Advanced Nanotechnology (Nanoscience)

Optical

Electrical

Thermal

Magnetic

Properties of

Top-down

Bottom-up

Nanomaterials and structures

Magnetism to Spintronics

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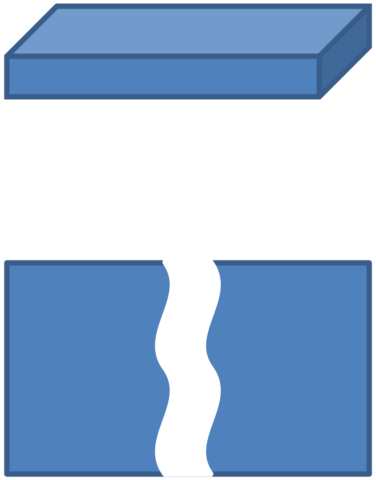
Institute of Physics, Academia Sinica

Introduction to Solid State Physics
Kittel 8th ed
Chap. 11-13,

Solid State Physics
Ashcroft and Mermin
Chap. 31-33,

Condensed Matter Physics
Marder 2nd ed
Chap. 24-26,

Why do most broken permanent magnets repel each other?



Cooperative phenomena

- Elementary excitations in solids describe the response of a solid to a perturbation
  - Quasiparticles

    usually fermions, resemble the particles that make the system, e.g. quasi-electrons
  - Collective excitations

    usually bosons, describe collective motions

    use second quantization with Fermi-Dirac or Bose-Einstein statistics

Magnetism

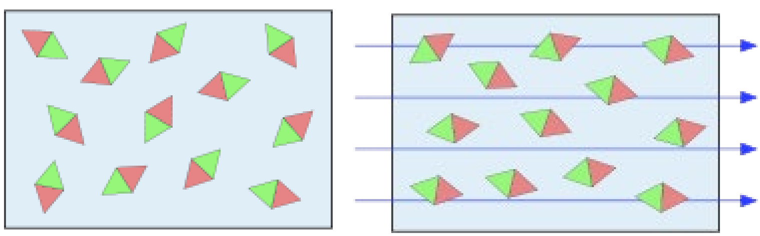
- the Bohr–van Leeuwen theorem

  when statistical mechanics and classical mechanics are applied consistently, the thermal average of the magnetization is always zero.
- Magnetism in solids is solely a quantum mechanical effect
- Origin of the magnetic moment:
  - Electron spin $\vec{S}$
  - Electron orbital momentum $\vec{L}$
- From (macroscopic) response to external magnetic field $\vec{H}$
  - Diamagnetism $\chi < 0$, $\chi \sim 1 \times 10^{-6}$, insensitive to temperature
  - Paramagnetism $\chi > 0$, $\chi = \frac{C}{T}$ Curie law

    $\chi = \frac{C}{T+\Delta}$ Curie-Weiss law
  - Ferromagnetism exchange interaction (quantum)

