Magnetism on the atom

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Fundamental properties of matter and Applications

Science is DIFFICULT and HARD to understand

Keep away from science

Fundamental properties of matter and Applications

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Physics is DIFFICULT and HARD to understand

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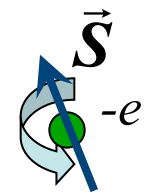
Keep away from physic

However !

Magnetism and magnetic materials

Magnetism and magnetic materials

Magnetic moments of the electrons



an elementary particle with
intrinsic angular moment (spin) of 1/2

Magnetism and magnetic materials

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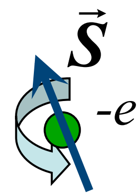

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The spin magnetic moment of the electron, $\boldsymbol{\mu_s}$

Magnetism and magnetic materials

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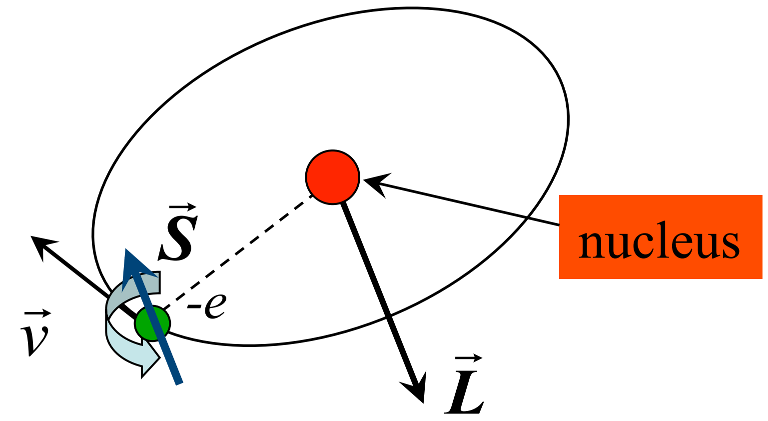

The orbital kinetic moment of the electron, ***L***

Magnetism and magnetic materials

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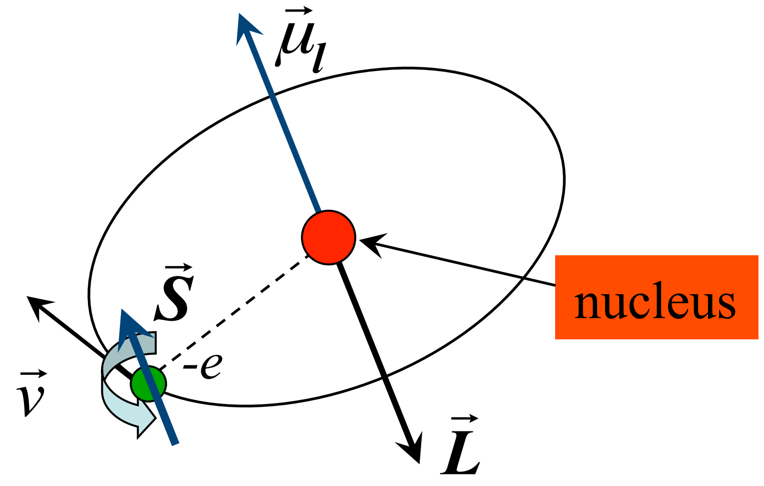

The orbital kinetic moment of the electron, $\boldsymbol{L}$

The orbital magnetic moment of the electron, $\boldsymbol{\mu_l}$

This are the fundamental "bricks" on which we can build the magnetism of matter.

Magnetism and magnetic materials

Magnetic moments of the electrons

Magnetic moment of the atoms

Magnetism in matter

Magnetic study of the matter

Fundamental properties and Applications

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Fundamental properties and Applications

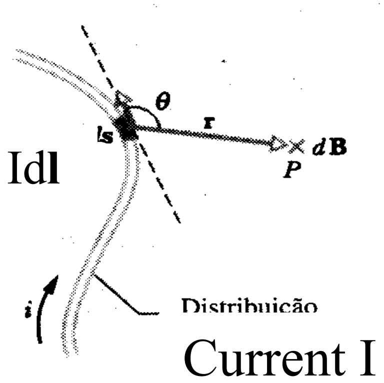
Magnetism is comprehensible, moreover, it is accessible and, above all, interesting!

Electric charges in motion

Kinetic moment → Magnetic moment

Magnetic moment

An electric current, I, is the source of the magnetic field B:



$$\vec{B} = \frac{\mu_0}{4\pi}\int_C \frac{Id\vec{l}}{r^2} \times \frac{\vec{r}}{r} \quad (1);$$ Biot–Savart law

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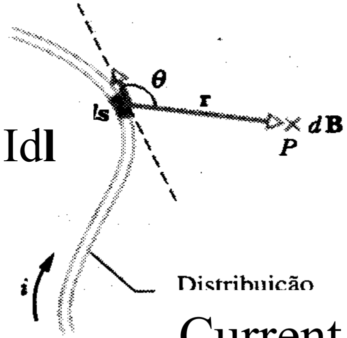
Idl



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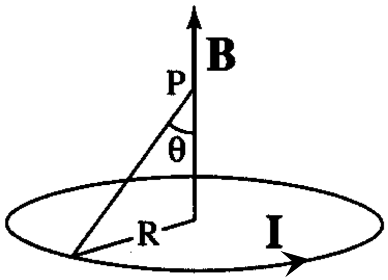
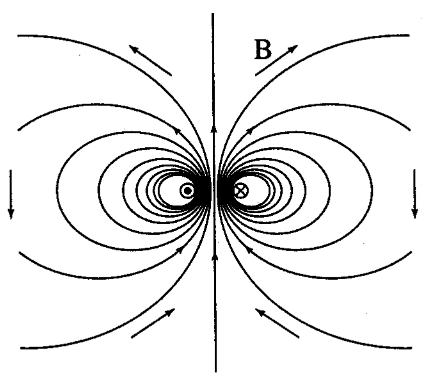
The magnetic field generated by a single coil of electric current:



$$B = \frac{\mu_0 I}{2R}\sin^3\theta$$



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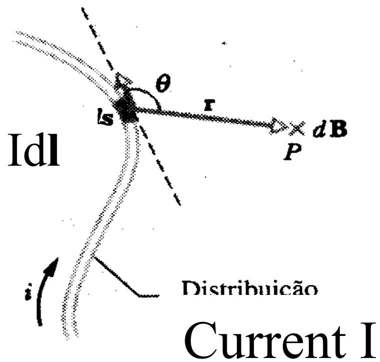

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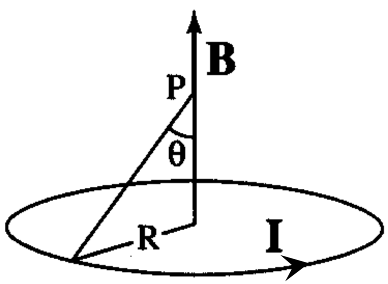

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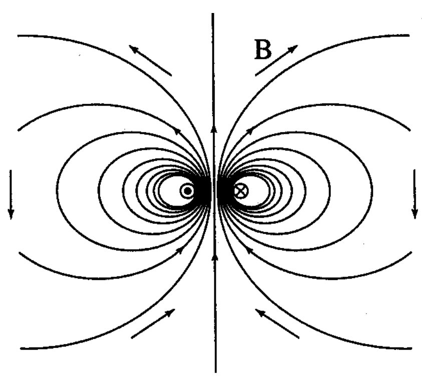
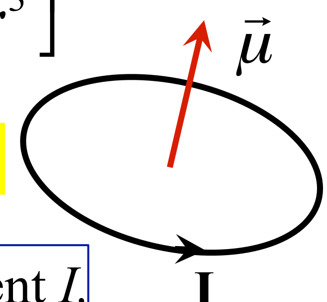


Far from the origin:

$$\vec{B} = \frac{\mu_0}{4\pi}\left[3\frac{(\vec{\mu}\cdot\vec{r})\vec{r}}{r^5} - \frac{\vec{\mu}}{r^3}\right] \quad (2)$$

were $\vec{\mu} = IS\vec{n} \quad (3)$



$\vec{\mu}$ - ***magnetic moment*** of the single coil traversed by the electric current *I*,
$\vec{n}$ - *normal to the surface,*
S - *surface of the loop.*

Magnetism in matter

An electric current consists of moving electrons

The movement of electrons in matter is the source of the

Magnetism in matter

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<u>Electric charges in motion</u>

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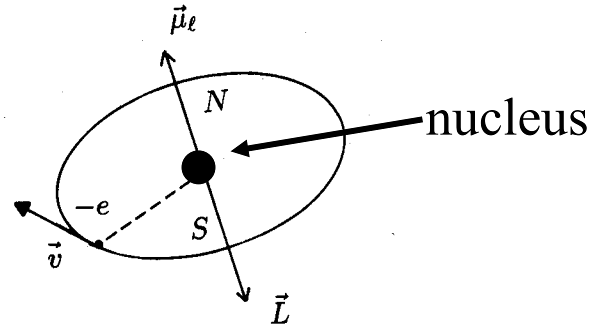
Angular momentum $$\vec{L} = \vec{r} \times \vec{p}$$

$L = m_e r^2 \omega$



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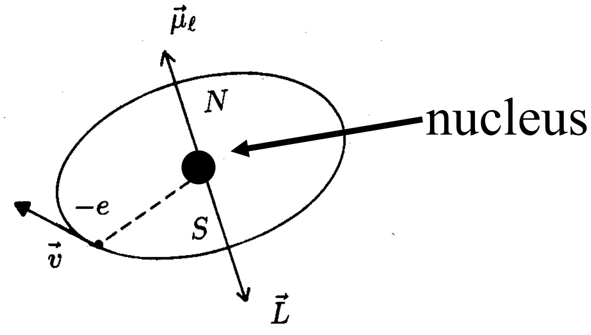

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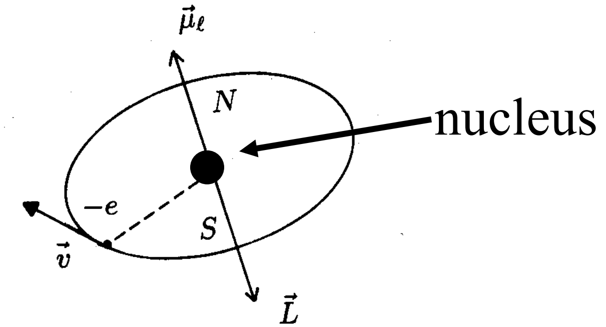

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$$\Rightarrow \quad \mu = \frac{e \cdot \omega}{2\pi} \pi r^2 = \frac{m_e \cdot e \cdot r^2 \cdot \omega}{2 \cdot m_e} = \frac{e}{2 \cdot m_e} \cdot L$$

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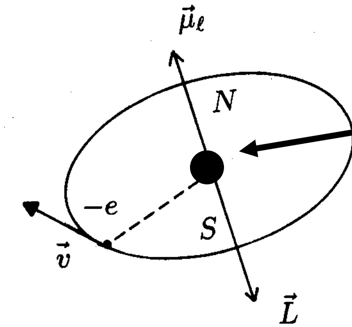

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$$\vec{\mu}_l = -\frac{e}{2 \cdot m_e} \vec{L}; \qquad (4)$$

$\gamma = e/2m_e$; gyromagnetic ratio (magnetomechanical ratio)

