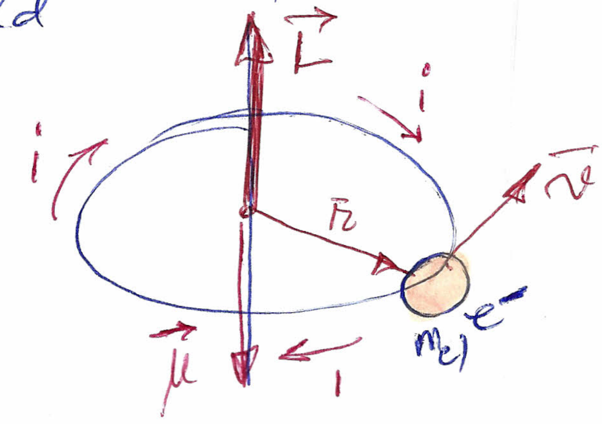
MAGNETIC MATERIALS

When discussing how currents cause magnetic fields we assumed that the conductors are surrounded by vacuum. However, coils in transformers, motors, generators, electromagnets nearly allways have iron cores to increase the magnetic field and confine it to desired regions

Permanent magnets, magnetic recording tapes, hard disks depend directly on the magnetic properties of the materials. Magnetic materials have extreme importance in technics and advanced technologies from sensors to data-storage (read-heads in hard-disks, ABS sensors, hard-disks, ..). We are going to describe some aspect of the magnetic properties of the materials. After describing the <u>atomic origin</u> of the magnetic properties we will discuss several classes of magnetic behavior that occur in materials: <u>diamagnetism</u>, <u>paramagnetism</u>, <u>ferromagnetism</u>, <u>antiferromagnetism</u>. Eventually, we will point-out how the magnetic properties of a material can be tailored by the dimensionality.

The Bohr magnetron

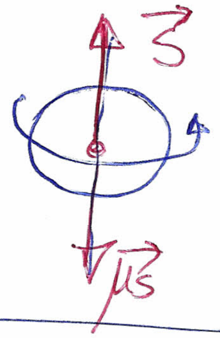
The atoms, contain moving electrons and these e^- form microscopic current loops that produce magnetic field



$\vec{L}$ = angular momentum of e^- and

$\vec{\mu}$ = magnetic dipole moment

The e^- will also have a SPIN angular momentum, and an oppositely oriented spin magnetic dipole moment.



Ok

Classical electronics : manipulate the electron charge

Spin-electronics* : manipulates both charge and spin.

electron = $\underset{\text{charge}}{\bigcirc\!\!\!\!\!\!-e\;\;}$ + spin ↑ or ↓

→ Nobel prize Physics 2007 (A. Fert & P. Grünberg)
Discovery of giant magnetoresistance
– huge impact in read-heads / data-storage technologies.

* see later course on SPINTRONICS and APPLICATIONS

Microscopic currents

The moving charge ⟺ current loop ; we found that the current loop with area A has a magnetic dipole moment $\mu = IA$; $A = \pi r^2$

The e^- associated current is: $I = \frac{e}{T}$
T = the orbital period
$T = \frac{2\pi r}{v}$

$$\left.\begin{array}{l} I = \frac{e}{T} \\ T = \frac{2\pi r}{v} \end{array}\right\} \Rightarrow i = \frac{ev}{2\pi r}$$

$$\Rightarrow \mu = \frac{e \cdot v}{2\pi r} \cdot \pi r^2 = \frac{e v r}{2}$$

if we consider the angular momentum of electron:

$L = m v r$

$$\Rightarrow \boxed{\mu = \frac{e}{2m} L}$$

We'll see later (QM) that the angular momentum is quantized (its component in a particular direction is allways an integer multiple of $\hbar = \frac{h}{2\pi}$) where h is a fundamental constant called Planck's constant

$$h = 6,625 \cdot 10^{-34}\ J \cdot s$$

Obs: $\hbar = h/2\pi$ is a fundamental unit of angular momentum likewise e is an elementary charge

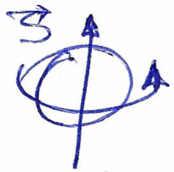
Associated with the fundamental unit of angular momentum L is a corresponding fundamental unit of magnetic momentum! If $L = \frac{h}{2\pi} = \hbar$

$$\Rightarrow \boxed{\mu = \frac{e}{2m}\left(\frac{h}{2\pi}\right) = \frac{e\hbar}{2m} = \mu_B}$$

Bohr magneton (Procopiu)

$$|\vec{\mu}_B| = 9,274 \cdot 10^{-24}\ A \cdot m^2 \ (\text{or } J/T)$$

Spin (angular moment)



Intrinsic angular momentum, classically pictured as consequence of spinning motion around own axis. (much more complex QM approach)

This angular momentum has also an associated magnetic moment, and its magnitude is one Bohr magnetron. (approx. because effects due to quantization of electromagnetic field cause spin magnetic moment to be $1.001\mu_B$)

1 PARAMAGNETISM

In an atom, most of the various orbital and spin magnetic moments of electrons add up to zero. However, in some cases the atom has a net magnetic moment that is in the order of μ_B. When such material is placed in a magnetic field $\vec{B}$, this will exert a torque on each magnetic moment:

$$\boxed{\vec{\tau} = \vec{\mu} \times \vec{B}}$$

These torque tend to allign the magnetic moments parallel to the field. In that position, the directions of the current loops are such as to add to the externally applied magnetic field. The additional $\vec{B}$ field produced by microscopic electron current loops is proportional to the total magnetic moment $\vec{\mu}_{total}$ per unit volume in the material. We call this vector quantity the MAGNETIZATION $\vec{M}$ of the material

$$\boxed{\vec{M} = \frac{\vec{\mu}_{total}}{V}}$$

(see analogy with electrostatic $\vec{P}$)

The additional magnetic field due to magnetization of the material turns out to be $\mu_0 \vec{M}$.