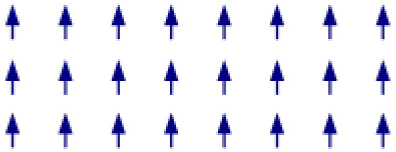
Magnetism

巨觀： 順磁性
Paramagnetism

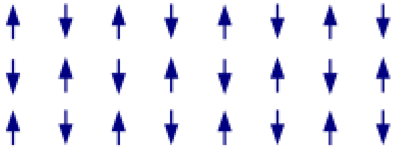


逆磁性
diamagnetism

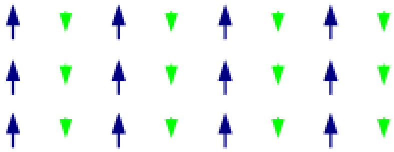
微觀： 鐵磁性
Ferromagnetism



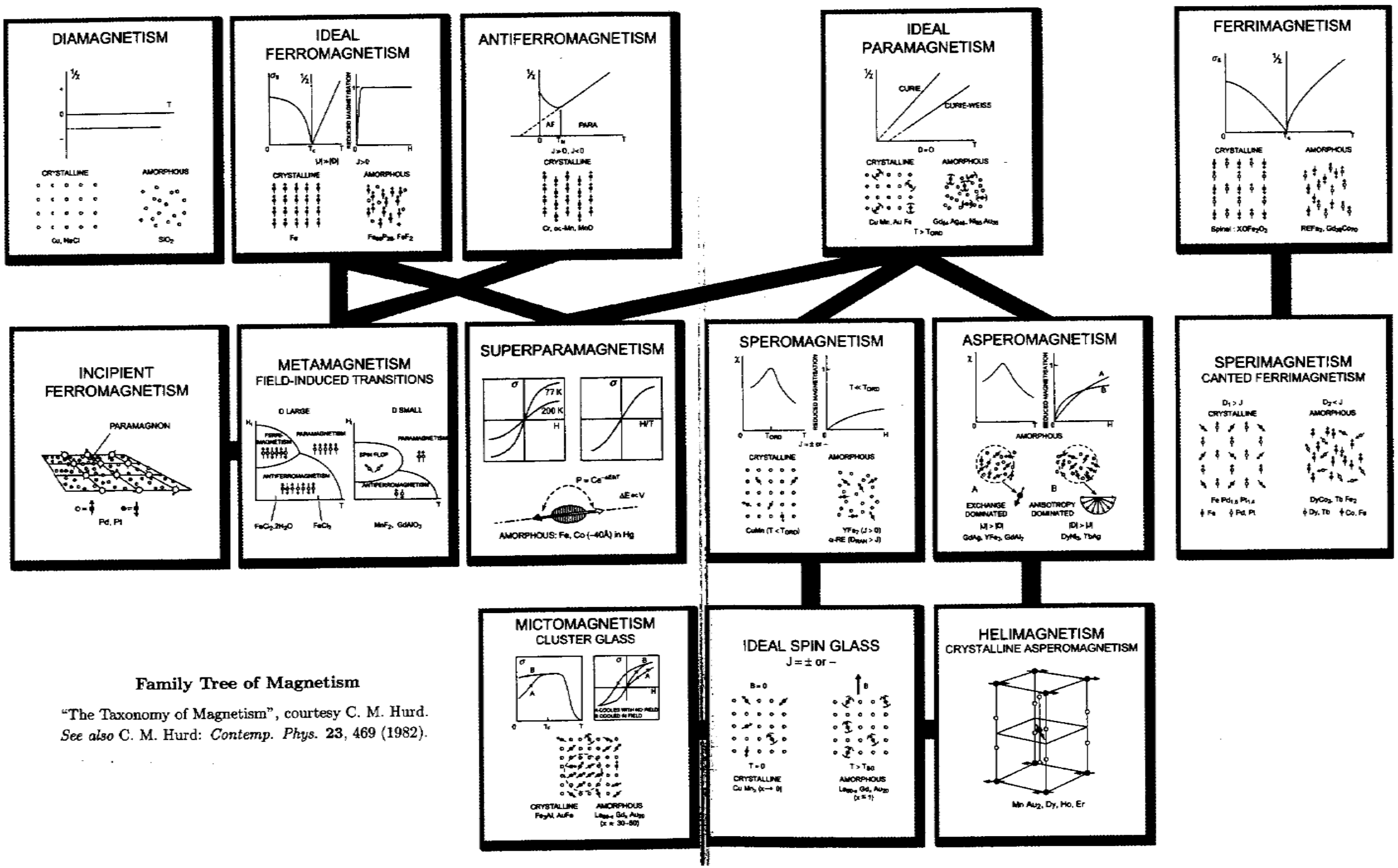
反鐵磁性
Antiferromagnetism



亞鐵磁性
Ferrimagnetism



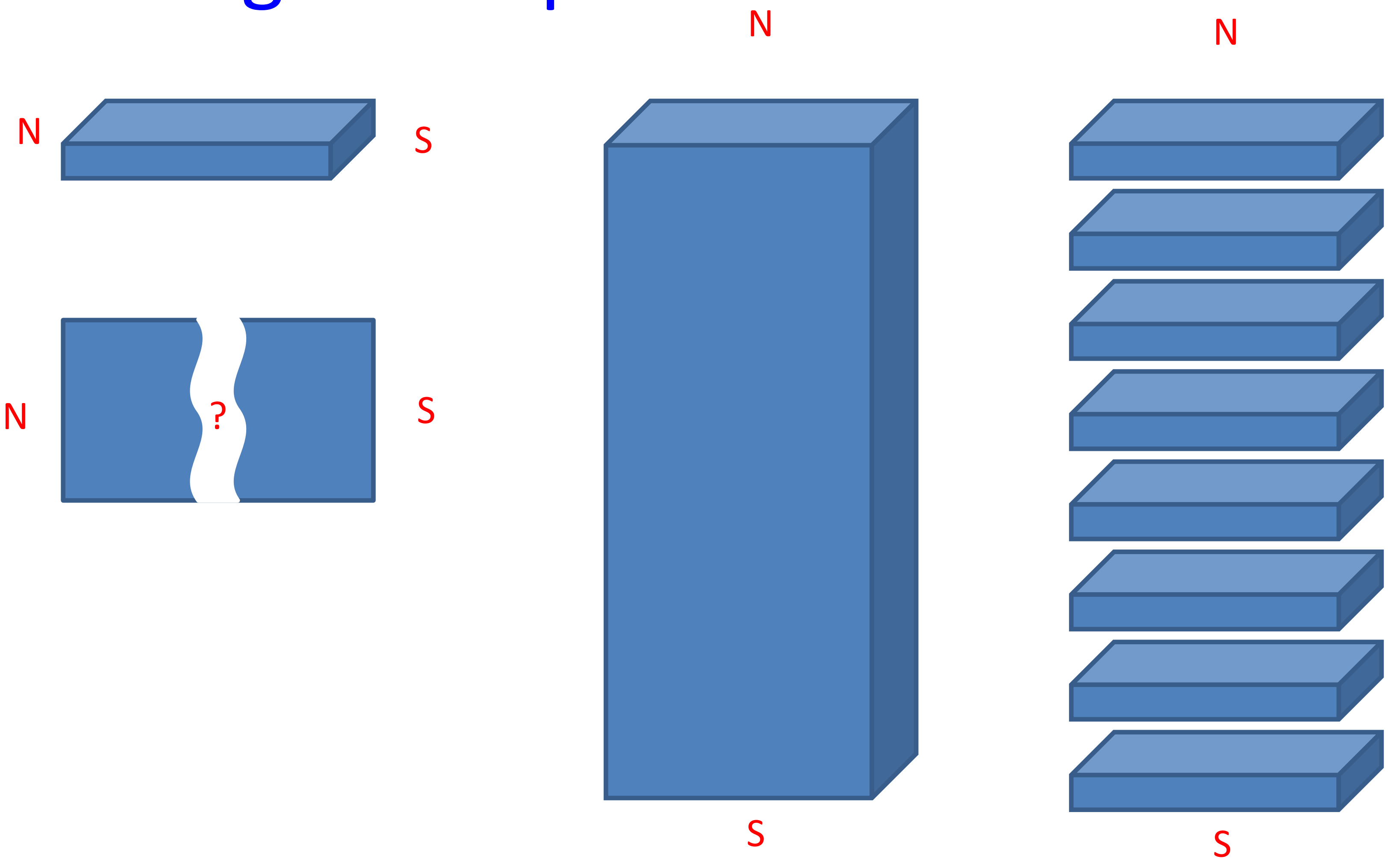
Family Tree of Magnetism



Family Tree of Magnetism

"The Taxonomy of Magnetism", courtesy C. M. Hurd.
See also C. M. Hurd: *Contemp. Phys.* **23**, 469 (1982).

Why do most broken permanent magnets repel each other?



- Classical and quantum theory for diamagnetism
  - Calculate $\langle r^2 \rangle$
- Classical and quantum theory for paramagnetism
  - Superparamagnetism, Langevin function
  - Hund's rules
  - Magnetic state ${}^{2S+1}L_J$
  - Crystal field
  - Quenching of orbital angular momentum L_z
    - **Angular momentum operator**
    - **Spherical harmonics**
  - Jahn-Teller effect
  - Paramagnetic susceptibility of conduction electrons

- Ferromagnetism
  - Microscopic – ferro, antiferro, ferri magnetism
  - Exchange interaction
  - Exchange splitting – source of magnetization

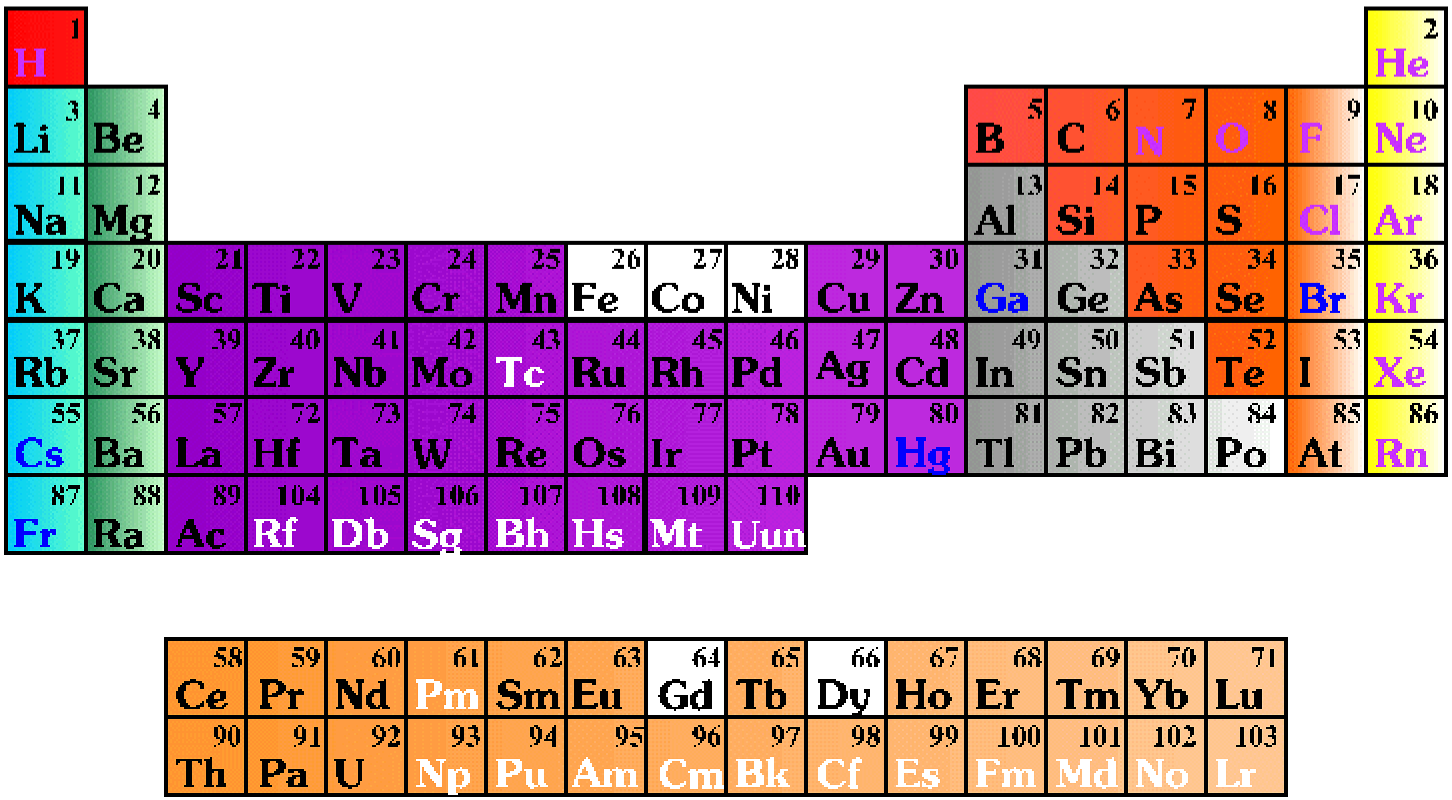
    two-electron system spin-independent Schrodinger equation
  - Type of exchange: direct exchange, super exchange, indirect exchange, itinerant exchange
  - Spin Hamiltonian and Heisenberg model
  - Molecular-field (mean-field) approximation

Ferromagnetic elements: 鐵 Fe, 鈷 Co, 鎳 Ni, 釓 Gd, 鏑 Dy,
錳 Mn, 鈀 Pd ??