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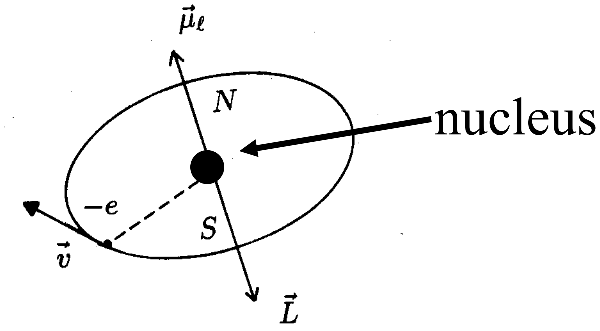

$$\left.\begin{aligned} &\vec{\mu}_l = I \cdot \vec{S} \\ &I = e\,\omega / 2\pi \\ &S = \pi r^2 \end{aligned}\right\} \Longrightarrow \quad \mu = \frac{e \cdot \omega}{2\pi} \pi r^2 = \frac{m_e \cdot e \cdot r^2 \cdot \omega}{2 \cdot m_e} = \frac{e}{2 \cdot m_e} \cdot L$$

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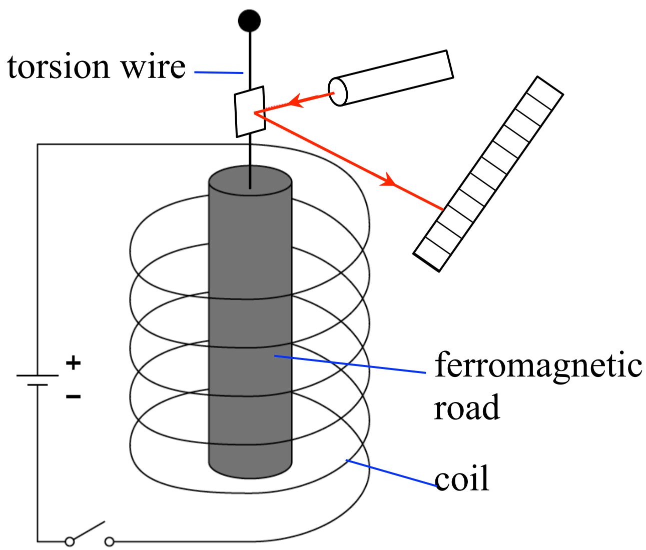
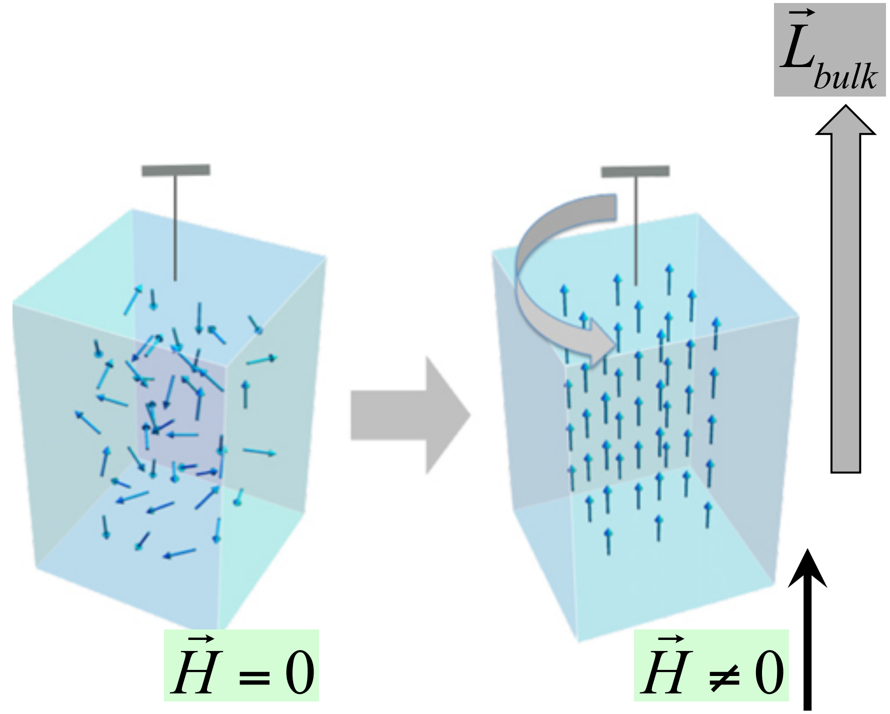
Generalization: A moving electric charge with kinetic moment *L* will create a magnetic moment: $\vec{\mu} = \gamma \vec{L}$ (5)

!!!

Einstein–de Haas effect





The **change** in the **magnetic moment** of a free body causes **this body to rotate.**

Einstein-de Haas effect

Conservation of angular momentum

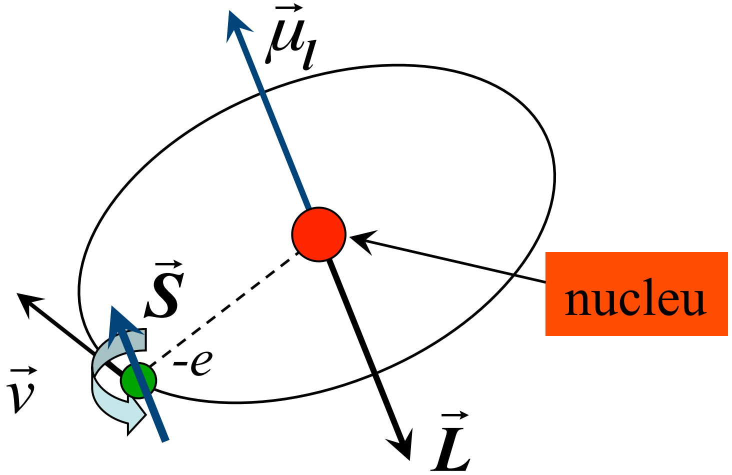
The close relation between the concepts of **angular momentum in classical and in quantum physics**.

https://en.wikipedia.org/wiki/Einstein–de_Haas_effect
Blundel

In the atoms, the **electrons** are characterized by **two kinetic moments**:

Orbital kinetic moment $\vec{L}$

$$\vec{\mu}_l = -g_l \frac{e}{2m_e}\vec{L}; \quad g_l = 1$$



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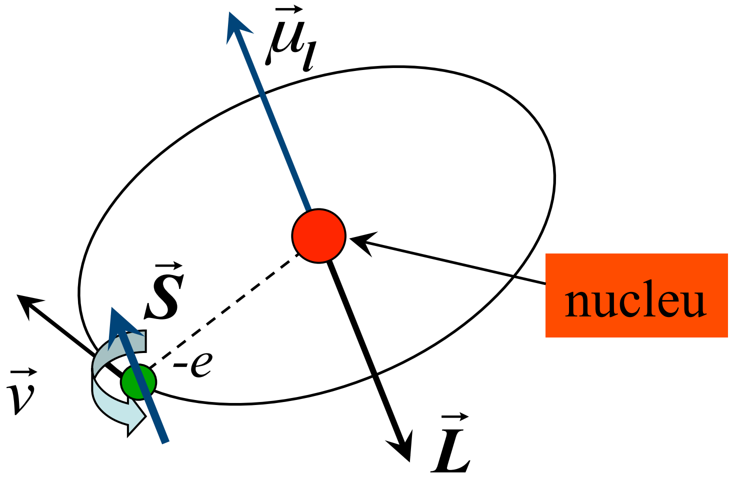
Spin kinetic moment $\vec{S}$

$$\vec{\mu}_s = -g_s \frac{e}{2m_e}\vec{S}; \quad g_s = 2 \quad (7)$$



Atomic magnetic moment

The allocation of electrons on orbits is done in accordance with the minimization of energy and can be estimated using **Hund's rules**.

→ The orbital and spin moment of the atom

Atomic magnetic moment

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Hund's rules:

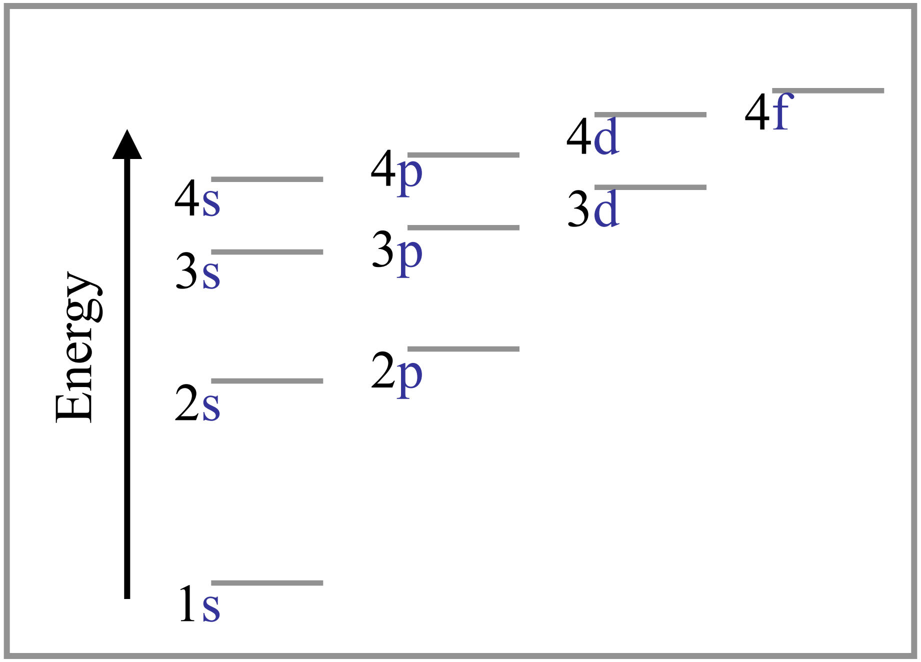
1) $S = \sum m_s,$ MAXIMUM, respecting Pauli's principle

2) $L = \sum m_\ell,$ MAXIMUM, respecting rule 1)

3) $J = |L + S|$ or $J = |L - S|$ (Spin-orbit coupling)

Electronic configuration for multi-electron atoms

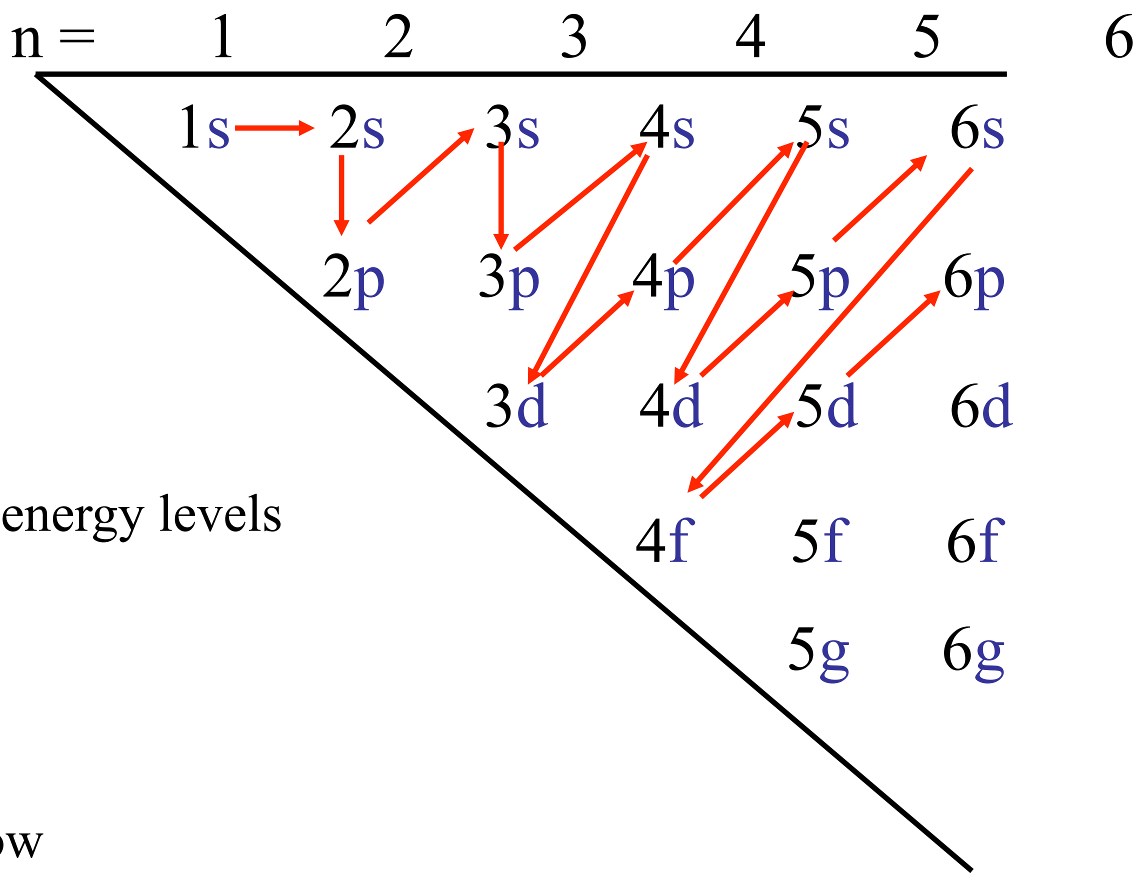
Energy is quantified and its value depends only on the values of *n* and *l*