When such a material completely surrounds a current carrying conductor, the total magnetic field in the material is:

$$\boxed{\vec{B} = \vec{B_0} + \mu_0 \vec{M}}$$

where $\vec{B_0}$ is the field caused by the current in the conductor.

A material showing this behavior is called PARAMAGNETIC. The result is that the magnetic field at any point in such a material is greater by a dimensionless factor K_m (called RELATIVE PERMEABILITY of the material) than it would be if the material were replaced by vacuum.

Obs ① K_m depends on material; for common paramagnetic solids and liquids at Room Temperature $K \in 1.00001 - 1.003$.

② All the equations that relate magnetic field to their sources can be adapted for a situation in which the current carrying conductor is embedded in a paramagnetic material by replacing $\mu_0 \longrightarrow \boxed{K_m \mu_0 = \mu}$

permeability of material

Magnetic susceptibility

$$\boxed{\chi_m = K_m - 1}$$

$$K_m = \frac{B}{B_0} = \frac{B_0 + \mu_0 M}{B_0} = 1 + \mu_0 \frac{M}{B_0}$$

$$\Rightarrow \chi_m = K_m - 1 = \frac{\mu_0 M}{B_0} \; ;$$

$$\boxed{\chi_m = \frac{\mu_0 M}{B_0}}$$

effect = magnetization

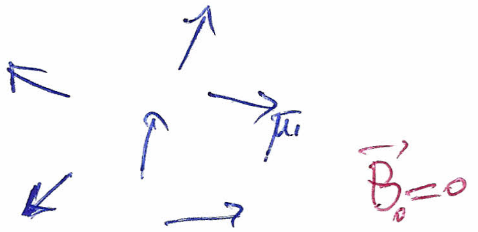
cause = applied field

susceptibility

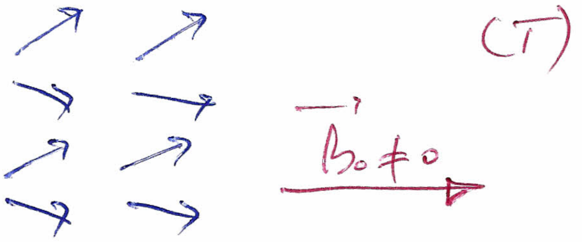
describes the response of a material (magnetization) in external field B_0

Phenomenologically

Material in zero field $\sum \vec{\mu_i} = 0$ due to thermal energy which tends to randomize orientations $\boxed{\vec{M} = \sum \vec{\mu_i} = 0}$



On an external field B_0 which tends to allign dipoles along the field (minimize potential energy), the thermal energy will allways compete and tend to randomize orientation. For this reason the magnetization $\vec{M}$ and the paramagnetic susceptibility allways decrease with increasing temperature T.



$\vec{M} = \sum \mu_i \neq 0$

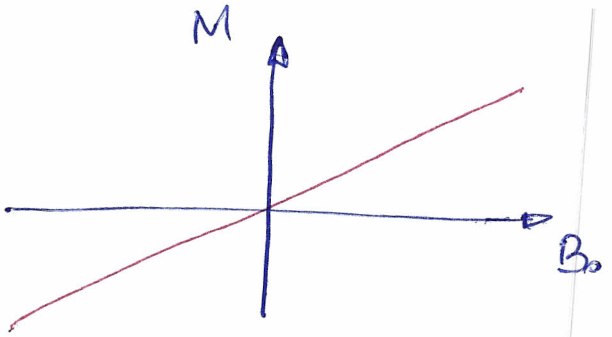
$$\boxed{M = C \frac{B}{T}}$$

absolute temperature

CURIE'S LAW

Curie constant (material constant)

(Pierre Curie 1859 – 1906)



Obs ① A body with atomic magnetic dipoles is attracted to the poles of a magnet! In most paramagnetic substances this attraction is very weak due to the thermal randomization of atomic magnetic moments, But, at very low temperatures the thermal effects are reduced, the magnetization increases (induce Curie's law) and attractive forces are greater.

2 DIAMAGNETISM

In some materials the total magnetic moment of the atomic current loops is zero, when no magnetic field is present. But, even these materials have magnetic effects because an external field alters electron's motion within the atoms, causing additional current loops and induced magnetic dipoles comparable to the induced electric dipoles (see. Electroshitics). In this case, the additional field caused by these current loops is allways opposite to the direction of the external field (this behavior will be later explained by Faraday law of induction: An induced current allways tend to cancel the field change that caused it).

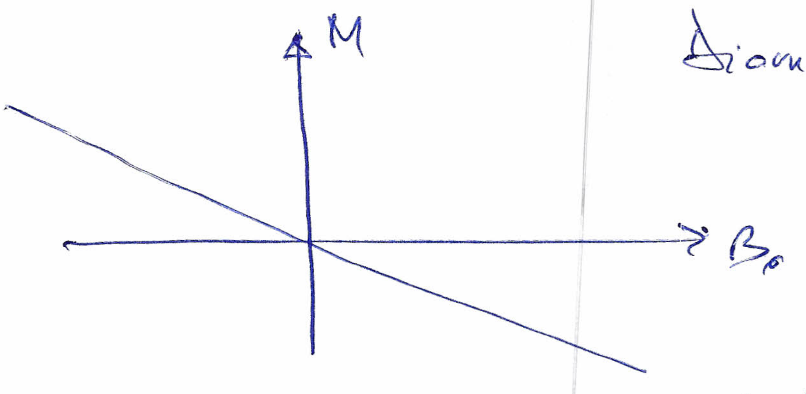
Such materials are called DIAMAGNETIC.

They will allways have negative susceptibility and relative permeability $K_m < 1$ (0.99990 to 0,99999) for liquids and solids

Obs: Diamagnetic susceptibilities are almost temperature independent.