Elements with ferromagnetic properties

合金, alloys

錳氧化物 MnOx, ……



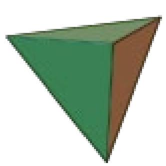
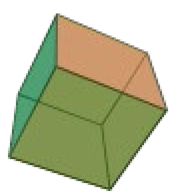
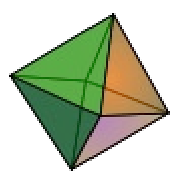
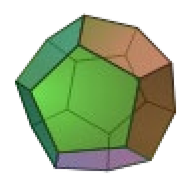
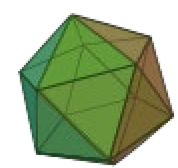
Platonic solid

From Wikipedia

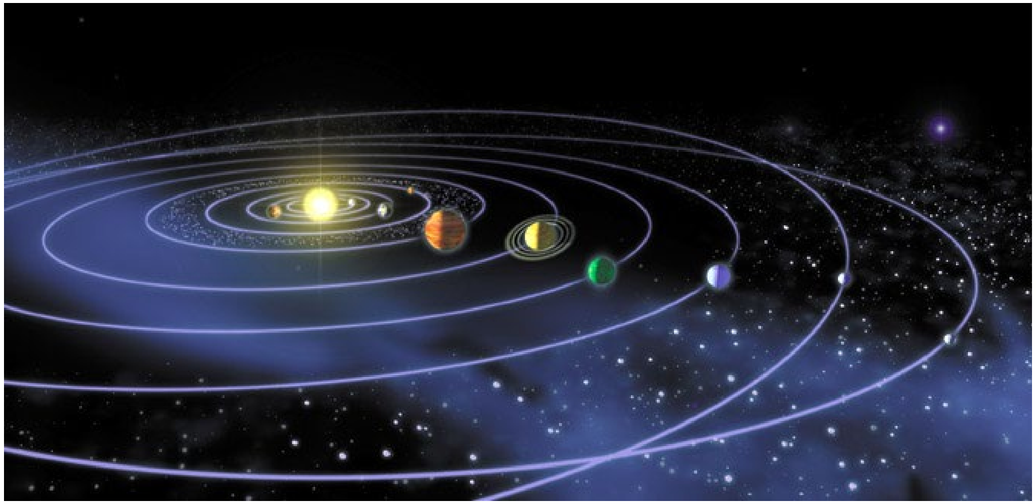
In geometry, a Platonic solid is a convex polyhedron that is regular, in the sense of a regular polygon. Specifically, the faces of a Platonic solid are congruent regular polygons, with the same number of faces meeting at each vertex; thus, all its edges are congruent, as are its vertices and angles. There are precisely five Platonic solids (shown below):

The name of each figure is derived from its number of faces: respectively 4, 6, 8, 12, and 20.

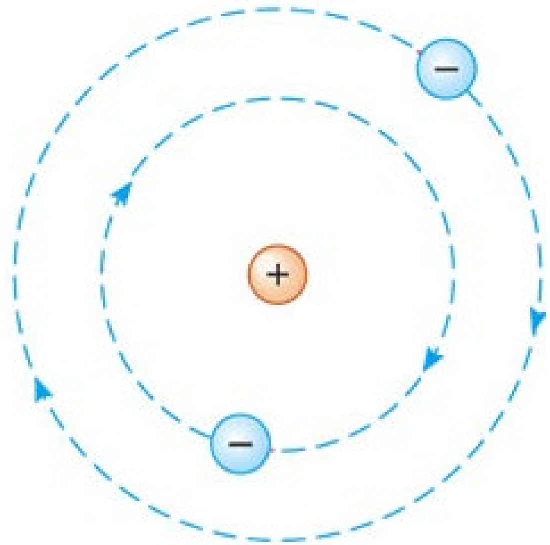
The aesthetic beauty and symmetry of the Platonic solids have made them a favorite subject of geometers for thousands of years. They are named for the ancient Greek philosopher Plato who theorized that the classical elements were constructed from the regular solids.