Energy levels are named giving the value of *n* and a letter corresponding to different values of *l*.

l = **0** orbital **s** *l* = **1** orbital **p** *l* = **2** orbital **d** *l* = **3** orbital **f**

Electronic configuration for multi-electron atoms



The rule of occupying the energy levels of electrons in atoms

1. *n* grows
2. for a given *n, l* grow
3. Exceptions transition elements (elements d and f)

Spin-orbit coupling

$$\vec{J} = \vec{L} + \vec{S}$$

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electron shell **less** than half full $\lambda < 0$ → $J = L - S$

electron shell **more** than half full $\lambda > 0$ → $J = L + S$

(8)

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$$\vec{\mu} = -g \frac{e}{2m_e} \vec{J} = -g \frac{e\hbar}{2m_e} \frac{\vec{J}}{\hbar}$$

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Therefore, to the atom of the total *kinetic moment* ***J*** (expressed in units $\hbar = h/2\pi$), given by the electrons from the incomplete shells, we can associate a *magnetic moment* $\boldsymbol{\mu}$:

$$\vec{\mu} = -g\mu_B\vec{J} \quad (9)$$

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- μ_B *Bohr magneton,*
- ***g*** *spectroscopic splitting factor (Landé g factor)*

$J = |L+S|$ *or* $|L-S|$

$-J < M_J < J$

$\boldsymbol{\mu_B} \equiv$ spin magnetic moment of the electron

$$L = 0$$

$$S = \frac{1}{2}$$

⇒ $g = 2, \mu = 2\mu_B \frac{1}{2} = 1\mu_B$

$\mu_B \equiv$ spin magnetic moment of the electron

$$\mu_B = \frac{e\hbar}{2m_e} \qquad (SI) \qquad \Rightarrow \qquad \mu_B = 9{,}2742 \cdot 10^{-24}\, Am^2 \tag{10}$$

$$\mu_B = \frac{e\hbar}{2m_e c} \qquad (CGS)$$

c is the speed of light in vacuum,
m_e is the mass of the electron.

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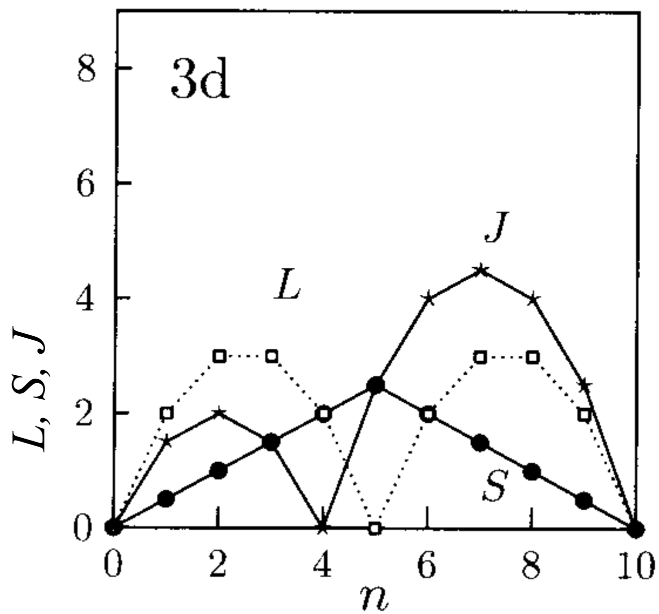
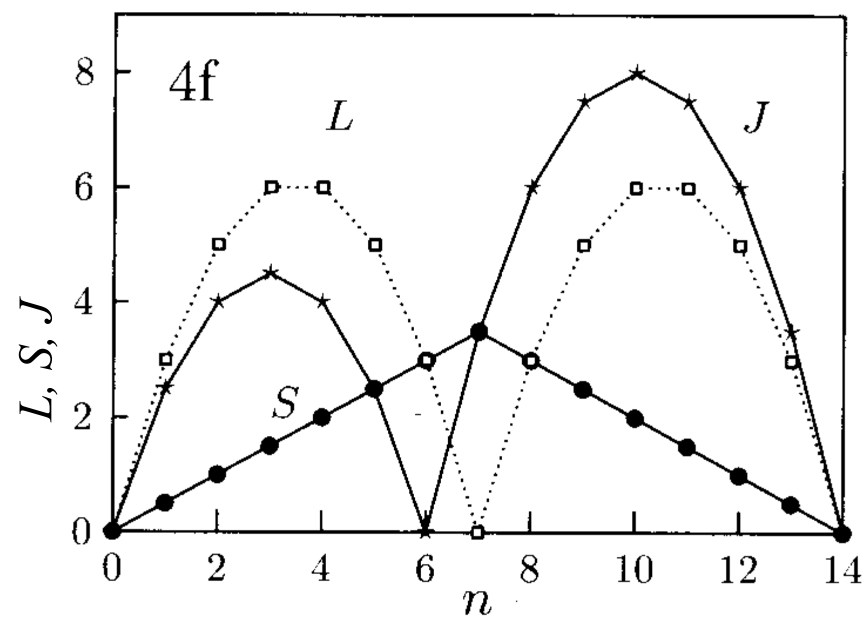
$\frac{m_n}{m_e} \approx 1836$ ⇒ The **magnetic moment of the atoms** are essentially due to the contributions of **electrons from incomplete electronic shells**. The magnetic moment of the nucleons play an important role in resonance experiments: NMR, Mössbauer ...

S, L and J for 3d and 4f ions according to Hund's rules*



(3d)



(4f)

n= the number of 3d or 4f electrons

Magnetization, magnetic susceptibility, magnetic permeability...

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*Magnetization, **M**,* of a substance is defined as the sum of the magnetic moments,, ***μ***, per unit volume.

$$\vec{\mathbf{M}} = \frac{\sum \vec{\mu}}{V} \quad (12)$$

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In a material, the relationship in SI between *magnetic induction* (or *magnetic flux density*), ***B***, *magnetic field strength,* ***H***, and *magnetization*, ***M***, is as follows

$$\vec{B} = \mu_0 \left(\vec{H} + \vec{M} \right) \quad (13)$$

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$\mu_0 = 4\pi\cdot10^{-7}$ H/m is *magnetic permeability of vacuum*.

In SI, *B* is measured in *Tesla* (T) and *H* and *M* in A/m. A useful unit of measurement for magnetic moment is the *Bohr magneton*.

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Which is more important (more used) in research, B or M?

Magnetic ***susceptibility***, χ,

$$\chi = \frac{M}{H} \quad (14)$$

The magnetic susceptibility of a material quantifies how much the material is magnetized when exposed to a magnetic field.

↔

The material's feedback to a magnetic field

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The magnetic susceptibility of a material quantifies how much the material is magnetized when exposed to a magnetic field. ⟷ The material's feedback to a magnetic field

$$\mathbf{B} = \mu_0\left(\mathbf{H} + \chi\mathbf{H}\right) = \mu_0\left(1 + \chi\right)\mathbf{H} = \mu\mathbf{H} \quad (15)$$

$\mu = \mu_0(1+\chi)$ is *magnetic permeability*

$\mu_r = \mu/\mu_0 = (1+\chi)$ is a positive dimensionless constant called *relative magnetic permeability*. In the case of vacuum $\mu_r = 1$.

Kinetic moments of the electron in the atoms:

- Orbital kinetic moment $\vec{L}$
- Spin kinetic moment $\vec{S}$

$$\begin{cases} \vec{\mu}_l = -g_l \dfrac{e}{2m_e}\vec{L}; & g_l = 1 \\ \vec{\mu}_s = -g_s \dfrac{e}{2m_e}\vec{S}; & g_s = 2 \end{cases}$$

Kinetic moment of an atom $\vec{J}$

Atomic magnetic moment: $\vec{\mu} = g\mu_B\vec{J}$

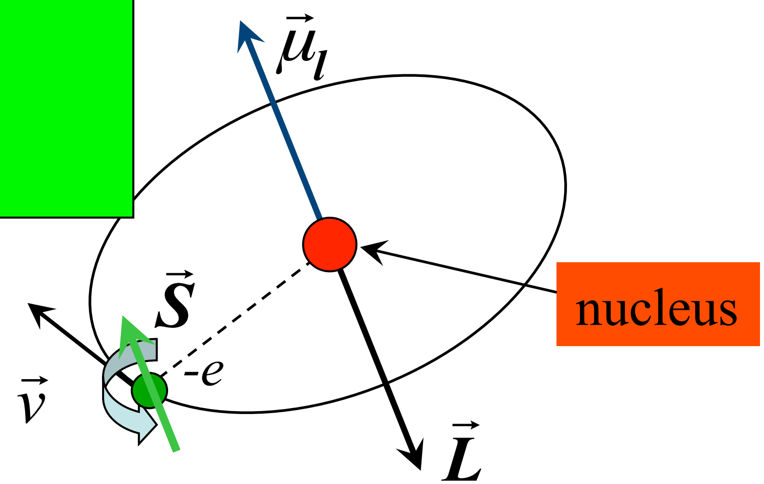
$\mu_B \equiv$ spin magnetic momentul of the electron

$$\mu_B = \frac{e\hbar}{2m_e} \quad (SI) \qquad \mu_B = 9{,}2742\cdot 10^{-24}\ \mathrm{A\cdot m^2}$$