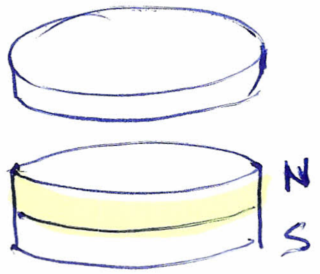
Table:

Material	$\chi_m = K_m - 1$ (10^{-5})
Paramagnetic	
Platinum	26
Al	2,2
Na	0,72
Oxygen gas	0,19
Diamagnetic	
Bi	−16,6
Hg	−2,9
Ag	−2,6
C (diamond)	−2,1
NaCl	−1,4
Cu	−1,0



Diamagnetic behavior
$\vec{M}$ opposes to $\vec{B}_0$

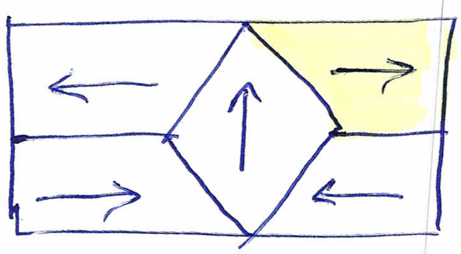
Superconductors = perfect diamagnets
→ Levitation



3 FERROMAGNETISM

There is a class of materials called ferromagnetic materials (Fe, Co, Ni, alloys with these elements). In this materials, strong interactions between atomic magnetic moments, can cause them to allign parallel to each-other in regions called MAGNETIC DOMAINS even when no external $\vec{B}$ field is present.

ⓐ



no field

domain magnetization can be randomly oriented.

ⓑ When a field $\vec{B_0}$ is present the domains tend to orient themself parallel with the field. Domain boundaries (walls) shift and domains were $\vec{M} \parallel \vec{B_0}$ grow and others shrink.

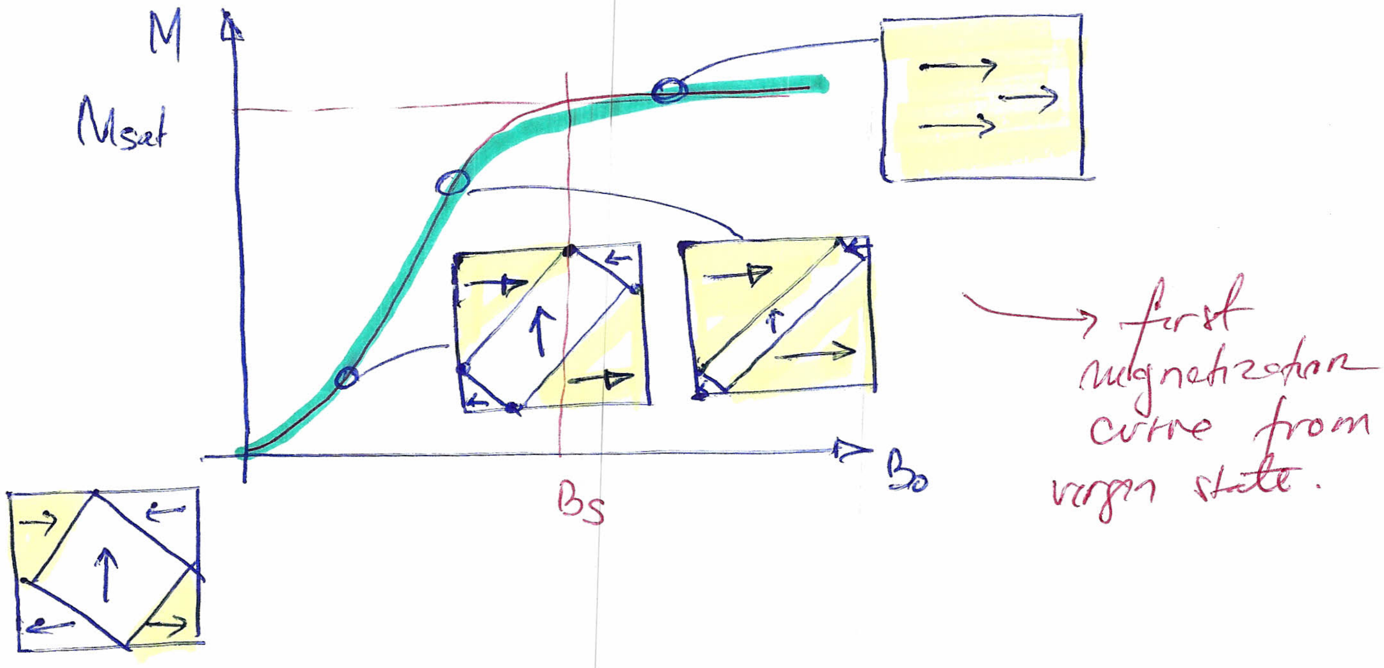
Ob The total magn. moment of a domain is large (thousants of μ_B) => the torques which tend to allign moment with field are large. The relative permeability K_m is much larger than 1 (1.000 to 100 000). As a result, such an object is strongly magnetized by the field of a permanent magnet and get attracted by it.

(a paramagnetic material (Al) is also attracted by a magnet but K_m is much smaller, so the force of attraction is very weak => a magnet can pick iron nails but no Al cans).