				
Tetrahedron	Cube hexahedron	Octahedron	Dodecahedron	Icosahedron

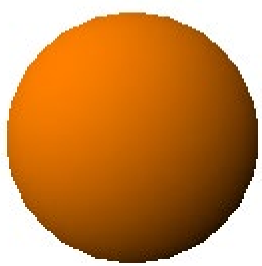
Solar system

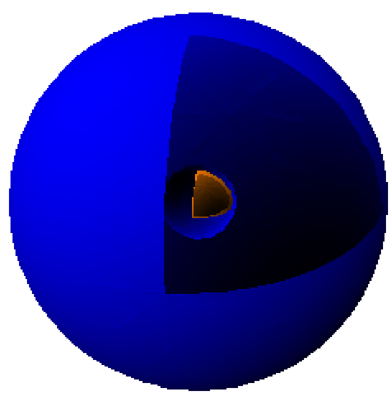


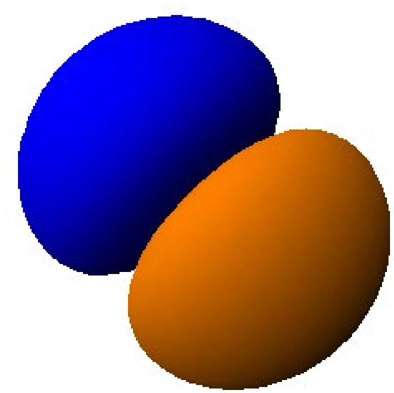
Electronic orbit



s, p electron orbits



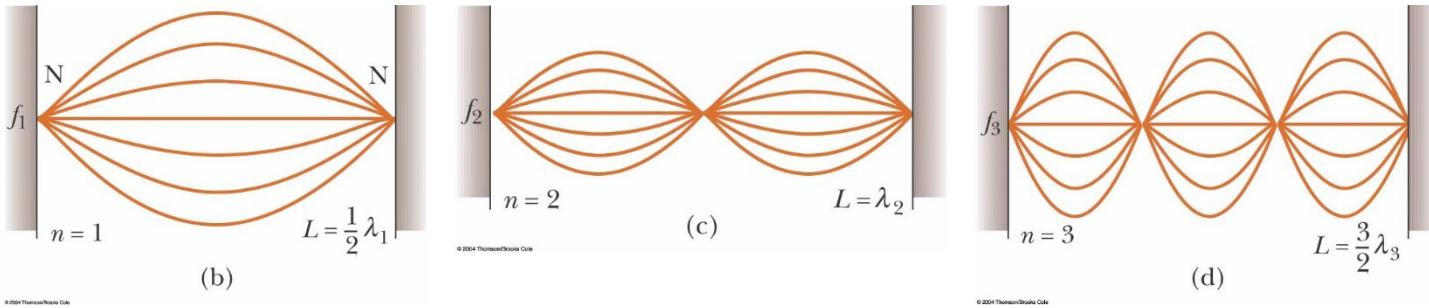




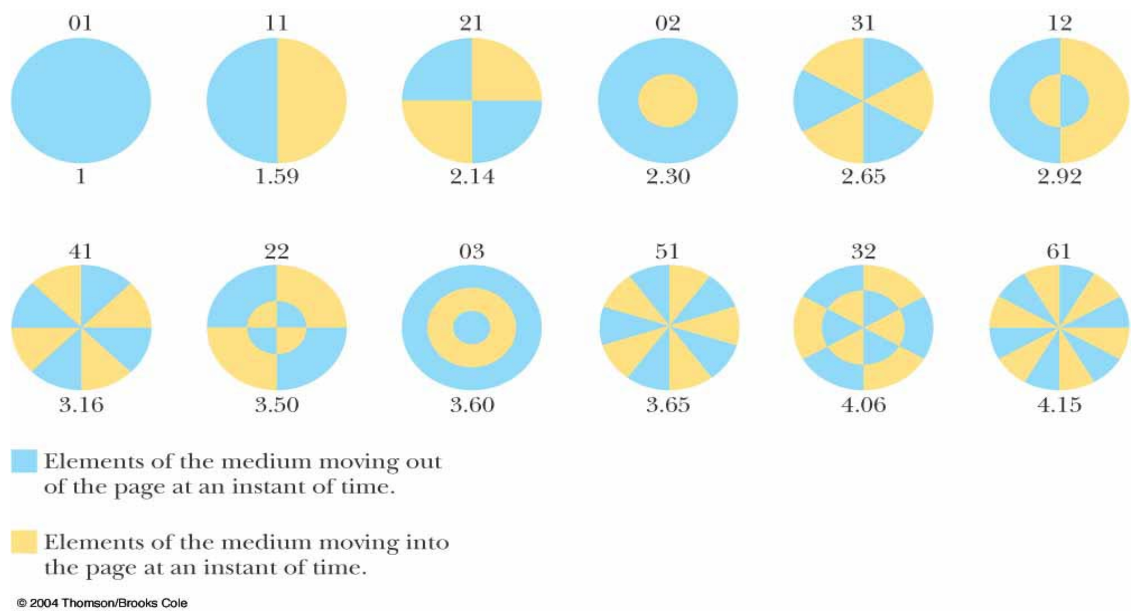
Orbital viewer

Resonance

One-dimensional



Two-dimensional



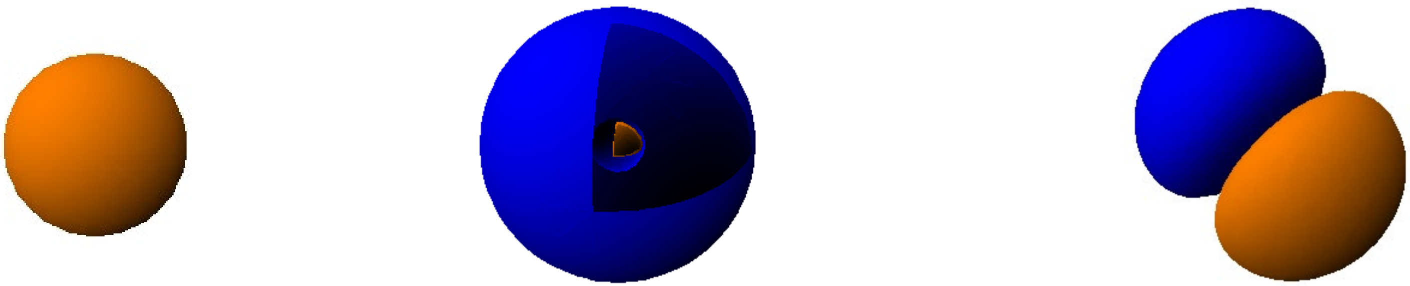
Three-dimensional

Hydrogen atom

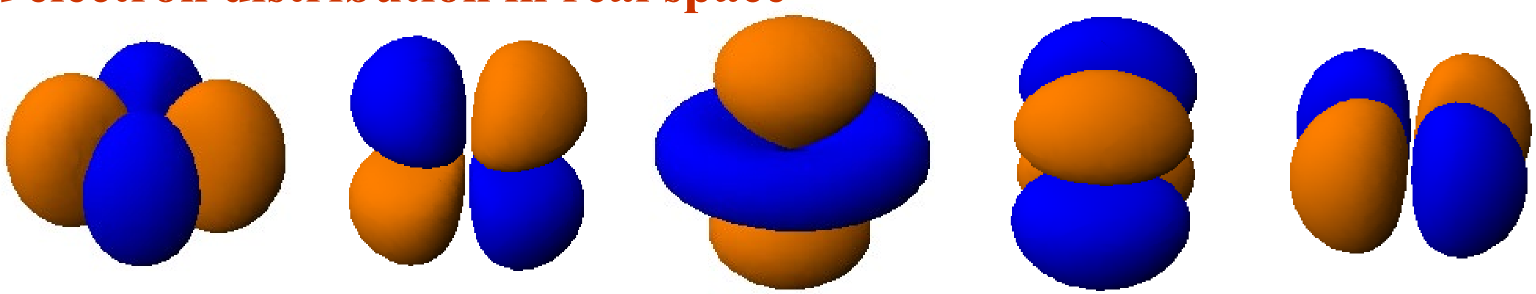
3d transition metals:

Mn atom has 5 d $\uparrow$ electrons   Bulk Mn is NOT magnetic

s, p electron orbital



3d electron distribution in real space

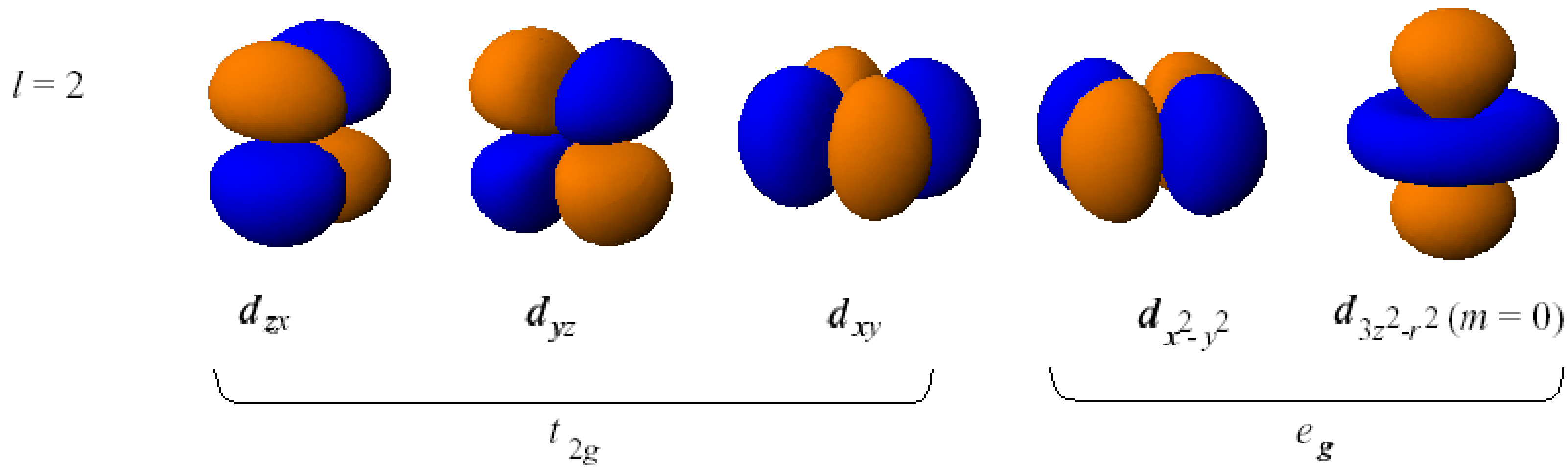


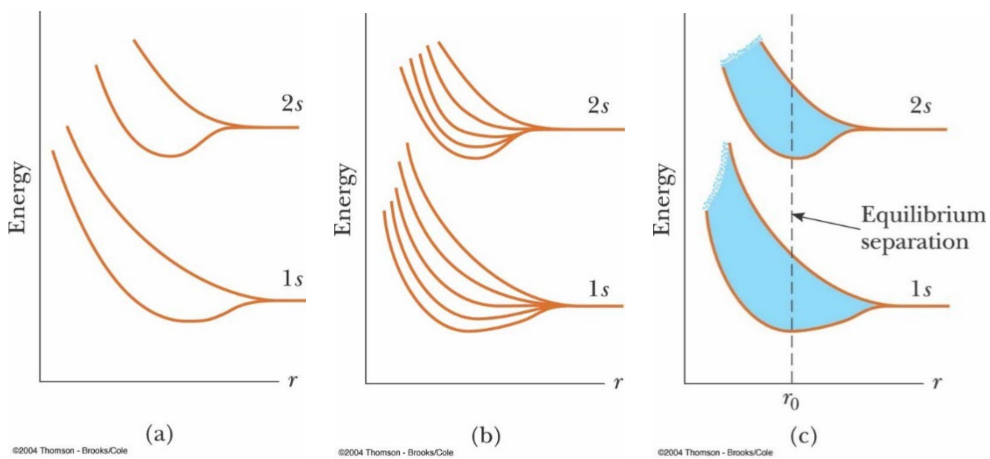
Co atom has 5 d $\uparrow$electrons and 2 d $\downarrow$ electrons

Bulk Co is magnetic.

