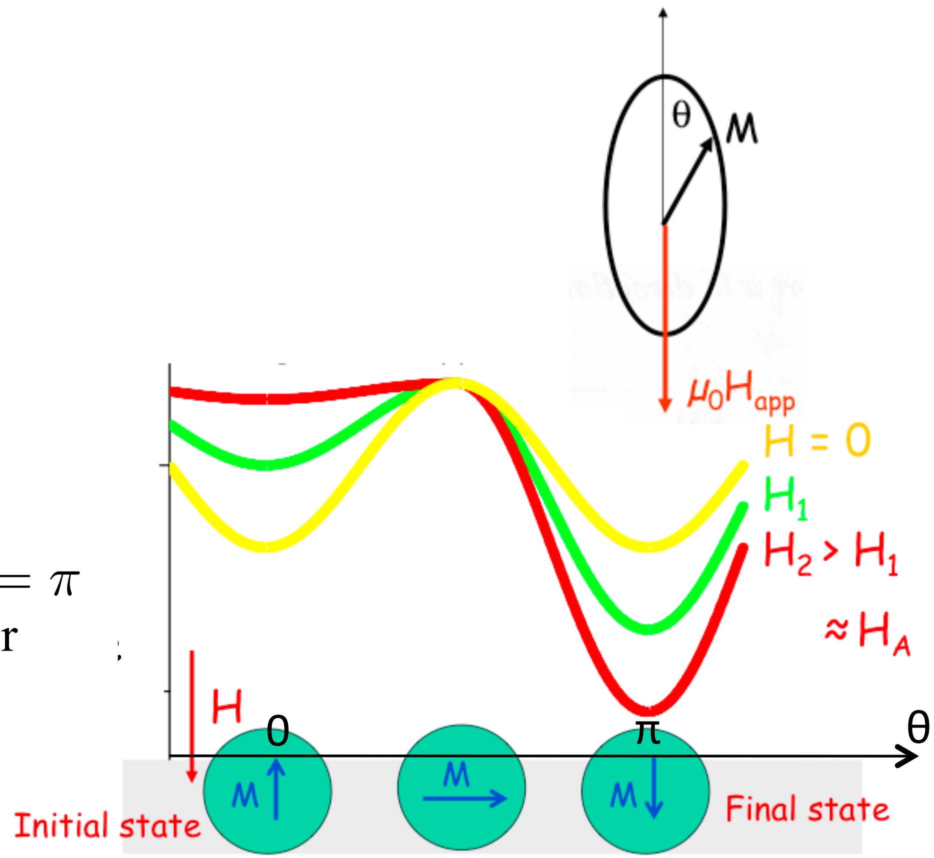
Uniaxial anisotropy Zeeman term

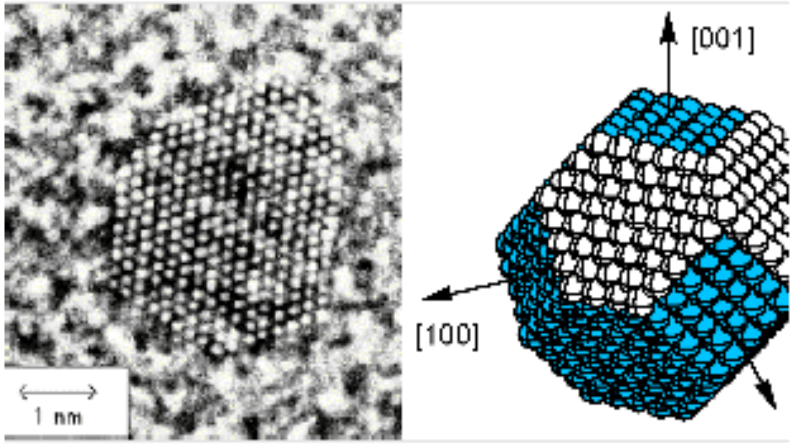


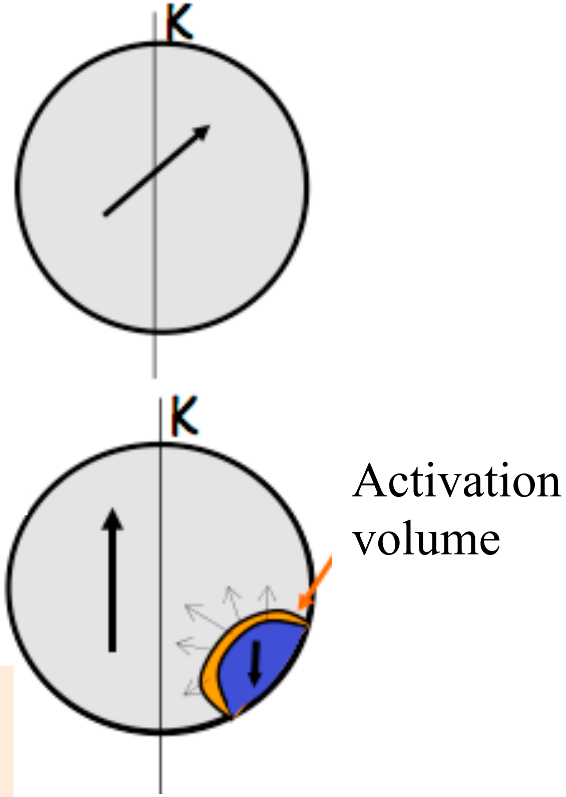
- As long as $H < 2K/\mu_0 M_s$, $\theta = 0$ and $\theta = \pi$ are two minima separated by an energy barrier
- When $H = 2K/\mu_0 M_s$, the barrier flattens and the magnetization can rotate to the minimum $\theta = \pi$