ⓒ As the external field is increased, after a certain extent all the moments in the ferromagnetic material get alligned along external field. This condition is called SATURATION MAGNETIZATION

After B_s ($B_0 > B_s$) no further increase of B can cause any increase of magnetization M

Magnetization curve for a ferromagnetic material)



Hysteresis curve

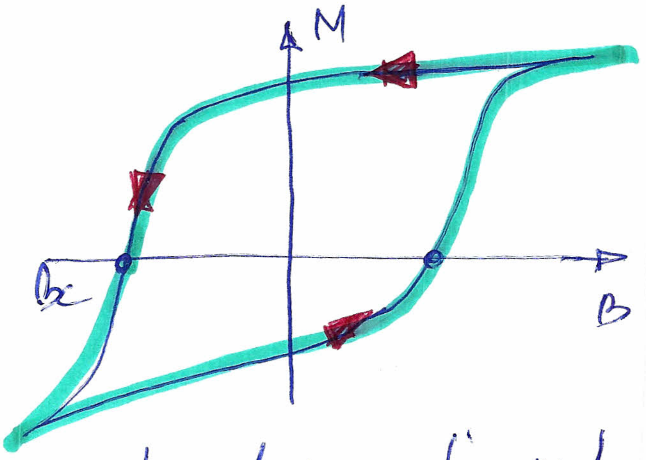
For many ferromagnetic material, the relationship of $\vec{M}$ with $\vec{B_0}$ is different when the external field is increasing from when it's decreasing. When the material is magnetized to saturation and then the external field is brought to zero some magnetization remain (M_r = remanent magnetization). This behavior is characteristic to PERMANENT MAGNETS which retains most of their saturation magnetization when the magnetizing field is removed. To reduce the magnetization, one has to apply a field in opposite direction.

$\Rightarrow$ HYSTERESYS behavior $\Rightarrow$

HYSTERESIS LOOPS $M(B)$

Magnetizing and demagnetizing a material with hysteresis involves dissipation of energy $\Rightarrow$ temperature variation during process.

Obs : - magneto-calorics effects, magnetic refrigeration

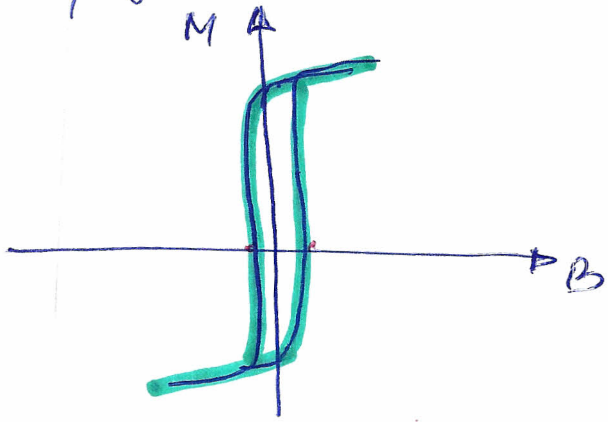


hard magnetic material

(good for permanent magnet large negative field required to reduce magnetization to zero and reverse

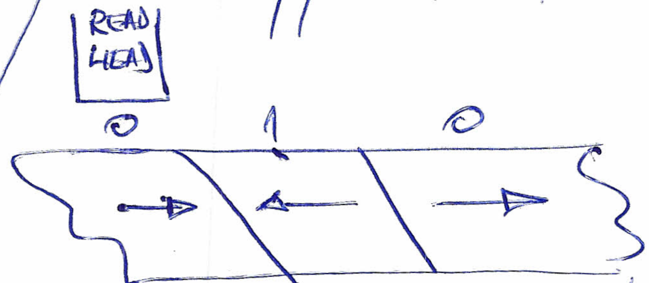
Alnico, NdFeB, $SmCo_5$, ...

$B_c \sim 1T$, $M_S = \frac{B}{\mu_0} \simeq 800000 \frac{A}{m}$

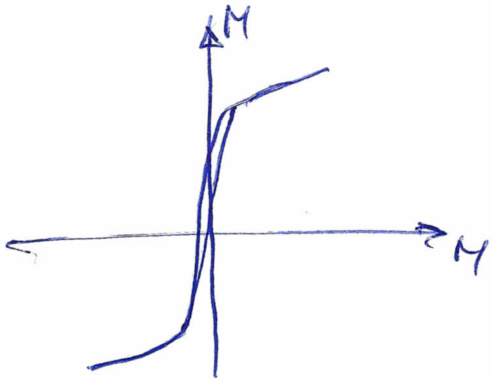


soft magnetic material

easy manipulation of magnetization => data storage / sensors applications.



memory track.



"Small" or zero hysteresis materials useful for transformers and other alternating current devices where zero hysteresys are optimal (to reduce dissipation).

ex : Soft Fe

Other applications

→ hyperthermia : magnetic nanoparticles for cancer therapy. Magnetic nanoparticles preferentially attach to tumor cells. Either external magnets are used to steer the particles out of body or magnetocaloric effects are used to locally enhance temperature and destroy tumors.

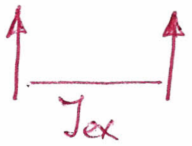
Exchange interaction

In ferromagnetic materials nearly spins tend to allign in the same direction due to a quantum mechanical effect called <u>EXCHANGE INTERACTION</u>

affects the Coulomb interaction

↳ related to the Pauli exclusion principle

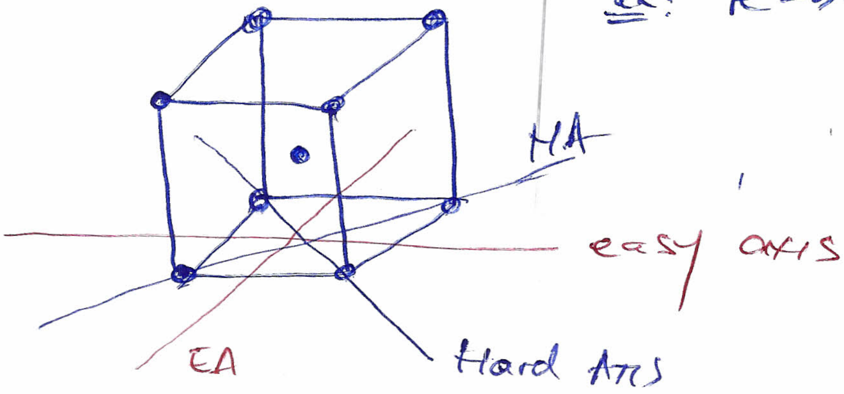
The electrostatic energy of two repeling electrons is reduced when their spins are parallel compared to energy when spins are antiparallel. This difference in energy is called <u>exchange energy</u>.