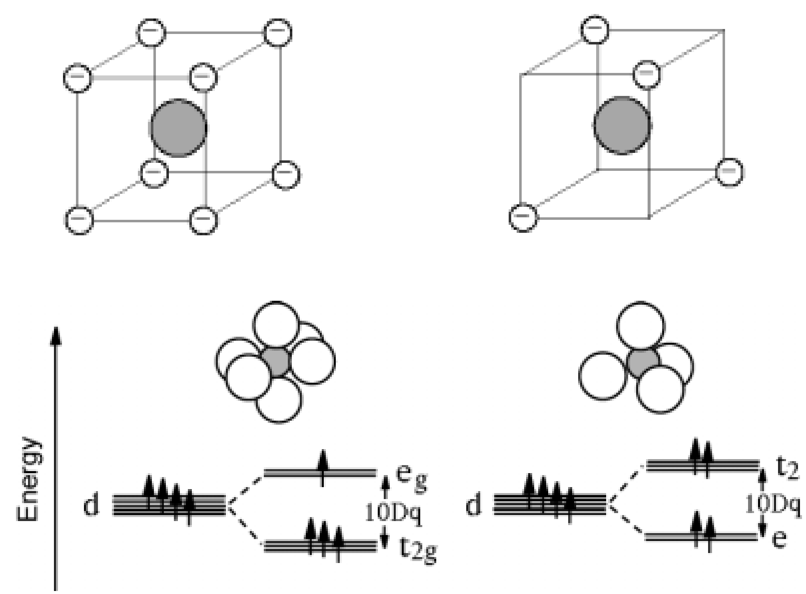
Orbital viewer

d orbitals

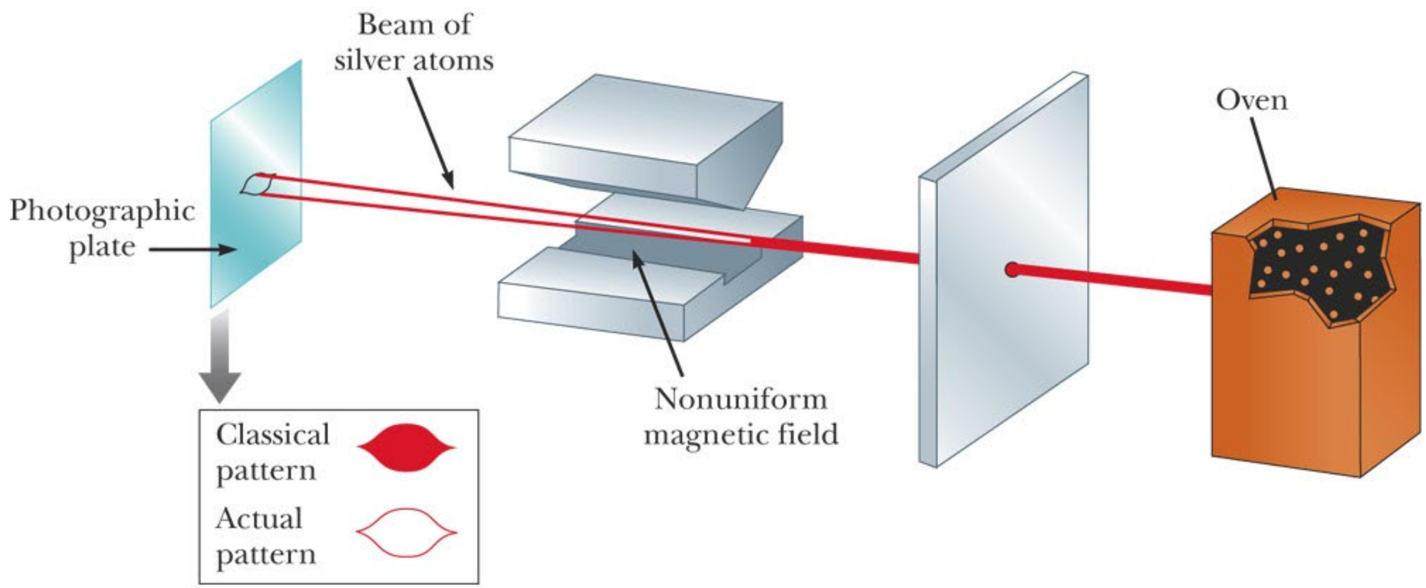


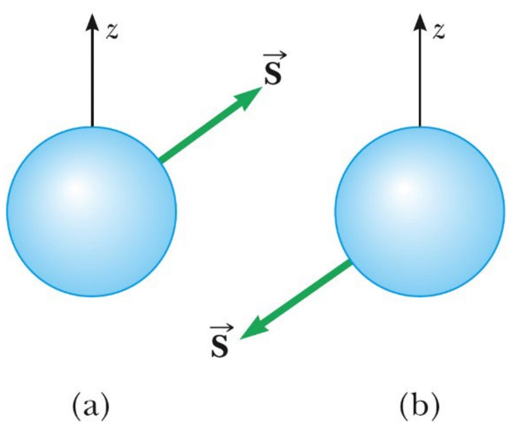


Crystal-field splitting



Stern-Gerlach Experiment



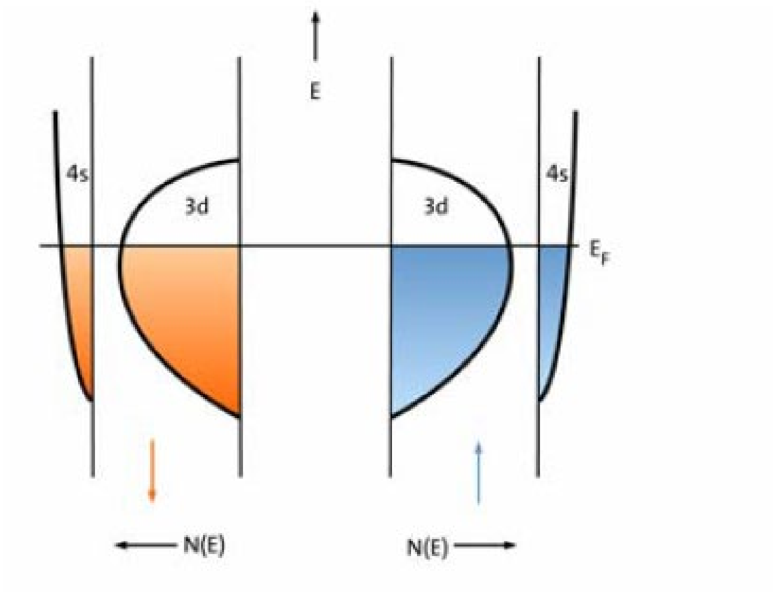


There are two kinds of electrons:
spin-up and spin-down.

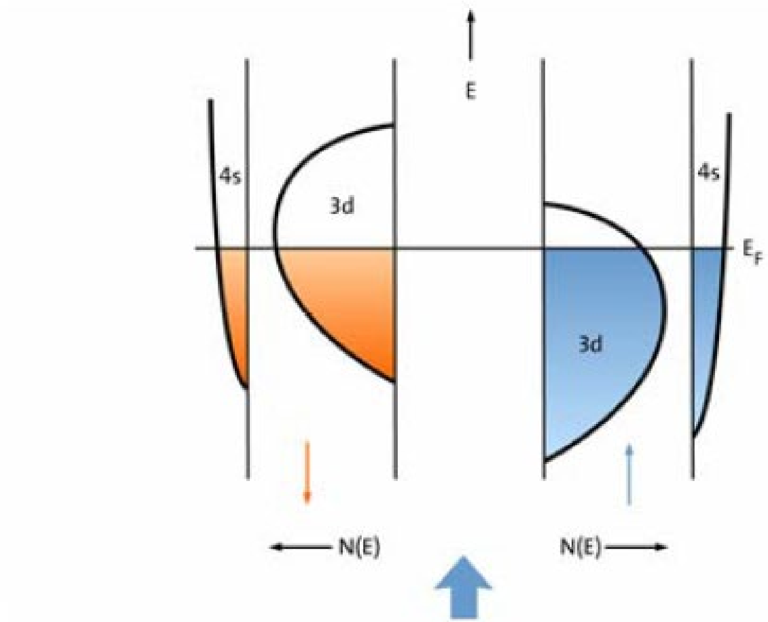
Stern and Gerlach: How a Bad Cigar Helped Reorient Atomic Physics
[Physics Today 56, 53 (2003) 10.1063/1.1650229]

Stoner criterion for ferromagnetism:

$I\,N(E_F) > 1$, I is the **Stoner exchange parameter** and $N(E_F)$ is the density of states at the Fermi energy.



For the non-magnetic state there are identical density of states for the two spins.



For a ferromagnetic state, N↑ > N↓. The polarization is indicated by the thick blue arrow.

Schematic plot for the energy band structure of 3d transition metals.

Teodorescu and Lungu, "Band ferromagnetism in systems of variable dimensionality". *J Optoelectronics and Adv. Mat.* **10,** 3058–3068 (2008).