$$\mu_B = \frac{e\hbar}{2m_e c} \quad (CGS)$$

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

Landé factor



magnetisation **M**

$$\vec{\mathbf{M}} = \frac{\sum \vec{\mathbf{m}}}{V}$$

magnetic susceptibility **χ**

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

magnetic permeability **μ**

$$\mu = \frac{B}{H}$$

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

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

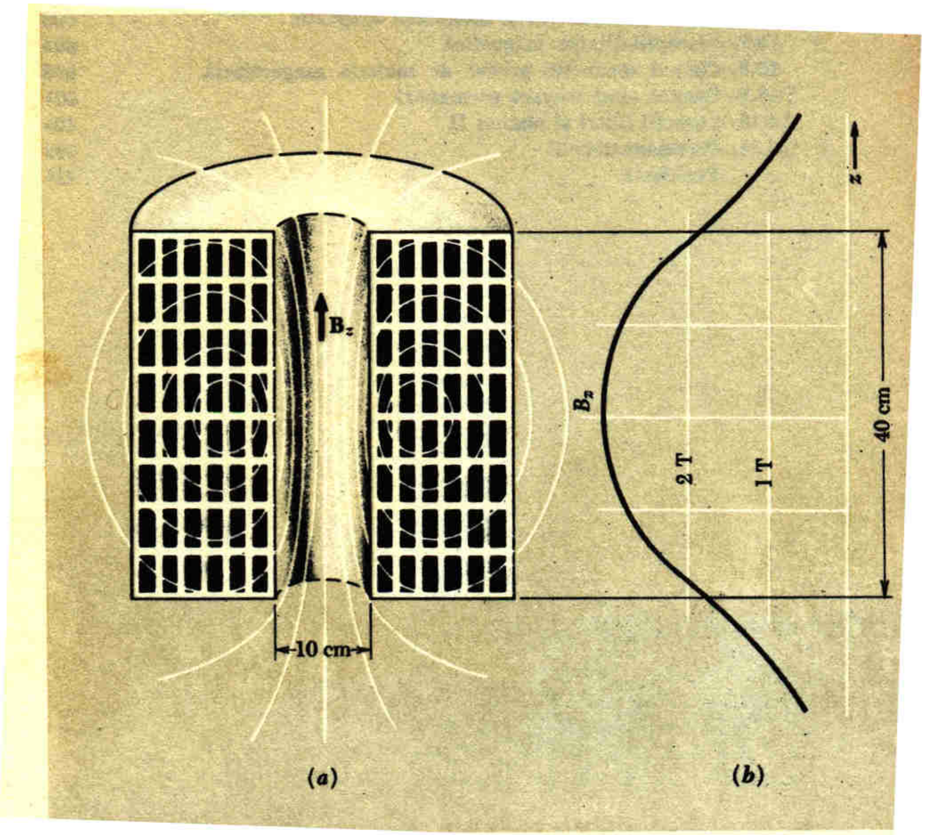
$B = \mu_0(H + \chi H) = \mu_0(1 + \chi)H = \mu H$

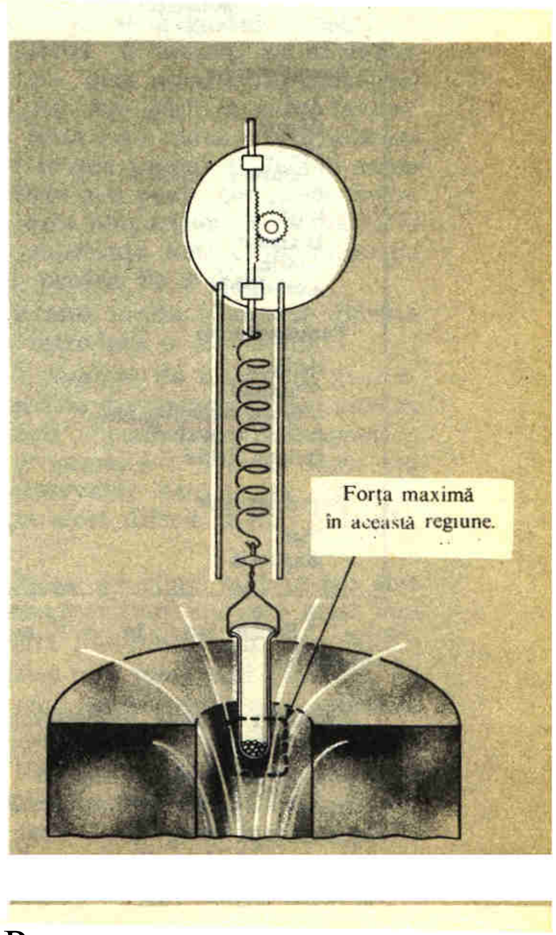
$\mu_0 = 4\pi \cdot 10^{-7}$ H/m

The main types of magnetic behavior of substances

The main types of magnetic behavior of substances

$$F = \mu_0 m \chi H \frac{dH}{dx} \qquad (16)$$





E. M. Purcell, Electricity and magnetism, Cambridge University Press

a). Diamagnetic substances

-substances *slightly repelled* by the magnetic field to lower values,

- $\chi < 0$,

- all *electronic shells* of atoms or molecules are *completely occupied,*

- in the zero magnetic field, the *atomic magnetic moment is zero.*

Diamagnetic substances	**Chemical formula**	**Force* (10^{-2} N/kg)**
water	H_2O	-22
copper	Cu	-2,6
lead	Pb	-37
sodium chloride	NaCl	-15
quartz	SiO_2	-16
sulphur	S	-16
diamond	C	-16
graphite	C	-110
liquid nitrogen	N_2	-10 (78 K)

****substances in a magnetic field of 1 T and gradient $\mu_0 dH/dz$=17 T/m. T=20 ºC***

b). *Paramagnetic substances*

- $\chi > 0$ (substances *slightly attracted* by the magnetic field to higher values of it),

- substances in which exist *partly occupied electronic shells,*

- a *non-zero magnetic moment per atom* results,

-*the interaction* between atomic (ionic) magnetic moments *is zero*.

Paramagnetic substances	Chemical formula	Force* (10^{-2} N/kg)
sodium	Na	+20
aluminium	Al	+17
copper chloride	$CuCl_2$	+280
nickel sulphate	$NiSO_4$	+830
liquid oxygen	O_2	+7 500 (90 K)

substances in a magnetic field of 1 T and gradient $\mu_0 dH/dz$=17 T/m. T=20 ºC

c). *Ordered magnetic substances*

- $\chi >> 0$ (*strongly attracted by the magnetic field*),
- as for paramagnetic substances, *electronic shells are partly occupied,*
- a *non-zero magnetic moment* per atom (ion) results,
- in addition, compared to paramagnets, *interaction between magnetic moments*!

Ordered magnetic substances	Chemical formula	Force* (10^{-2} N/kg)
iron	Fe	+400 000
magnetite	Fe_3O_4	+120 000

substances in a magnetic field of 1 T and gradient $\mu_0 dH/dz$=17 T/m. T=20 ºC

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substances in a magnetic field of 1 T and gradient $\mu_0 dH/dz$=17 T/m. T=20 ºC

The most known and used ordered magnetic materials:
ferromagnetic, ferrimagnetic and antiferromagnetic.

Note: in the usual language, ferromagnetic and ferrimagnetic substances, having a non-zero magnetization even in the zero field, are also called magnetic substances, while for the other types we also find the common name of non-magnetic substances.
Remark: Physically this classification is not rigorous.

Diamagnetic substances	Chemical formula	Force* (10^{-2} N/kg)
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Ordered magnetic substances	Chemical formula	Force* (10^{-2} N/kg)
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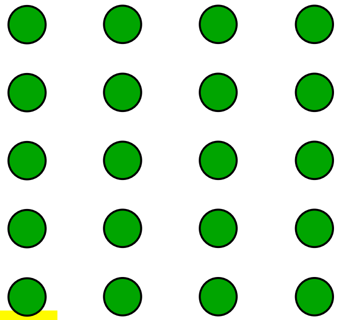
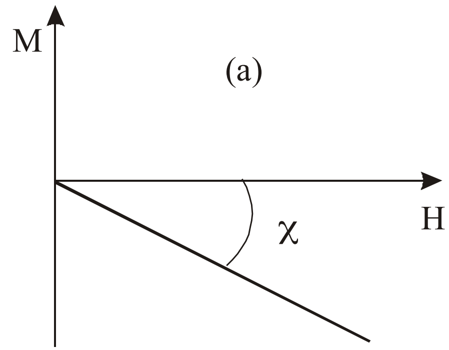
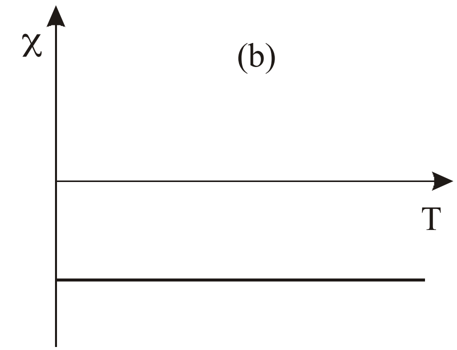
Diamagnetic

$$\vec{\mu} = 0$$

$$\chi < 0$$





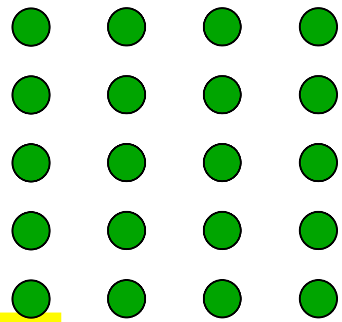


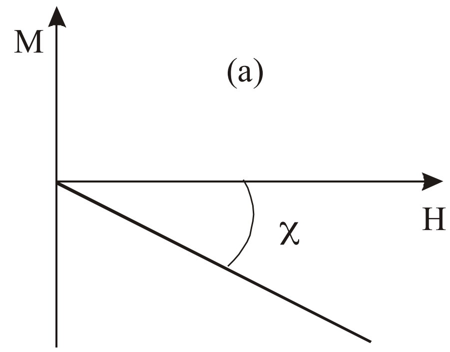
C, Cu, Pb, H_2O, NaCl, SiO_2

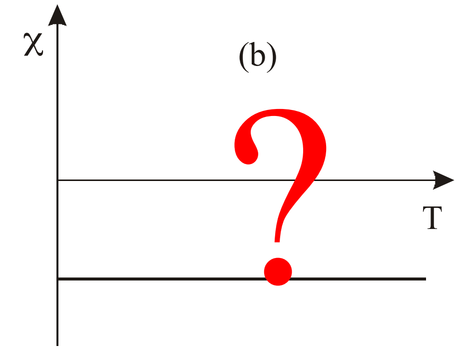
Diamagnetic

$$\vec{\mu} = 0$$

$$\chi < 0$$







C, Cu, Pb, H_2O, NaCl, SiO_2

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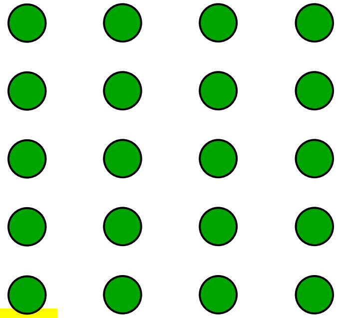
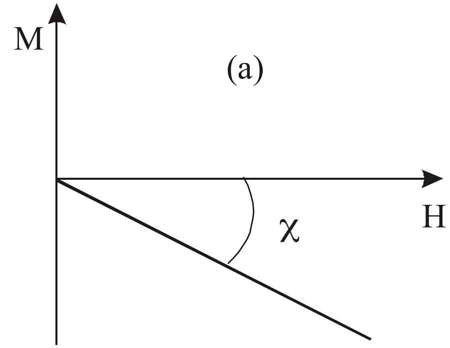
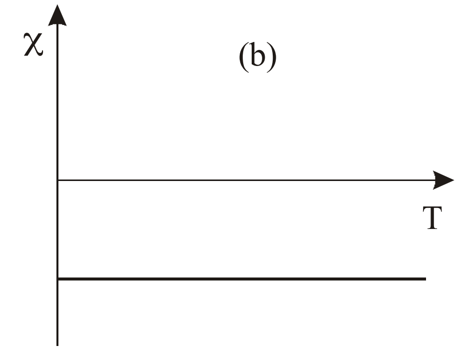
C, Cu, Pb, H_2O, NaCl, SiO_2