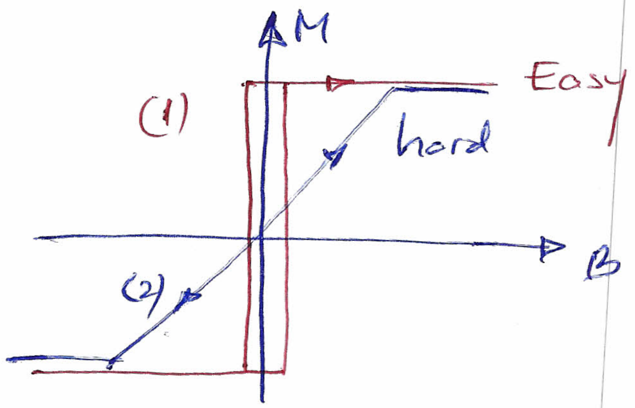


Magnetic anisotropy

Although the exchange interaction keeps spins alligned, it does not give them a particular direction. Without magnetic anisotropy, the spins in a magnet randomly change direction in response of thermal fluctuations and the magnet would become <u>superparamagnetic</u>. There are several magnetic anisotropies; the most common one being the <u>magneto-cristalline anisotropy</u>: dependence of the energy on the $\bar{M}$ direction with respect to cristallographic axes in a cristal:

<u>ex</u>: Fe-bcc





EA: small B need to saturate

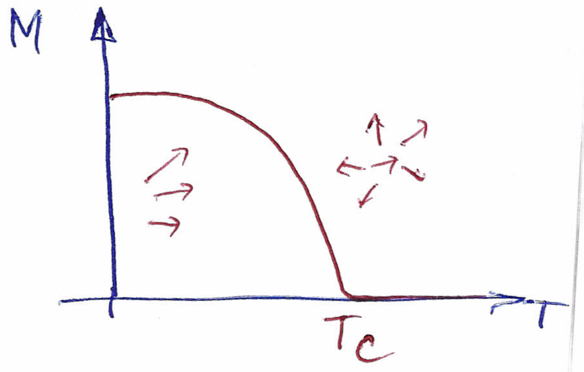
HA: large B needed to saturate

Obs: linear M-B for HA magnetization curve useful for sensor applications [linear response of signal = f(field)]

Curie temperature

As temperature increases, thermal effects (entropy) competes with the ferromagnetic tendency to allign moments (exchange). Above a critical temperature (Curie temperature) a ferromagnet will transit via a 2nd order transition, in a paramagnetic state. ⇒

Bellow T_c, there is a spontaneous symmetry breaking and magnetic moments become alligned with their neighbors.



Curie-Weiss law

$$\boxed{\chi = \frac{\mu_0 M}{B} = \frac{C}{T - T_c}}$$

C = Curie constant

T_c = Curie temperature

Materials with T_c above room temperature are required for technological applications in sensors ⇔ data storage.

Obs: Thermal stability of a ferromagnet depends on material itself but also on the dimensionality via the anisotropy energy. Ek. Larger Ek implicates larger T where $\overline{M}$ remains stable.

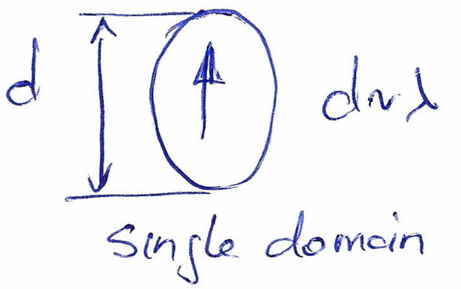
When reducing size of a magnet, the anisotropy energy, proportional with the volume V reduces

=> problems for ultimate miniaturization of hard-disks (HDD); the bit become unstable for standard magnetic materials operating at RT

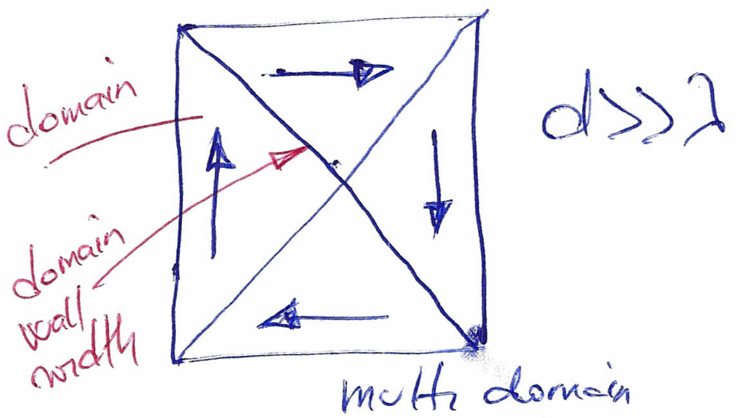
Solutions: cryogenic conditions (undesirable) versus new innovative materials (active research field), or tayloring the magnetic properties by dimensionality, shape, aspect ratios.