- Stoner band ferromagnetism

Teodorescu, C. M.; Lungu, G. A. (November 2008). "Band ferromagnetism in systems of variable dimensionality". *Journal of Optoelectronics and Advanced Materials* **10** (11): 3058–3068.

$$\mathcal{E} = \int_0^{\mathcal{E}_F-\Delta} d\mathcal{E}'\, D(\mathcal{E}')\mathcal{E}' + \frac{1}{2}\int_{\mathcal{E}_F-\Delta}^{\mathcal{E}_F+\Delta} d\mathcal{E}'\, D(\mathcal{E}')\mathcal{E}' - \frac{1}{2}nJ\,\langle S\rangle^2$$

$$\langle S\rangle = \frac{1}{2n}\int_{\mathcal{E}_F-\Delta}^{\mathcal{E}_F+\Delta} d\mathcal{E}'\,\frac{1}{2}D(\mathcal{E}') = \frac{1}{2n}D(\mathcal{E}_F)\Delta$$

$$\left.\frac{\partial\mathcal{E}}{\partial\Delta}\right|_{\mathcal{E}_F} = \Delta D(\mathcal{E}_F) - \frac{J}{4n}D(\mathcal{E}_F)^2\Delta$$

$$\left.\frac{\partial\mathcal{E}}{\partial\Delta}\right|_{\mathcal{E}_F} = 0 \Rightarrow \frac{J}{n}D(\mathcal{E}_F) = 4$$

Exchange interaction

Русский
Українська
Tiếng Việt
Edit links

Exchange Interactions between localized electron magnetic moments [edit]

Quantum mechanical particles are classified as bosons or fermions. The spin–statistics theorem of quantum field theory demands that all particles with half-integer spin behave as fermions and all particles with integer spin behave as bosons. Multiple bosons may occupy the same quantum state; by the Pauli exclusion principle, however, no two fermions can occupy the same state. Since electrons have spin 1/2, they are fermions. This means that the overall wave function of a system must be antisymmetric when two electrons are exchanged, i.e. interchanged with respect to both spatial and spin coordinates. First, however, exchange will be explained with the neglect of spin.

Exchange of spatial coordinates [edit]

Taking a hydrogen molecule-like system (i.e. one with two electrons), we may attempt to model the state of each electron by first assuming the electrons behave independently, and taking wave functions in position space of $\Phi_a(r_1)$ for the first electron and $\Phi_b(r_2)$ for the second electron. We assume that Φ_a and Φ_b are orthogonal, and that each corresponds to an energy eigenstate of its electron. Now, we may construct a wave function for the overall system in position space by using an antisymmetric combination of the product wave functions in position space:

$$\Psi_A(\vec{r}_1,\vec{r}_2) = \frac{1}{\sqrt{2}}[\Phi_a(\vec{r}_1)\Phi_b(\vec{r}_2) - \Phi_b(\vec{r}_1)\Phi_a(\vec{r}_2)] \qquad (1)$$

Alternatively, we may also construct the overall position–space wave function by using a symmetric combination of the product wave functions in position space:

$$\Psi_S(\vec{r}_1,\vec{r}_2) = \frac{1}{\sqrt{2}}[\Phi_a(\vec{r}_1)\Phi_b(\vec{r}_2) + \Phi_b(\vec{r}_1)\Phi_a(\vec{r}_2)] \qquad (2)$$

Treating the exchange interaction in the hydrogen molecule by the perturbation method, the overall Hamiltonian is:

$\mathcal{H} = \mathcal{H}^{(0)} + \mathcal{H}^{(1)}$

where $\mathcal{H}^{(0)} = -\frac{\hbar^2}{2m}(\nabla_1^2 + \nabla_2^2) - \frac{e^2}{r_1} - \frac{e^2}{r_2}$ and $\mathcal{H}^{(1)} = \left(\frac{e^2}{R_{ab}} + \frac{e^2}{r_{12}} - \frac{e^2}{r_{a1}} - \frac{e^2}{r_{b2}}\right)$

Two eigenvalues for the system energy are found:

$$E_{+/-} = E_{(0)} + \frac{C \pm J_{ex}}{1 \pm B^2} \qquad (3)$$

where the E_+ is the spatially symmetric solution and E_- is the spatially antisymmetric solution. A variational calculation yields similar results. $\mathcal{H}$ can be diagonalized by using the position–space functions given by Eqs. (1) and (2). In Eq. (3), C is the **Coulomb integral**, B is the **overlap integral**, and J_{ex} is the **exchange integral**. These integrals are given by:

$$C = \int \Phi_a(\vec{r}_1)^2 \left(\frac{1}{R_{ab}} + \frac{1}{r_{12}} - \frac{1}{r_{a1}} - \frac{1}{r_{b2}}\right) \Phi_b(\vec{r}_2)^2 \, d^3r_1 \, d^3r_2 \qquad (4)$$

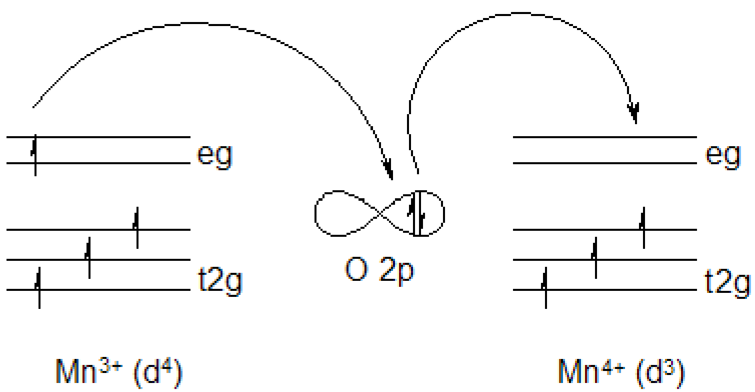
$$B = \int \Phi_b(\vec{r}_2)\Phi_a(\vec{r}_2) \, d^3r_2 \qquad (5)$$

$$J_{ex} = \int \Phi_a(\vec{r}_1)\Phi_b(\vec{r}_2) \left(\frac{1}{R_{ab}} + \frac{1}{r_{12}} - \frac{1}{r_{a1}} - \frac{1}{r_{b2}}\right) \Phi_b(\vec{r}_1)\Phi_a(\vec{r}_2) \, d^3r_1 \, d^3r_2 \qquad (6)$$

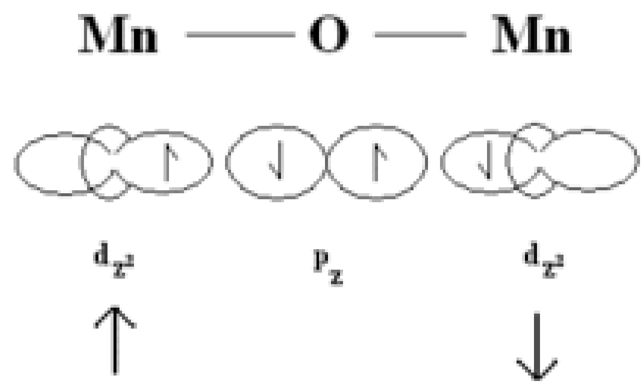
The terms in parentheses in Eqs. (4) and (6) correspond to: proton–proton repulsion (R_{ab}), electron–electron repulsion (r_{12}), and electron–proton attraction ($r_{a1/a2/b1/b2}$).All quantities are assumed to be real.