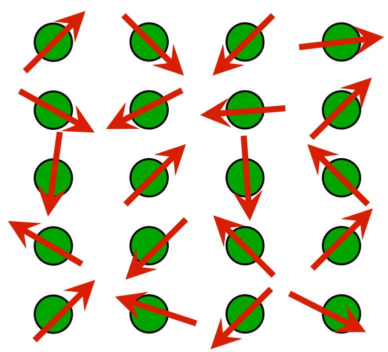
Paramagnetic

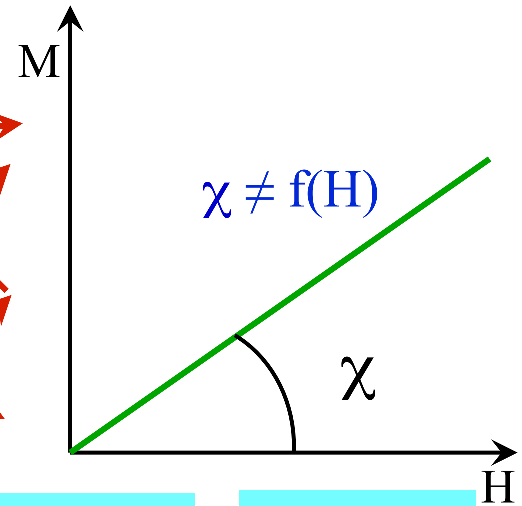
$$\vec{\mu} \neq 0$$

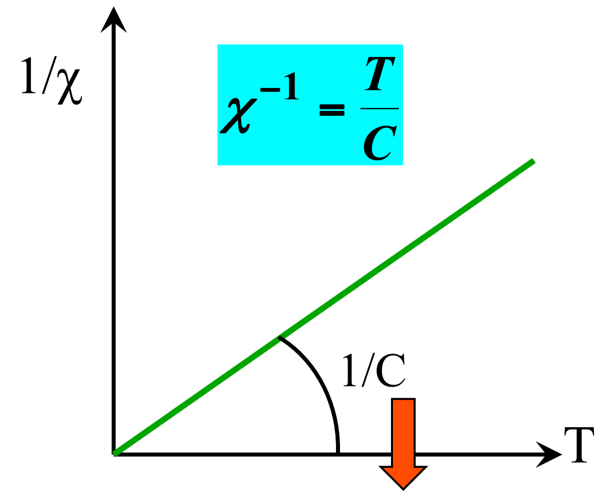
$$J_{ij} = 0$$

$$\chi > 0$$

$NiSO_4$, $CuCl_2$







$$\chi^{-1} = \frac{T}{C}$$

$$\mu_{eff} = \sqrt{\frac{3k_B}{N \cdot \mu_0} C}$$

if $\chi(\mu_B/T \cdot f.u)$

$$\mu_{eff}(\mu_B) = \sqrt{4{,}466 \cdot C}$$

if χ(emu/mole)

$$\mu_{eff}(\mu_B) = \sqrt{8 \cdot C}$$

$$J$$

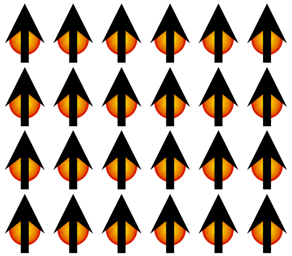
$$\mu_{eff} = g\mu_B\sqrt{J(J+1)}$$

Ferromagnets

$\vec{\mu} \neq 0$; $M_s \neq 0$

$J_{ij} > 0$

$\chi >> 0$



Ferromagnets

$\vec{\mu} \neq 0$; $M_s \neq 0$

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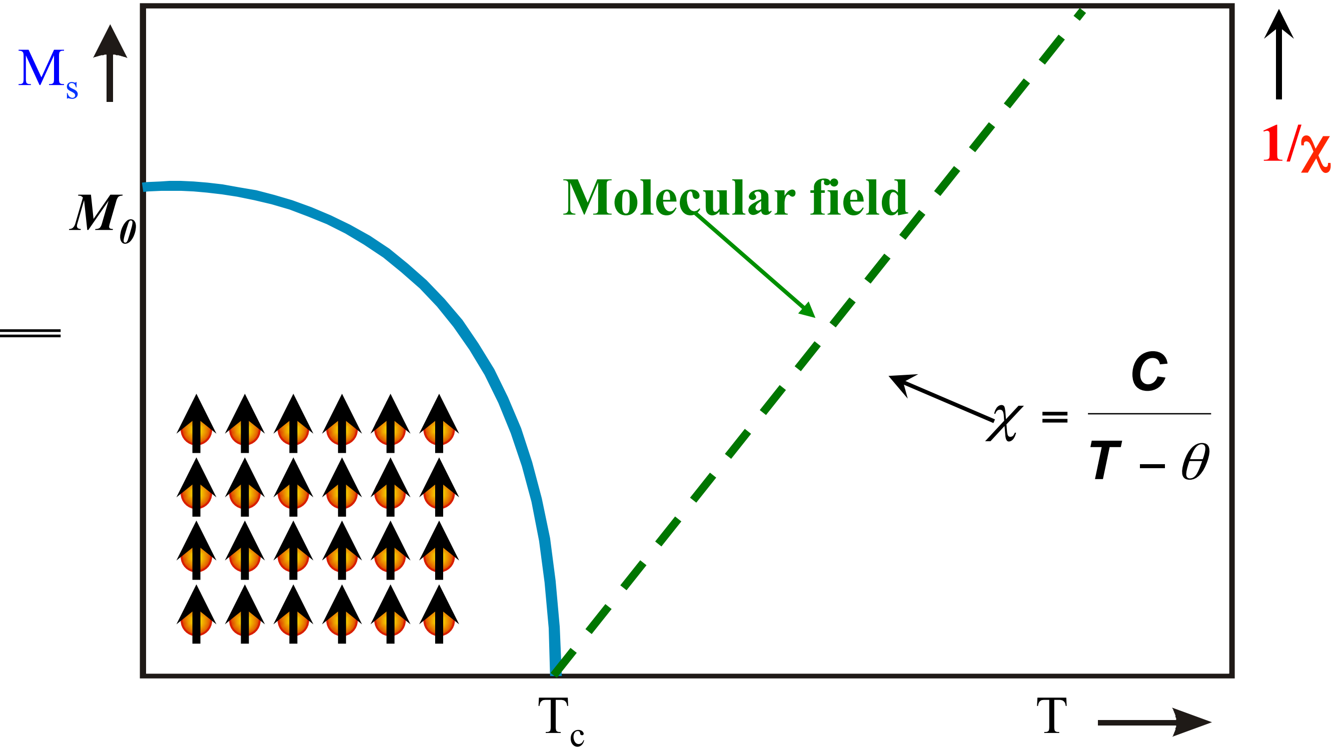

Ferromagnets

$\vec{\mu} \neq 0$; $M_s \neq 0$

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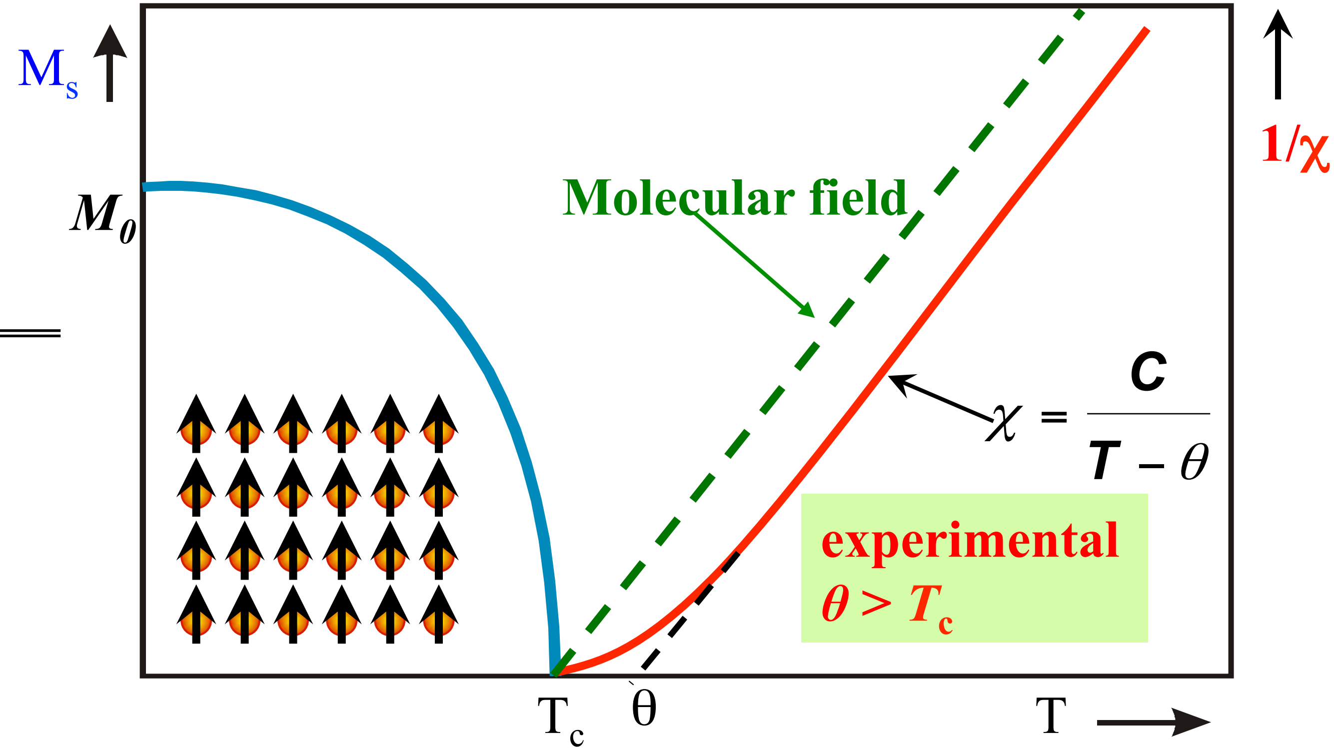


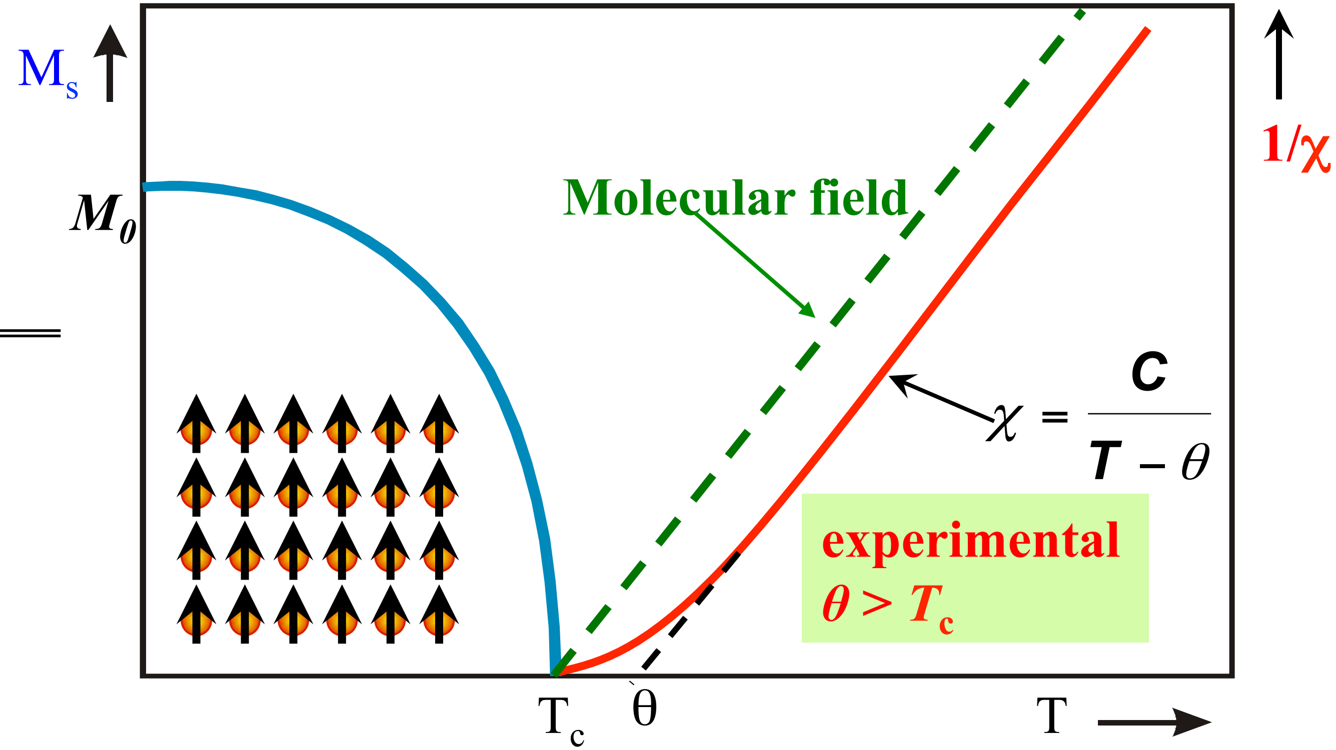
Molecular field → $T_c = \theta$

Ferromagnets

$\vec{\mu} \neq 0$; $M_s \neq 0$

$J_{ij} > 0$

$\chi >> 0$



Molecular field → $T_c = \theta$ experimental ?