From microscopic to macroscopic

Stoner-Wohlfarth model works well for nanoparticles

The coercive field $H_c = 2K/\mu_0 M_s$



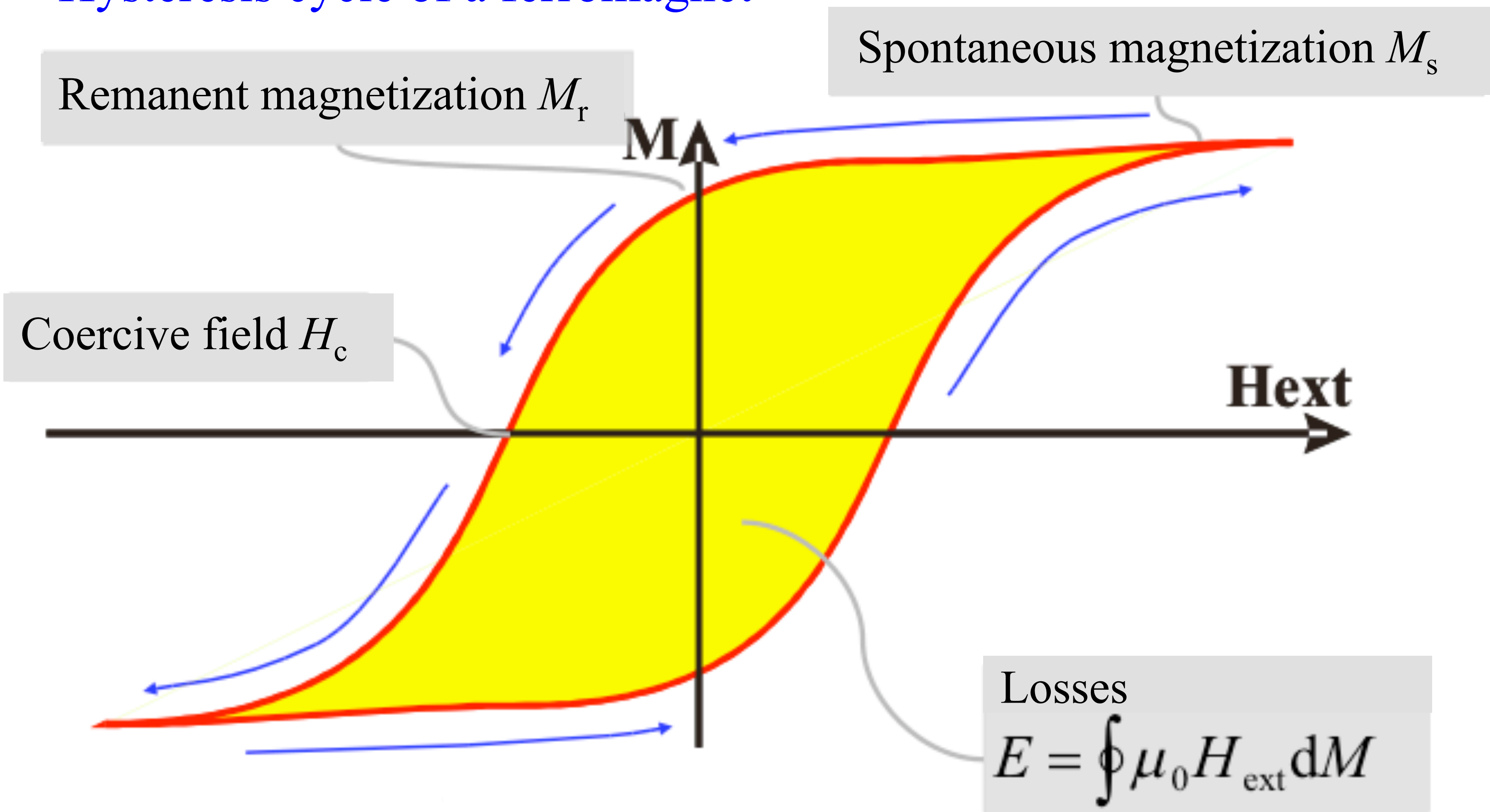


But $H_c << 2K/\mu_0 M_s$ for most systems

In macroscopic materials, influence of defects:
Rotation occurs by nucleation on defects
and propagation of domain walls