Although in the hydrogen molecule the exchange integral, Eq. (6), is negative, Heisenberg first suggested that it changes sign at some critical ratio of internuclear distance to

Double exchange interaction



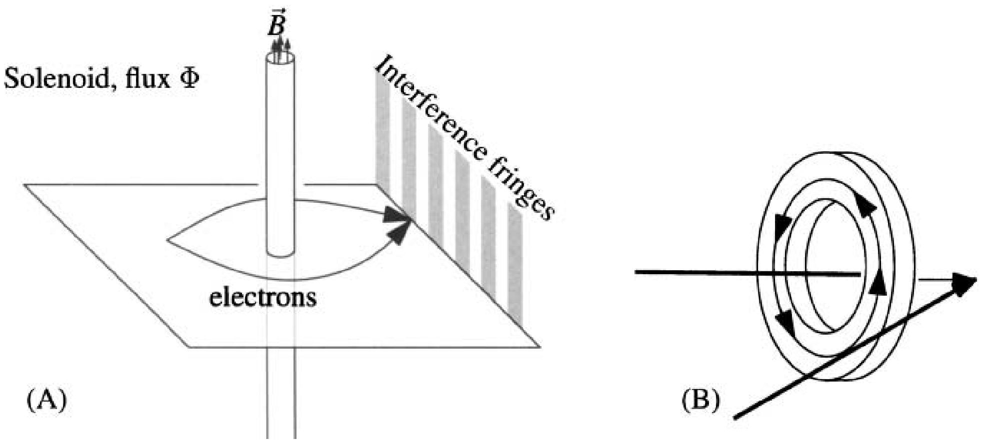
Super exchange interaction

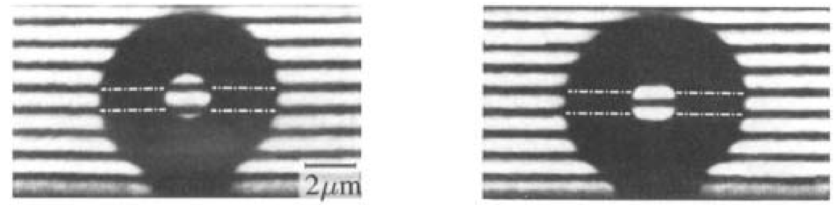


In superexchange, a ferromagnetic or antiferromagnetic alignment occurs between two atoms with the same valence (number of electrons) or differs by two, and the electrons are localized;
while in double-exchange, the interaction occurs only when one atom has an extra electron compared to the other, the electrons are itinerant (delocalized); this results in the material displaying magnetic exchange coupling, as well as metallic conductivity.

Berry Phase

Aharonov-Bohm Effect



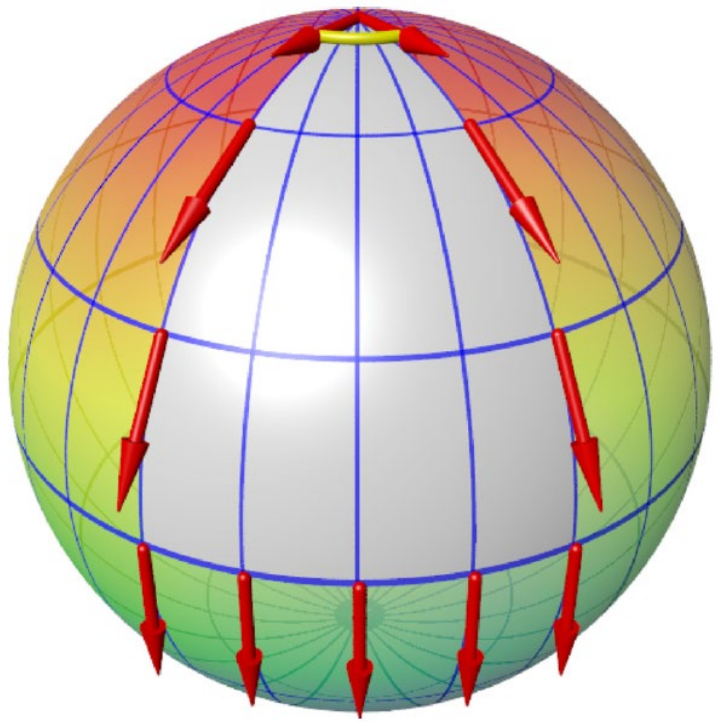


Electrons traveling around a flux tube suffer a phase change and can interfere with themselves even if they only travel through regions where B = 0.
(B) An open flux tube is not experimentally realizable, but a small toroidal magnet with no flux leakage can be constructed instead.

Electron hologram showing interference fringes of electrons passing through small toroidal magnet. The magnetic flux passing through the torus is quantized so as to produce an integer multiple of π phase change in the electron wave functions. The electron is completely screened from the magnetic induction in the magnet. In (A) the phase change is 0, while in (B) the phase change is π. [Source: Tonomura (1993), p. 67.]

$$\Phi = \int d^2r\, B_z = \oint d\vec{r} \cdot \vec{A}$$

$$A_\phi = \frac{\Phi}{2\pi r}$$



Parallel transport of a vector along a closed path on the sphere S_2 leads to a geometric phase between initial and final state.

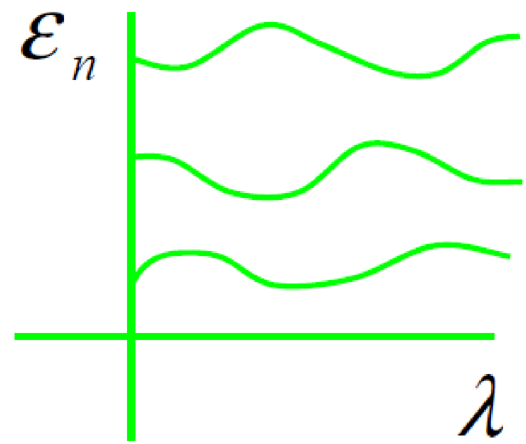
Real-space Berry phases: Skyrmion soccer (invited)
Karin Everschor-Sitte and Matthias Sitte
Journal of Applied Physics **115**, 172602 (2014); doi: 10.1063/1.4870695

Berry phase formalism for intrinsic Hall effects

Berry phase

From Prof. Guo Guang-Yu

[Berry, Proc. Roy. Soc. London A 392, 451 (1984)]

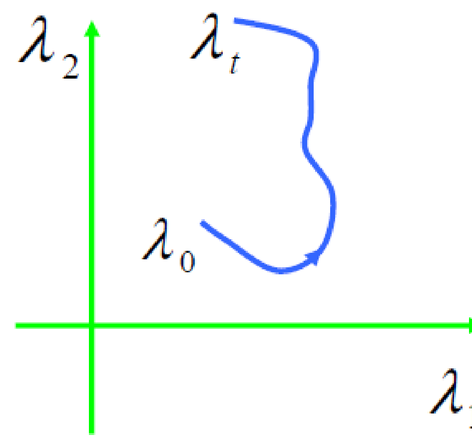


Parameter dependent system:

$$\{\, \varepsilon_n(\lambda),\ \psi_n(\lambda) \,\}$$

Adiabatic theorem:

$$\Psi(t) = \psi_n(\lambda(t))\ e^{-i\int_0^t dt\, \varepsilon_n/\hbar}\ e^{-i\gamma_n(t)}$$



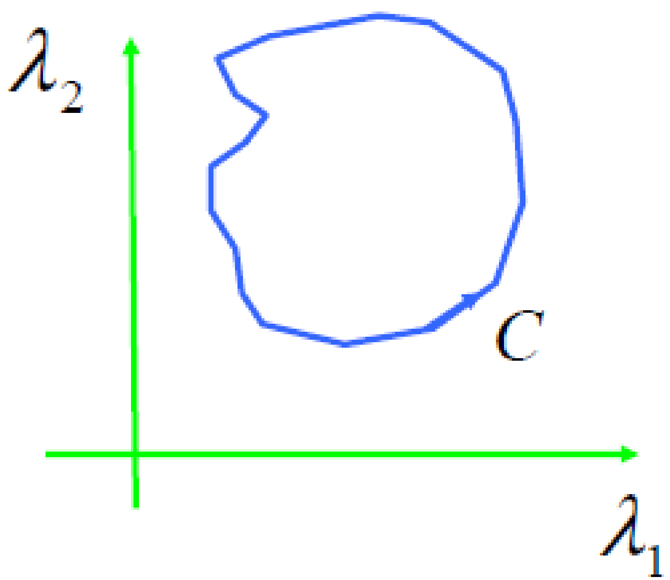
Geometric phase:

$$\gamma_n = \int_{\lambda_0}^{\lambda_t} d\lambda \,\langle \psi_n | \, i\frac{\partial}{\partial\lambda} | \psi_n \rangle$$

Well defined for a closed path

From Prof. Guo Guang-Yu

$$\gamma_n = \oint_C d\lambda \langle \psi_n | i \frac{\partial}{\partial \lambda} | \psi_n \rangle$$



Stokes theorem

$$\gamma_n = \iint d\lambda_1 d\lambda_2\, \Omega$$

Berry Curvature

$$\Omega = i \frac{\partial}{\partial \lambda_1} \langle \psi | \frac{\partial}{\partial \lambda_2} | \psi \rangle - i \frac{\partial}{\partial \lambda_2} \langle \psi | \frac{\partial}{\partial \lambda_1} | \psi \rangle$$