Exchange length: scale length of magnetism

What determines wheather a magnetic structure is made-up a single domain or multi-domain?



single domain



multi domain

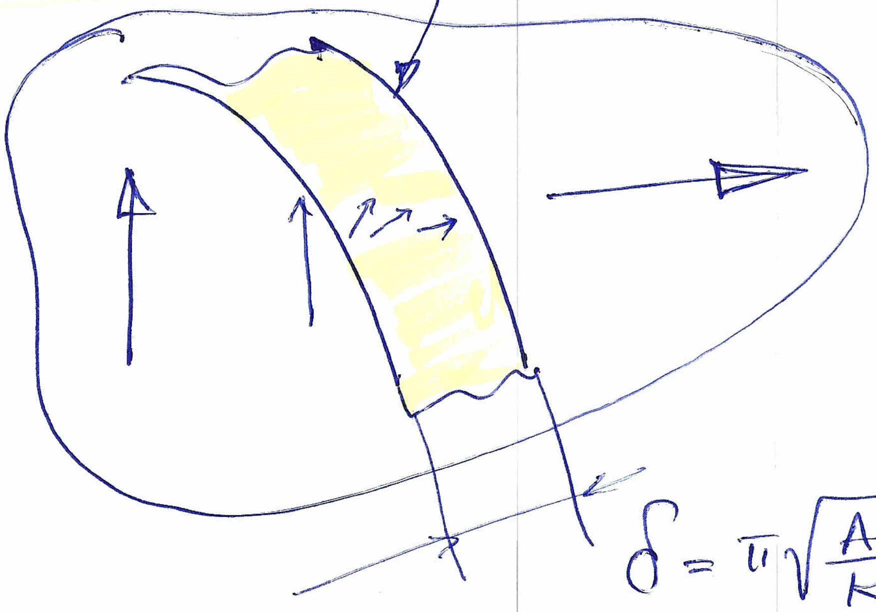
λ = exchange length

$$\boxed{\lambda_{ex} = \sqrt{\frac{A}{M_s}}}$$

A = exchange constant

M_s = saturation magnetization

Domain wall

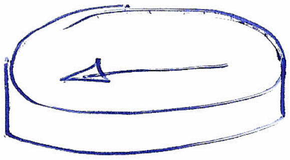


Progressive transition from direction of adjacent domains.

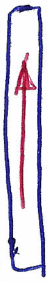
$$\delta = \pi\sqrt{\frac{A}{K}}$$

K = anisotropy constant.

Concept: When the size of a magnetic object become comparable with λ_{ex}, its properties can fully change with dimensionality, shape, ...

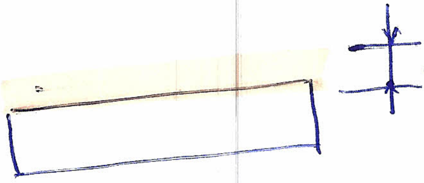


disk: in plane M



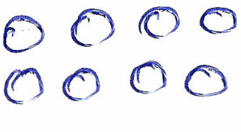
wire: longitudinal $\vec{M}$

thin films.



either in plane → or perp to plane ↑ $\vec{M}$ configurations

ex: Patterned media (HDD applications)



nanometric size magnetic element with PMA as memory elements in hard-disks.

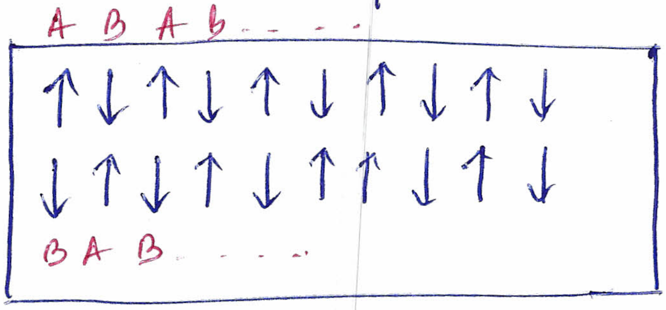
Obs : Micro and nano- lithography techniques used to tailor shape / size of magnetic structures $\Rightarrow$ innovative properties...

→ see attached slides

→ see visit of the research lab. Center of superconductivity, spintronics and Surface science, Technical University of Cluj.

4 ANTIFERROMAGNETISM

In materials that exhibit antiferromagnetism the magnetic moments of atoms, molecules, usually related to the spins of electrons, allign in a regular pattern on different sublattices pointing in opposite directions.



total $\vec{M} = 0$
because $\vec{M}_A = -\vec{M}_B$
(moment of lattice A opposite to moment of lattice B)

Antiferromagnetic order persist up to a limit temperature called Néel temperature T_N.
(Louis Néel)

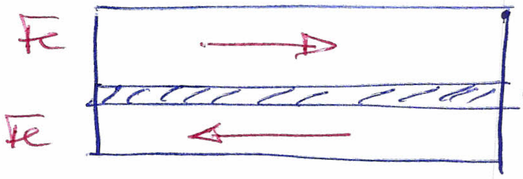
Above T_N the material became paramagnetic.

AF materials : transition metal oxides (NiO)
metals (Cr)
alloys (FeMn, IrMn) ....

important applications in hardening a magn. field by EXCHANGE BIAS phenomena

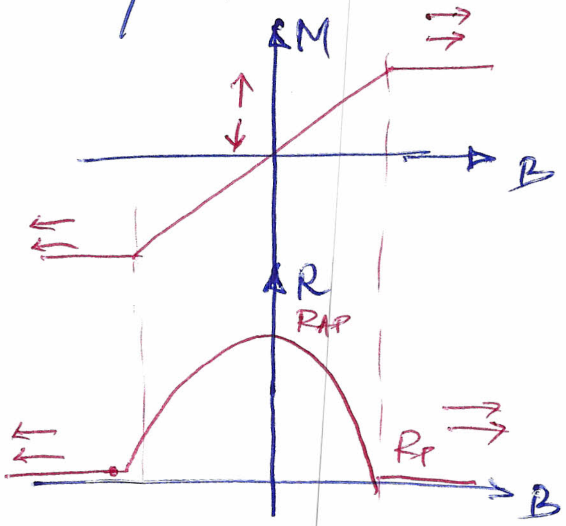
Antiferromagnetism in thin films

=> synthetic AF



Giant-magnetoresistance effect [GMR]