From microscopic to macroscopic

Hysteresis cycle of a ferromagnet



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

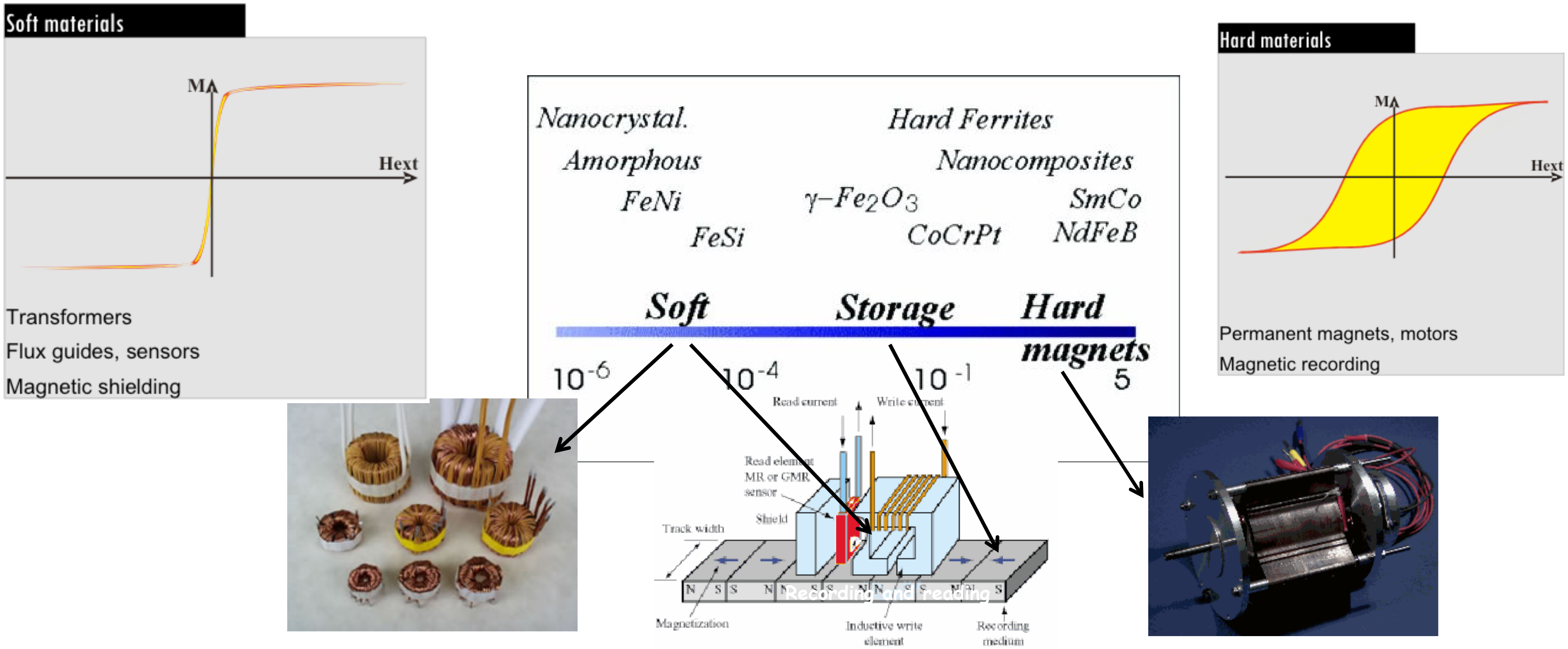
Applications

Applied research ➔ lots of applications, concerns mostly ferromagnetic materials

Hard magnetic materials: reasonable value of remanence, high coercitivity

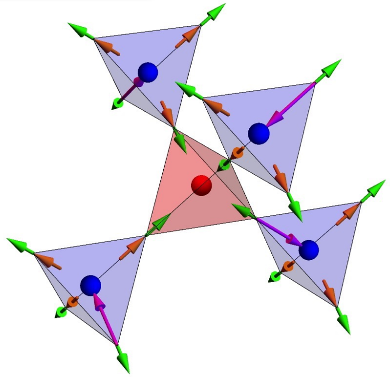
Soft magnetic materials: high remanence, low coercitivity

Materials for electronics: operate at high frequencies

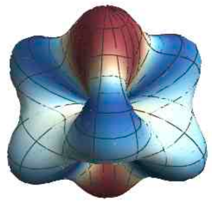


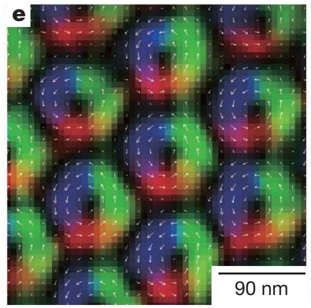
Recording and reading

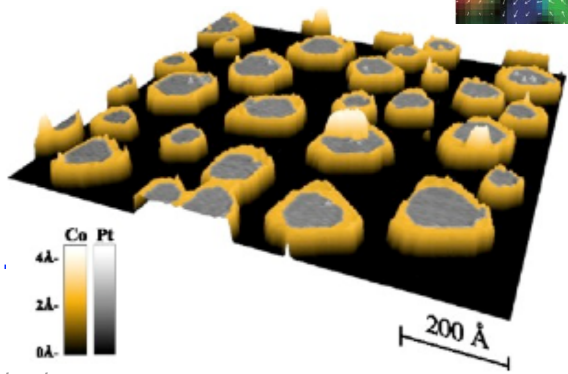
Research in magnetism: modern trends



- Magnetic frustration: complex magnetic (dis)ordered ground states
- Molecular magnetism: photoswitshable, quantum tunneling
- Mesoscopic scale (from quantum to classical) ➔ quantum computer
- Multiferroism: coexisting ferroic orders (magnetic, electric…)
- Quantum phase transition (at T=0)
- Low dimensional systems: Haldane, Bose-Einstein condensate, Luttinger liquids
- Iridates and topological matter
- Magnetism and superconductivity
- Nanomaterials: thin films, multilayers, nanoparticles
- Spintronics: use of the spin of the electrons in electronic devices
- Skyrmionics
- Magnetoscience: magnetic field effects on physics, chemistry, biology …







Further reading

- "**Magnetism in Condensed Matter**" by Stephen Blundell, *Oxford University press (2003)*

- "**Introduction to magnetism**" by Laurent Ranno, *collection SFN 13, 01001 (2014), EDP Sciences, editors V. Simonet, B. Canals, J. Robert, S. Petit, H. Mutka*,

  free access DOI: http://dx.doi.org/10.1051/sfn/20141301001

- "**Magnetism and Magnetic Materials**" by J.M.D. Coey, Cambridge Univ. Press (2009)

- "**Magnétisme**" by Trémolet de Lacheisserie, EDP Sciences (2000)

- Any questions: virginie.simonet@neel.cnrs.fr