Ferromagnets

$\vec{\mu} \neq 0$; $M_s \neq 0$

$J_{ij} > 0$

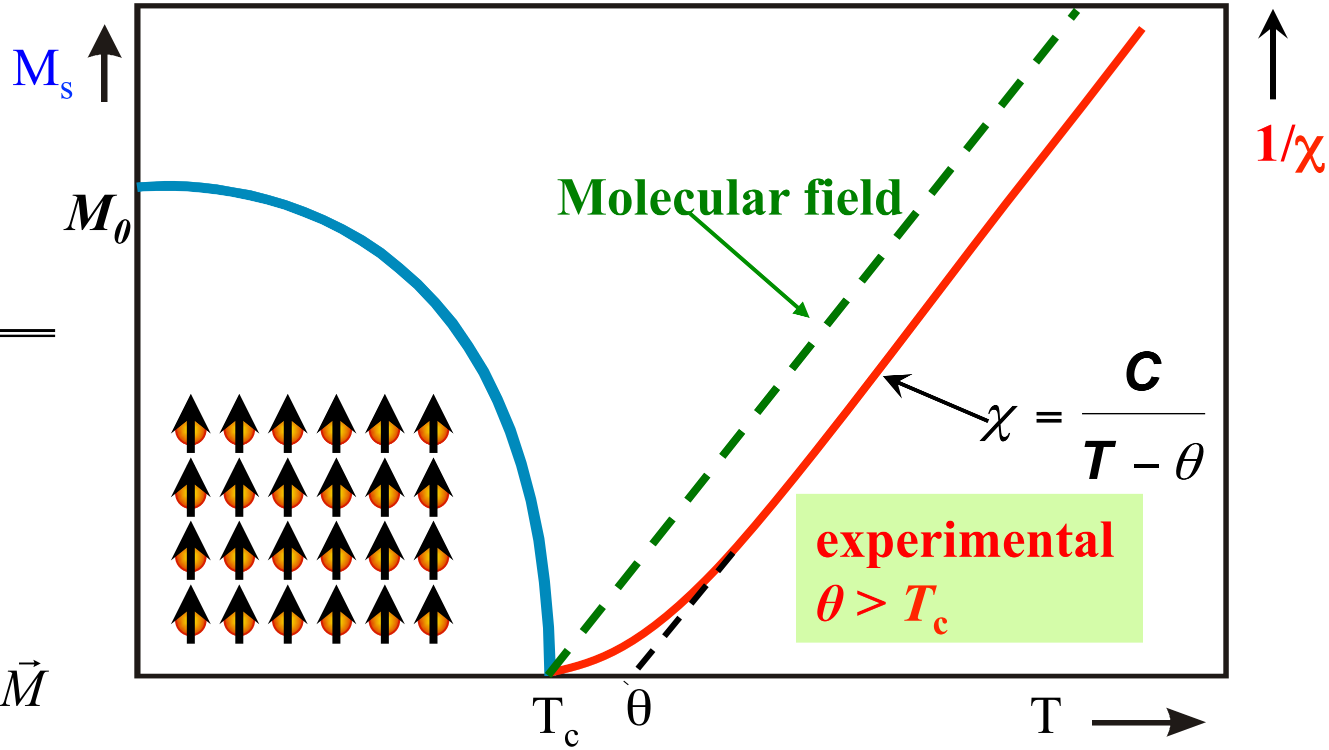
$\chi >> 0$

$$M = M_0 B_J(x)$$

$$x = \frac{g\mu_o \mu_B J H_T}{k_B T}$$

$$\vec{H}_T = \vec{H} + \vec{H}_m = \vec{H} + N_{ii}\vec{M}$$

$$M_0 = Ng\mu_B J$$



$$\chi = \frac{M}{H} = \frac{C}{T - \theta} \quad (17)$$

Curie-Weiss law

$$C = \frac{N\mu_0 g^2 \mu_B^2 J(J+1)}{3k_B} \quad (18)$$

Curie constant

$$T_c = \frac{N_{ii} N\mu_o g^2 \mu_B^2 J(J+1)}{3k_B} \quad (19)$$

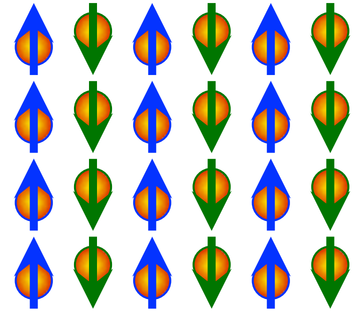
Ferromagnetic Curie temperature

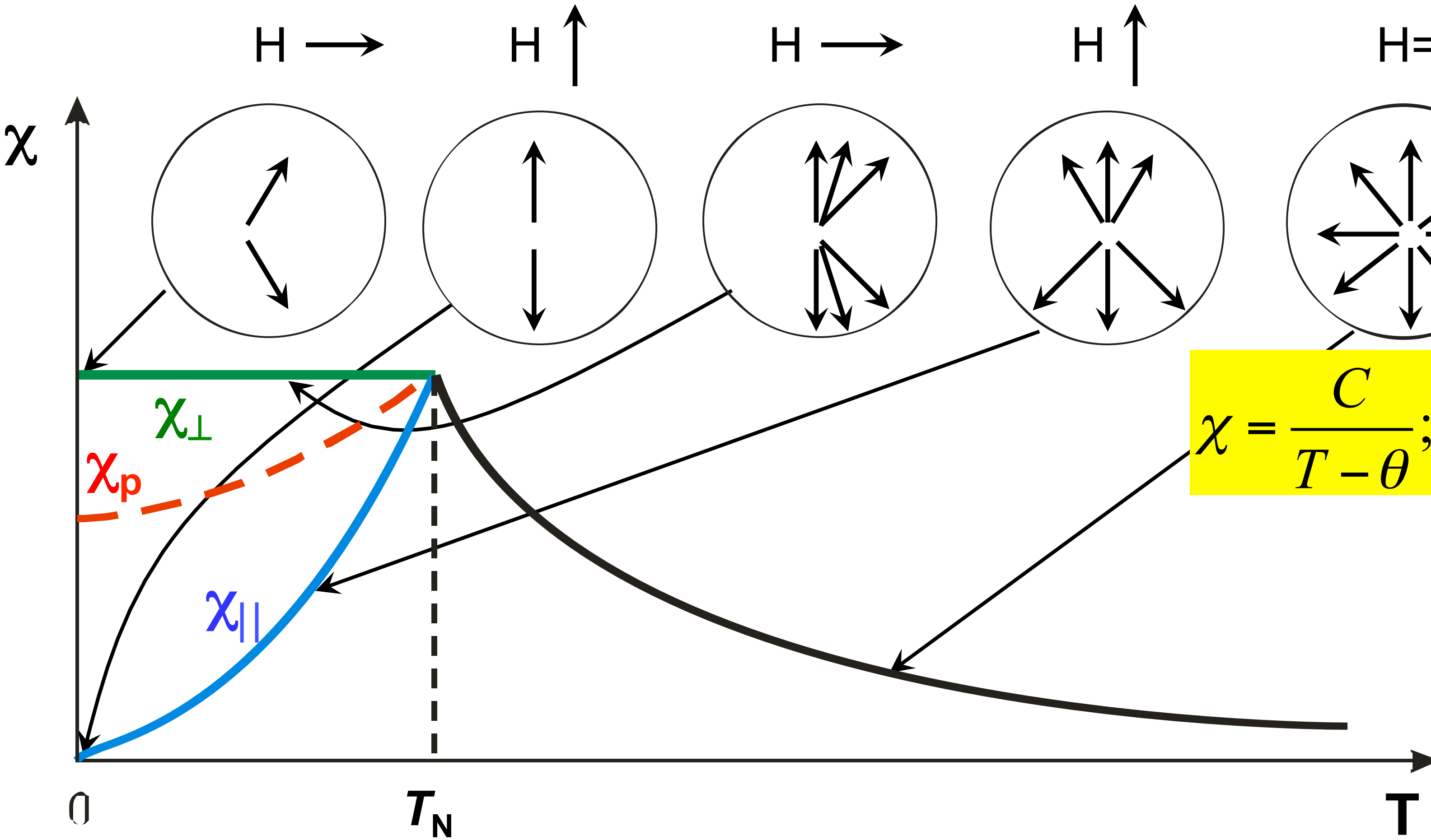
Antiferromagnets

$\vec{\mu} \neq 0$; $M_s = 0$

$J_{ij} < 0$

$\chi >> 0$





$$\chi = \frac{C}{T-\theta}; \theta < 0$$

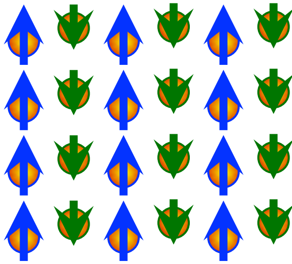
$T<T_C$

Ferrimagnets

$\vec{\mu} \neq 0$; $M_s \neq 0$

$J_{ij} < 0$

$\chi >> 0$



Fe_3O_4, ferrites, $GdCo_5$,…

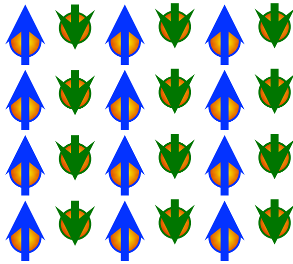
$T<T_C$

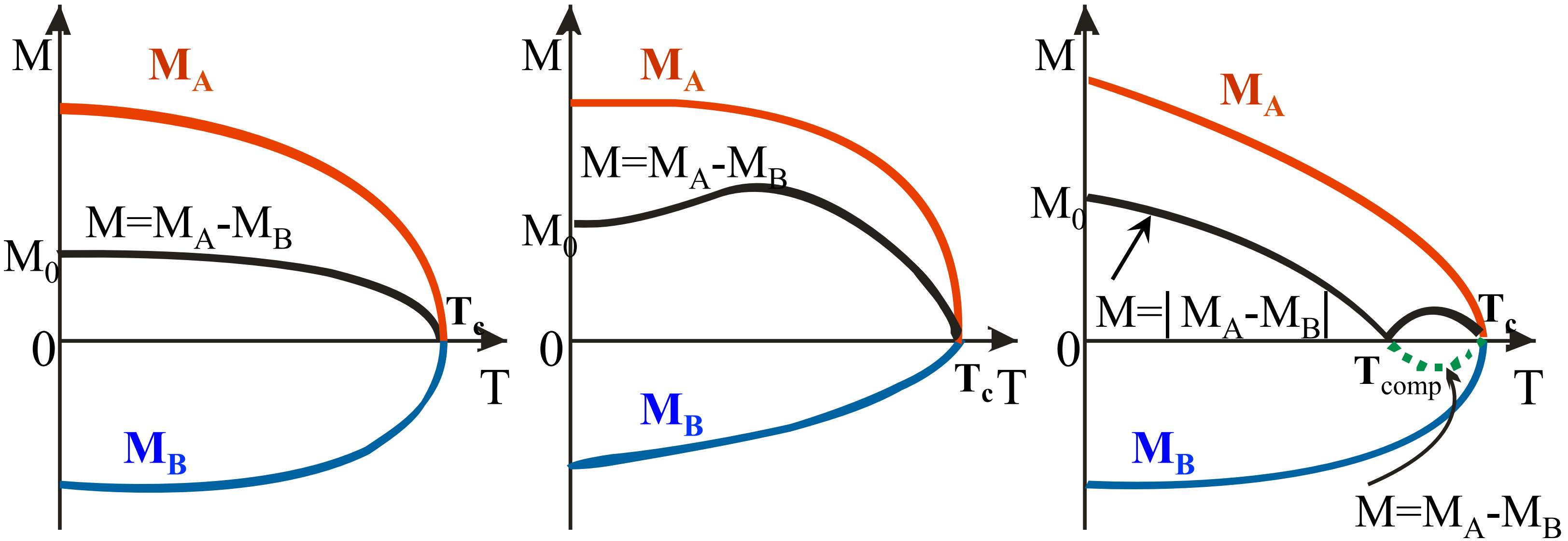
Ferrimagnets

$\vec{\mu} \neq 0$; $M_s \neq 0$

$J_{ij} < 0$

$\chi >> 0$





(a) (b) (c)

Fe_3O_4, ferrites, $GdCo_5$,...

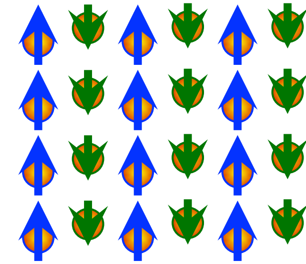