Nobel Prize Physics 2007 (A. Fert & P. Grünberg)

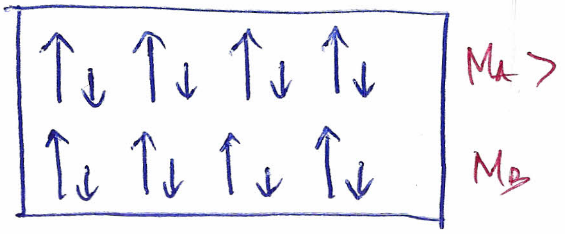


$$\boxed{GMR = \frac{R_{AP}-R_P}{R_P}}$$

(see seminary / visit lab C45)

$\boxed{5}$ FERRIMAGNETISM

Occurs in materials where magnetic fields associated with individual atoms spontanously allign themselfes, some parallel in the same direction (as in ferromagnetism) and others antiparallel or paired off in opposite directions (⇄) two lattices A and B with unequal moments

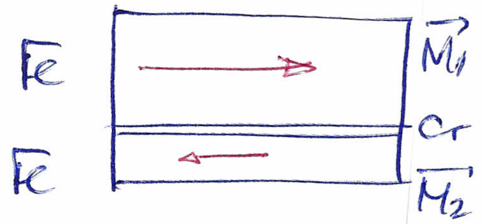


ferrimagnetism = uncompensated antiferromagnetism

Ferrimagnetism occur in :

→ magnetic oxides (ferrites, monganites ...)
Fe_3O_4

→ artificial ferrimagnetism in multilayered magnetic thin films spaced by nomagnetic films.



unequal $\vec{M_1}$ and $\vec{M_2}$ by different thickness of thin films.

* extremelly used in spintronics applications.

Effect of temperature

Like ferromagnets, above the Curie temperature the net magnetization cancels by thermal fluctuations and materials become paramagnetic.

However, in some materials, due to different temperature variation of magnetization of two sub-lattices below T_c the moments of the two sublattices may become equal and opposite at a certain temperature called magnetization compensation temperature

6 Materials with compensated spin / orbital magnetic moments

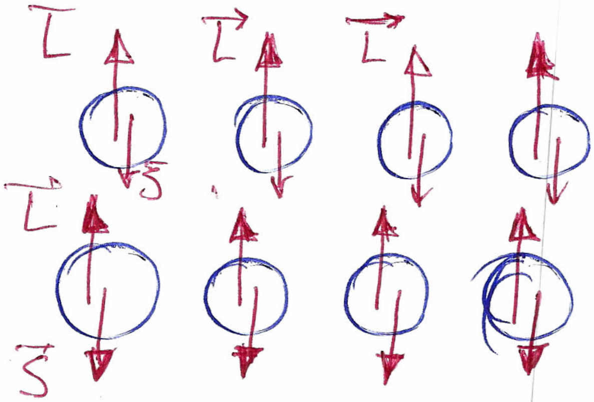
At the beginning we observed that ~~there~~ the magnetic moment of atom is correlated to the magnetic moments of electrons, directly related to their angular moment.

→ orbital angular moment $\vec{L}$

→ spin angular moment $\vec{S}$

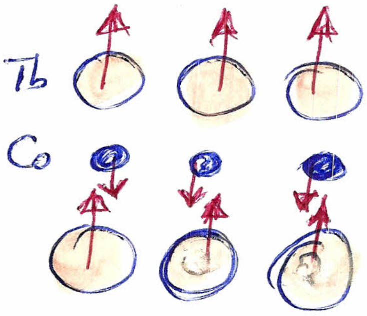
Typically, in transition-metals the total magnetic moment is given by the spin angular moments, the angular moments of random orbites cancelling out.

However, there are materials (e.g. $SmAl_2$) where $\vec{L}$ and $\vec{S}$ for individual atoms are both non-zero and allign antiparallel ⇒ "self-ferrimagnet" compound



$SmAl_2$

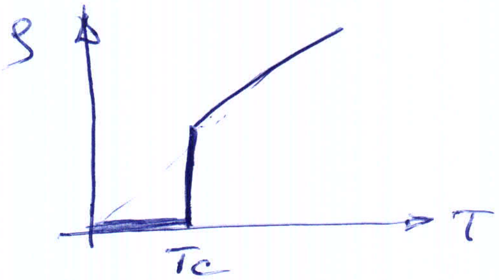
as compared to a classical ferrimagnet compound



Again, due to different temperature variation of $\vec{L}$ and $\vec{S}$ oppositelly oriented associated magnetic moments, at a certain compensation temperature the material will lose magnetization. However, at compensation temperature neither $\vec{L}$ nore $\vec{S}$ are zero.! ⇒ <u>Zero magnetization ferromagnet</u>

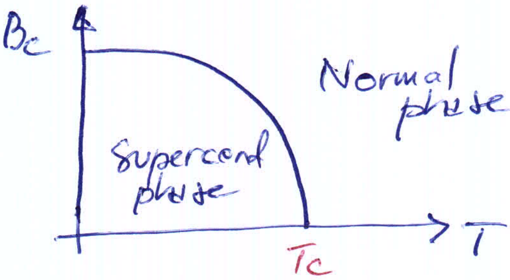
SUPERCONDUCTIVITY

The most familiar property of a superconductor is the sudden dissapearance of all electrical resistance when the material is cooled below a temperature called critical temperature T_c.