T<T$_C$

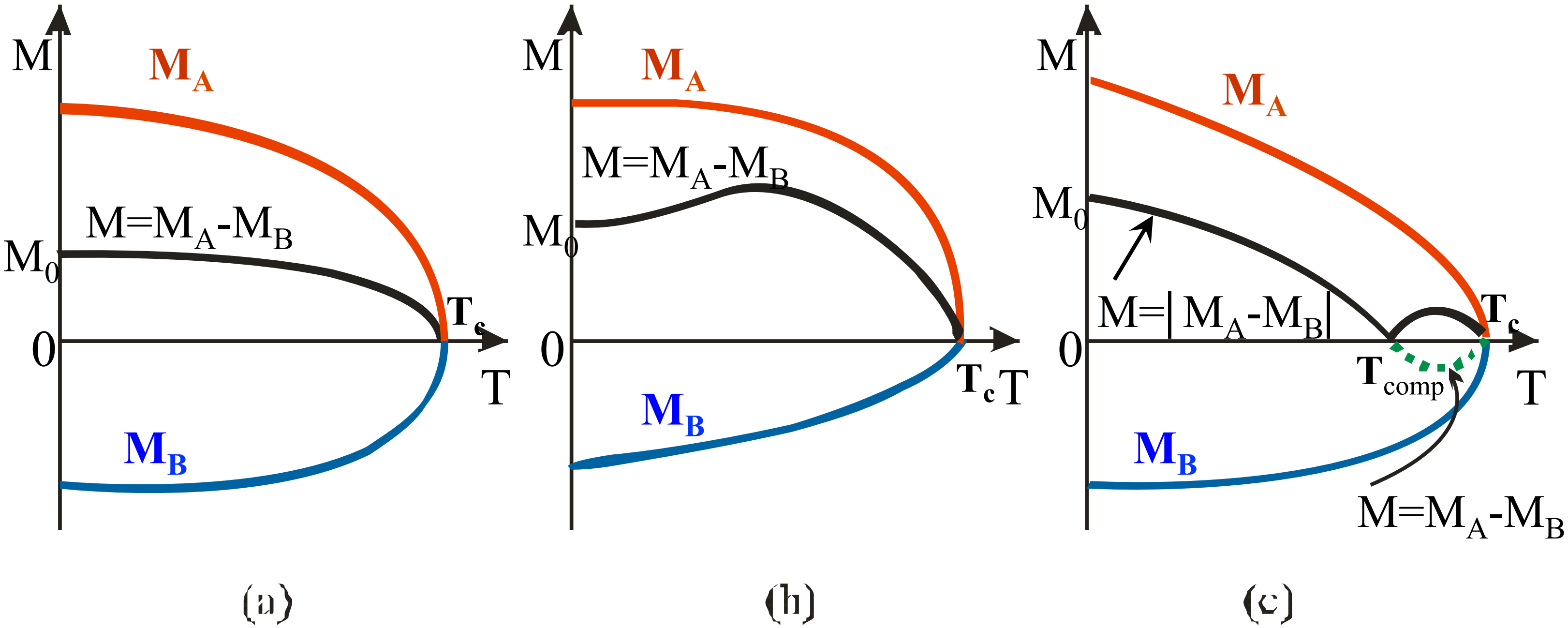
Ferrimagnets

$\vec{\mu} \neq 0; M_s \neq 0$

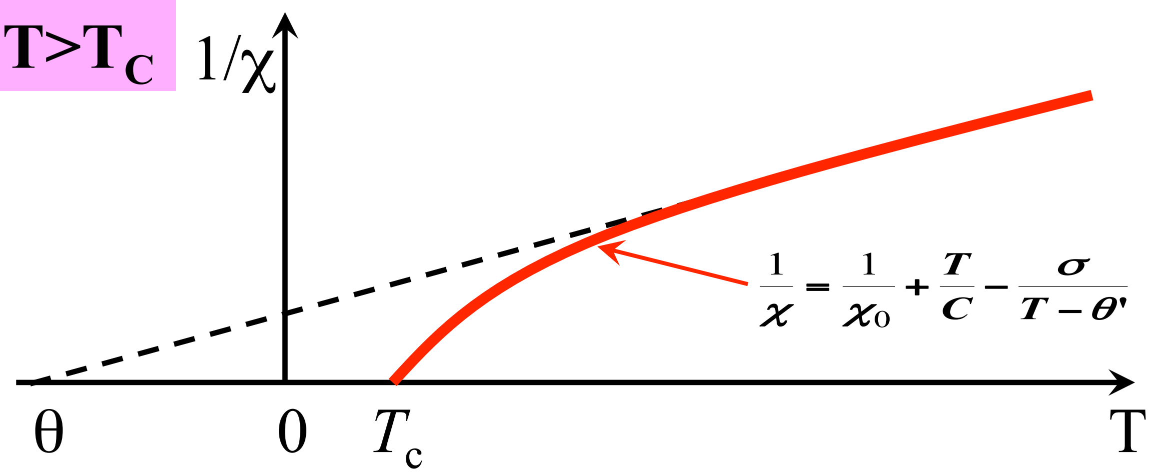
$J_{ij} < 0$

$\chi >> 0$



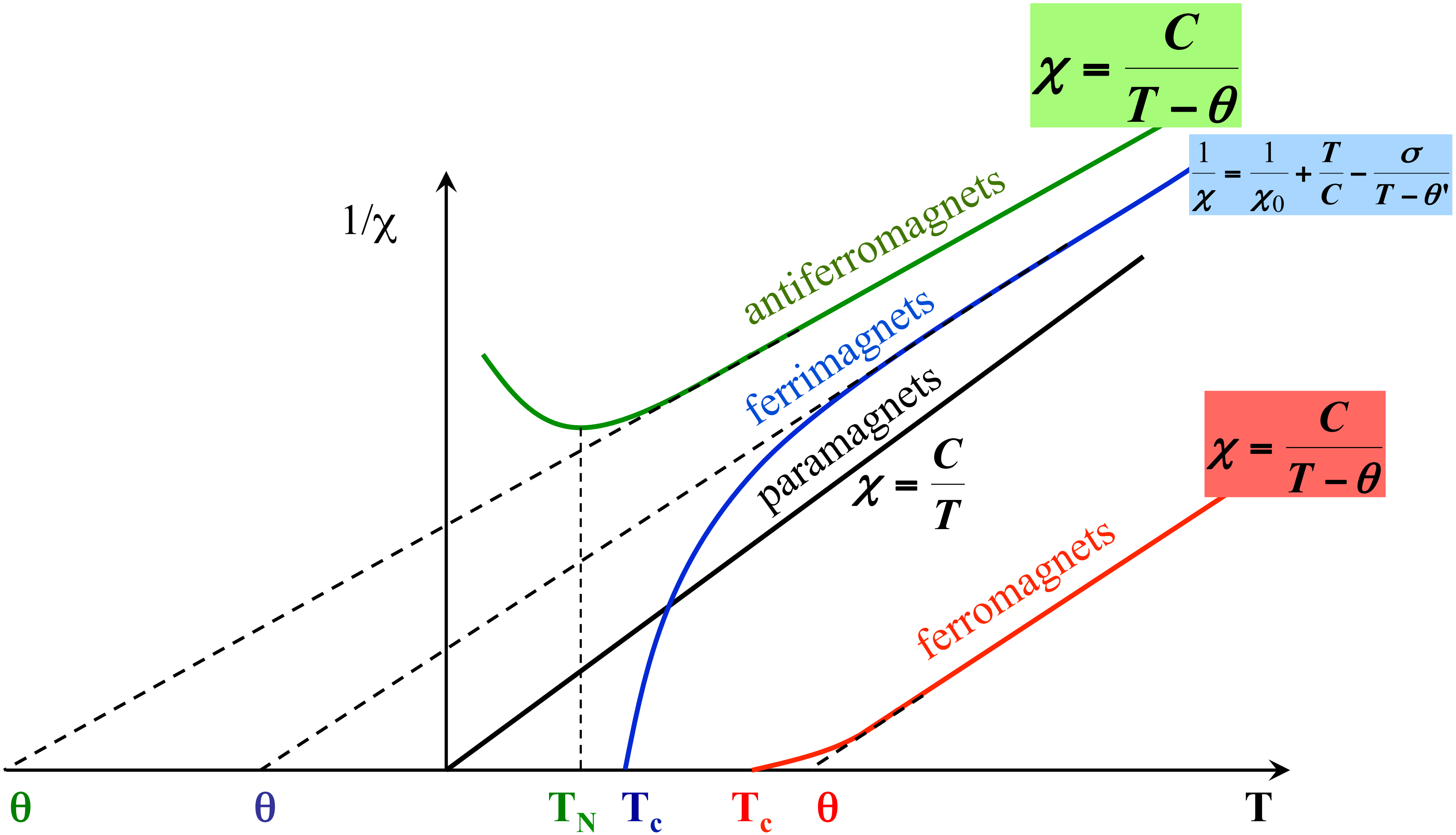


T>T$_C$



Fe_3O_4, ferrites, $GdCo_5$,…

Magnetic susceptibility, χ, above the magnetic order temperature



Free energy in magnetic systems

The free energy of a magnetic material is given by:

$$E = E_z + E_{ex} + E_K + E_D + E_\lambda$$

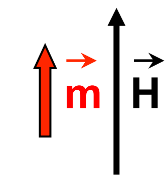
Free energy in magnetic systems

The free energy of a magnetic material is given by:

$$\boldsymbol{E = E_z + E_{ex} + E_K + E_D + E_\lambda}$$

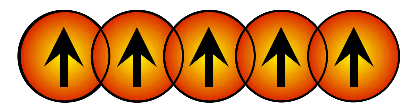
E_z = energy in the external field (Zeeman)

$$E_z = -\mu_0 \vec{M} \cdot \vec{H}$$



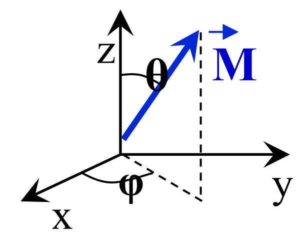
E_{ex} = exchange energy

$$\boldsymbol{E_{ex} = -2J_{ij}\vec{S}_i \cdot \vec{S}_j}$$



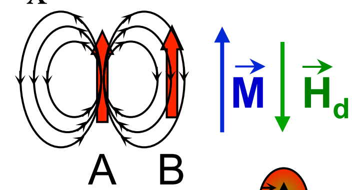
E_K =anisotropy energy

$$\boldsymbol{E_K} \approx \boldsymbol{K_1}\left(\alpha_1^2\alpha_2^2 + \alpha_1^2\alpha_3^2 + \alpha_2^2\alpha_3^2\right) \qquad \boldsymbol{E_K = K_1 \sin^2\theta}$$



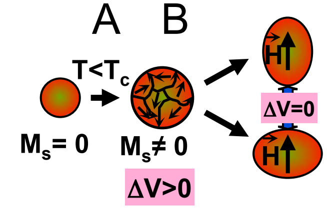
E_D = demagnetization energy

$$\boldsymbol{E_D} = -\frac{1}{2}\mu_0 \boldsymbol{\vec{M} \cdot \vec{H}_d}$$



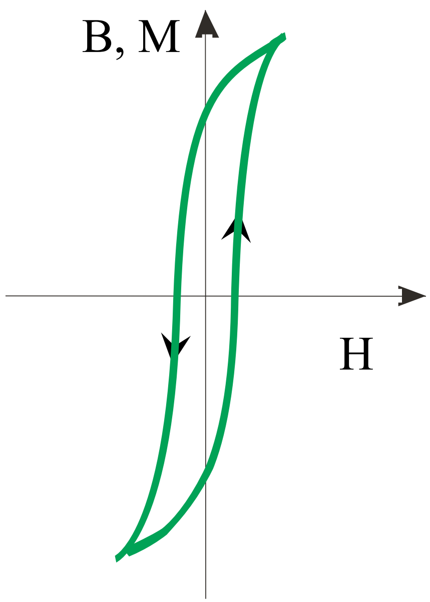
E_λ = magnetostrictive energy

$$\boldsymbol{E_\lambda} = -\frac{3}{2}\lambda_s \sigma \cos^2\theta$$



The main types of magnetic materials

Soft magnetic materials



H_c – small~0,001÷10 A/m

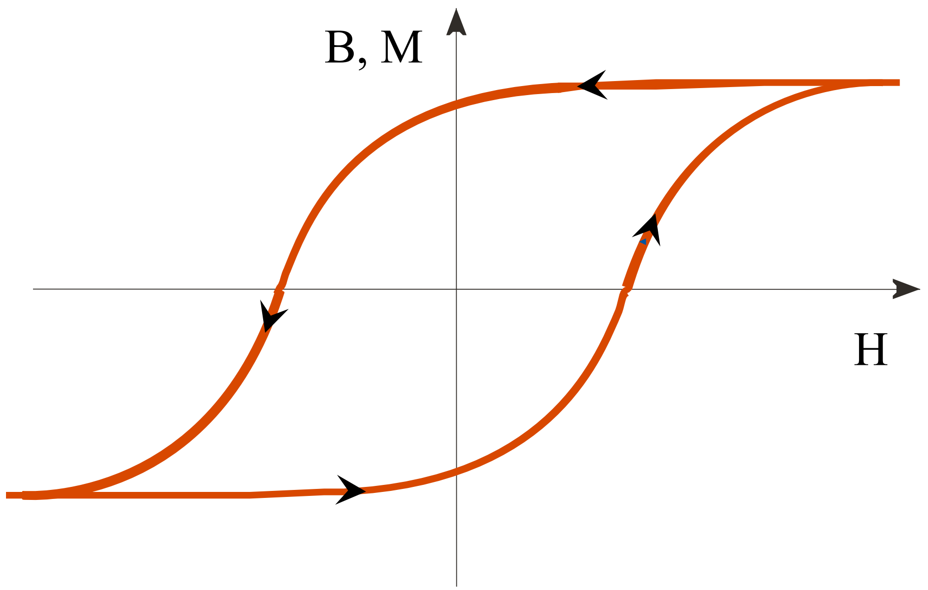
T_c – large

B_s – large

μ- large

ρ – large **(important for ac applications)**

Hard magnetic materials



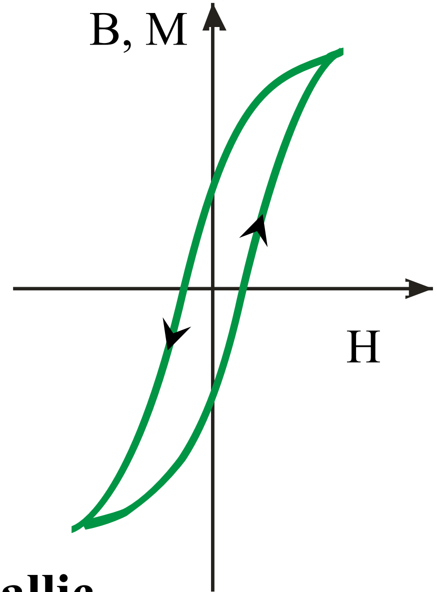
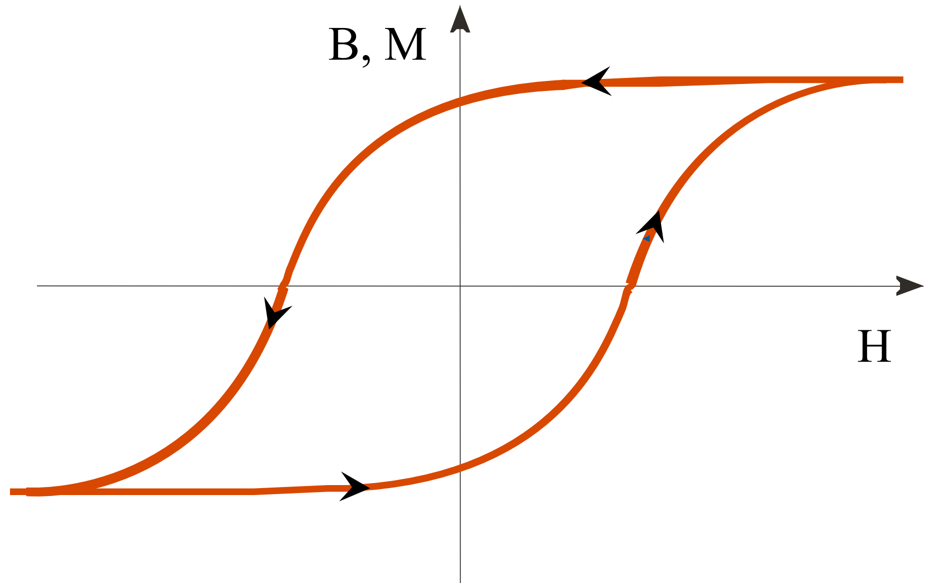
H_c – LARGE~10^2÷10^6 A/m

T_c – large

B_r - large

$(BH)_{max}$ - large

The main types of magnetic materials

Soft magnetic materials	*Hard magnetic materials*
	

Metallic

Fe, FeP, FeSi, CoFe, NiFe, NiFeMo	Steel (3), Alnico (50), CrCoFe (40) $Sm_2(Co,Cu,Fe,Zr)_{17}$ (220), $SmCo_5$ (240), **$Nd_2Fe_{14}B$ (400)**

Ceramics

MnZn ferrite, NiZn ferrite	Ba ferrites (30), Sr ferrites(30)

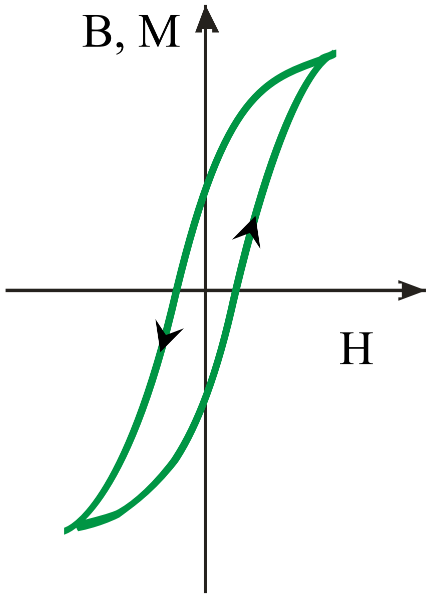
Composites

Polymers+ amorphous or crystalline magnetic powders of Fe, NiFe, SiFe	**(~80):** Polymers+ Alnico, hard ferrites, $Sm_2(Co,Cu,Fe,Zr)_{17}$, $SmCo_5$, $Nd_2Fe_{14}B$

(……) ≡ $(BH)_{max}$ in kJ/m³

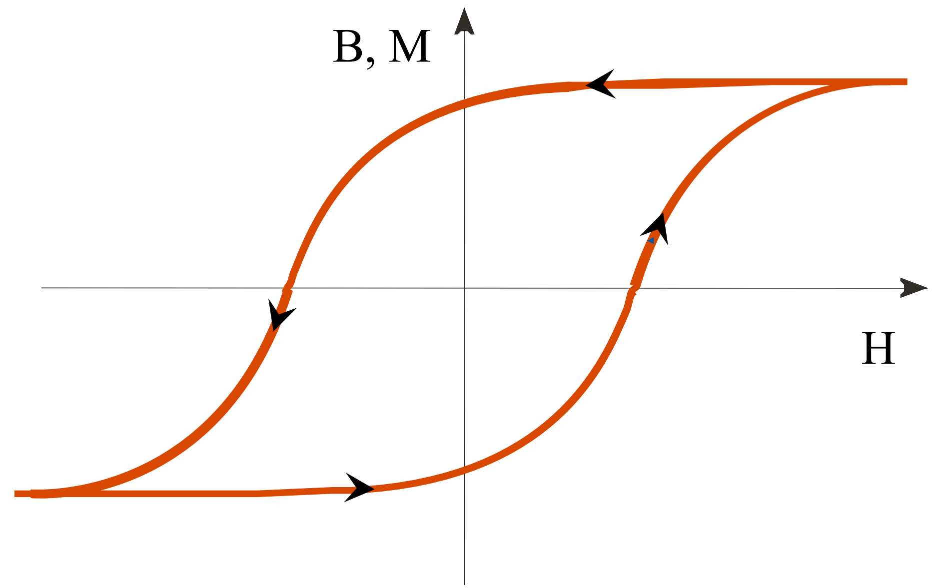
The main types of magnetic materials - *Applications*

Soft magnetic materials



Transformers, audio and video equipment, sensors, computer peripherals, reading / recording heads, the automotive industry (motors, actuator components, valves ...), magnetic flux concentrators, magnetic shields, etc.

Hard magnetic materials



Electrical motors, stepper motors, linear motors, audio equipment (microphones, speakers ...), magnetic field sources, magnetic scales, microwave sources, magnetic separators, magnetic couplings, NMR, detection systems, fasteners, etc.

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