Superconductors have also unusual magnetic properties

① T_c changes when the material is placed in externaly magnetic field $\vec{B}_0$. As the external field increases, T_c becomes lower and lower. The minimum magnitude of magnetic field needed to eliminate supraconductivity, below T_c is called the critical field B_c

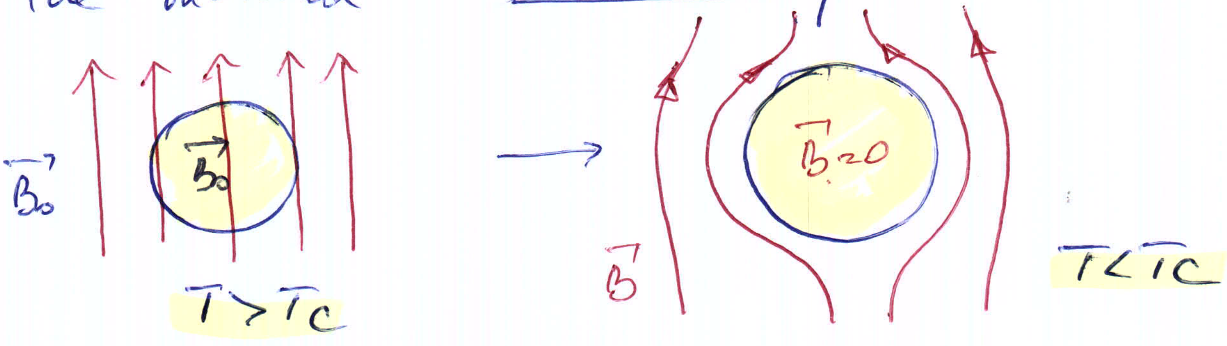


Phase diagram

$$\boxed{B_c = B_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]}$$

The Meissner effect

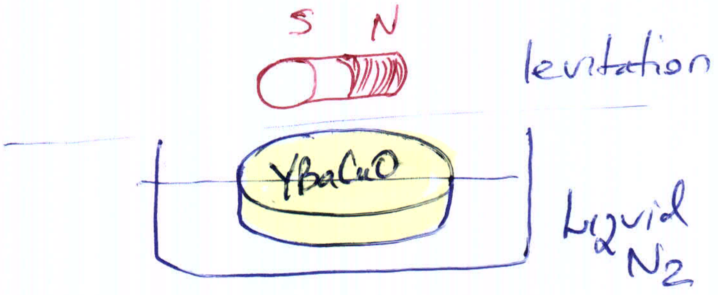
When a superconducting materials has a transition from normal phase to superconducting phase in an external field $\vec{B}_0$ all the magnetic flux is expelled from the material $\Rightarrow$ Meissner effet



Superconductor levitation

A superconductor behaves as a perfect diamagnetic system.

This has interesting mechanical consequences. For a diamagnetic material the magnetization oposes the direction of external magnetic field. This induces a repel by a permanent magnet. From 3rd Newton law ⇒ the magnet is also repeled by a superconductor; i.e. the magnet can levitate above a superconductor.

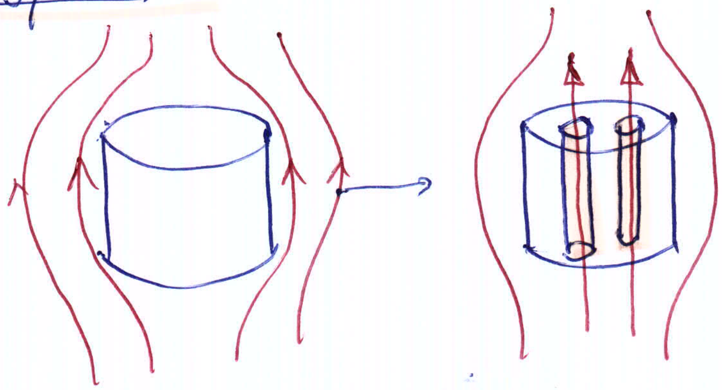


Types of superconductors

Type I : direct transition from N ⟷ S at T_c and B_c

<u>ex</u>: metals: Hg, Al, ...

Type II : transition via intermediate vortex-state.



vorteces are normal zones embedded into superconducting bulk.

$\vec{B}$ Field can penetrate through vorteces

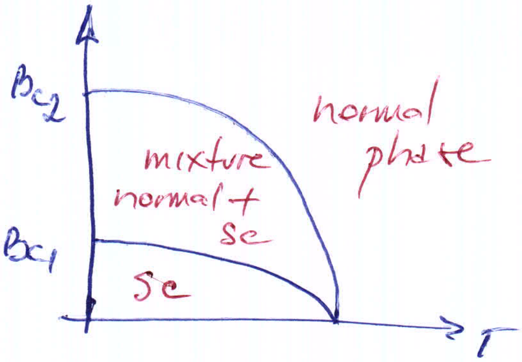
Two critical fieds

B_{c1} = vorteces appear

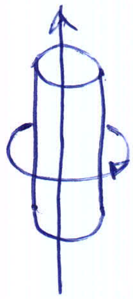
B_{c2} = full transition into normal state.

Phase diagram
type II superconductor

ex: V, Nb, MgB_2 ...
oxides: $YBa_2Cu_3O_7$, ...



currents circulate around boundaries of vortices and magnetic flux can penetrate inside



Type II superconductors allow larger B_c than type I superconductors before destroying superconducting state.

Applications

→ superconducting electromagnets: allow large fields (~10T) not attainable in classical electromagnets. Once the current is established in the superconducting coil no additional power input is required because there is no energy loss. The coils are made also more compact because no cooling circuit is required.

→ long distance electric power transmission and energy conversion devices (generators, motors, transformers)

→ sensitive measurements of magnetic field in SQUIDS (superconducting quantum interference devices) which can detect changes of magnetic flux less than 10^{-4} Wb. They have important applications in medicine, magnetism researches (thin films), etc...

→ High temperature superconductors have $T_c > 77K$ (Liquid N_2) e.g. $YBa_2Cu_3O_7$ (~80K), new generations of HT_c superconductors with T_c ↗ 110K ...
They have complex physics underlying and amazing perspective applications.