Analogies

From Prof. Guo Guang-Yu

Berry curvature	Magnetic field
$\Omega(\vec{\lambda})$	$B(\vec{r})$
Berry connection	Vector pot
$\langle\psi\vert i\dfrac{\partial}{\partial\lambda}\vert\psi\rangle$	$A(\vec{r})$
Geometric phase	Aharonov-Bohm phase
$\oint d\lambda\,\langle\psi\vert i\dfrac{\partial}{\partial\lambda}\vert\psi\rangle=\iint d^2\lambda\;\Omega(\vec{\lambda})$	$\oint dr\,A(\vec{r})=\iint d^2r\,B(\vec{r})$
Chern number	Dirac monopole
$\oiint d^2\lambda\;\Omega(\vec{\lambda})=\text{integer}$	$\oiint d^2r\;B(\vec{r})=\text{integer}\,h/e$

Semiclassical dynamics of Bloch electrons

From Prof. Guo Guang-Yu

Ol… …976]

$$\dot{\mathbf{x}}_c = \frac{1}{\hbar}\frac{\partial \varepsilon_n(\mathbf{k})}{\partial \mathbf{k}},$$

$$\dot{\mathbf{k}} = -\frac{e}{\hbar}\mathbf{E} - \frac{e}{\hbar}\dot{\mathbf{x}}_c \times \mathbf{B} = \frac{e}{\hbar}\frac{\partial \varphi(\mathbf{r})}{\partial \mathbf{r}} - \frac{e}{\hbar}\dot{\mathbf{x}}_c \times \mathbf{B}$$

New version [Marder, 2000]

Berry phase correction [Chang & Niu, PRL (1995), PRB (1996)]

$$\dot{\mathbf{x}}_c = \frac{1}{\hbar}\frac{\partial \varepsilon_n(\mathbf{k})}{\partial \mathbf{k}} - \dot{\mathbf{k}} \times \mathbf{\Omega}_n(\mathbf{k}),$$

$$\dot{\mathbf{k}} = \frac{e}{\hbar}\frac{\partial \varphi(\mathbf{r})}{\partial \mathbf{r}} - \frac{e}{\hbar}\dot{\mathbf{x}}_c \times \mathbf{B},$$

$$\mathbf{\Omega}_n(\mathbf{k}) = -\mathrm{Im}\left\langle \frac{\partial u_{n\mathbf{k}}}{\partial \mathbf{k}} \right| \times \left| \frac{\partial u_{n\mathbf{k}}}{\partial \mathbf{k}} \right\rangle$$

(Berry curvature)

Demagnetization factor D

can be solved analytically in some cases, numerically in others

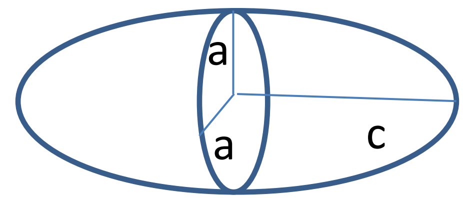
For an ellipsoid $D_x + D_y + D_z = 1$ (SI units) $D_x + D_y + D_z = 4\pi$ (cgs units)

Solution for Spheroid $a = b \neq c$

1. Prolate spheroid (football shape) $c/a = r > 1$; $a = b$, In cgs units

$$D_c = \frac{4\pi}{r^2-1}\left[\frac{r}{\sqrt{r^2-1}}\ln\left(r+\sqrt{r^2-1}\right)-1\right]$$

$$D_a = D_b = \frac{4\pi - D_c}{2}$$

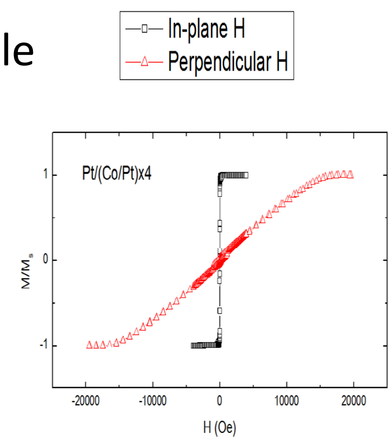


Limiting case r >> 1 (long rod)

$$D_c = \frac{4\pi}{r^2}\left[\ln(2r)-1\right] \ll 1$$

$$D_a = D_b = 2\pi$$

Note: you measure $2\pi M$ *without* knowing the sample

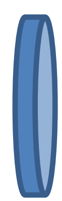


2. Oblate Spheroid (pancake shape) $c/a = r < 1$; $a = b$

$$D_c = \frac{4\pi}{1-r^2}\left[1-\frac{r}{\sqrt{1-r^2}}\cos^{-1} r\right]$$

$$D_a = D_b = \frac{4\pi - D_c}{2}$$

Limiting case r >> 1 (flat disk)



$$D_c = 4\pi$$

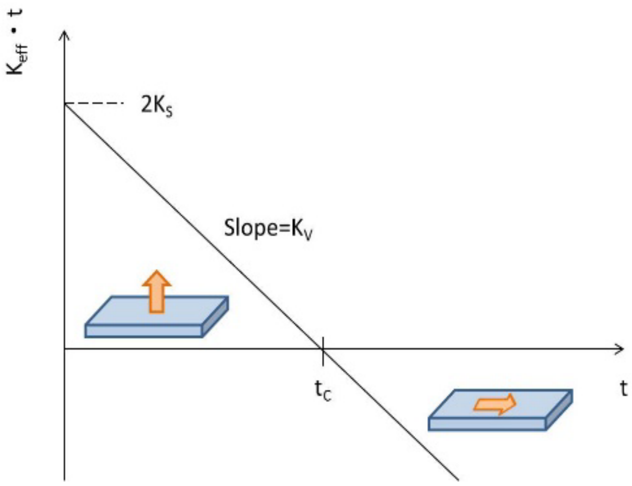
$$D_a = D_b = \pi^2 r \ll 1$$

Note: you measure $4\pi M$ *without* knowing the sample

Surface anisotropy

$$E = E_{exchange} + E_{Zeeman} + E_{mag} + E_{anisotropy} + \cdots$$

- $E_{ex}: \sum 2J\overrightarrow{S_i} \cdot \overrightarrow{S_j}$
- $E_{Zeeman}: \vec{M} \cdot \vec{H}$
- $E_{mag}: \frac{1}{8\pi}\int B^2 dV$
- $E_{anisotropy}$



For hcp Co$= K_1' \sin^2\theta + K_2{}' \sin^4\theta$

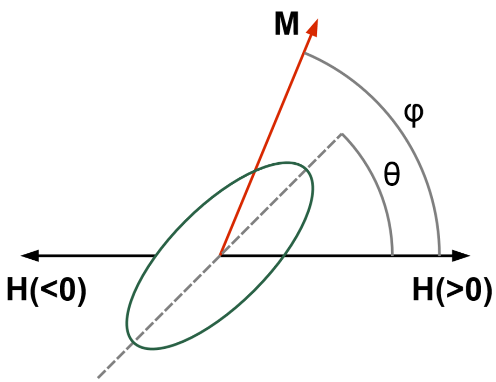
For bcc Fe $= K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2)$

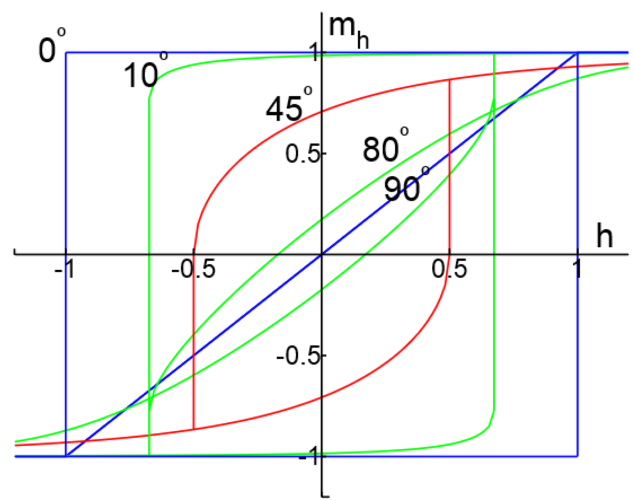
α_i : directional cosines

Surface anisotropy $K_{\text{eff}} = \frac{2K_S}{t} + K_V$ ➔ $K_{\text{eff}} \cdot t = 2K_S + K_V \cdot t$

Stoner–Wohlfarth model

A widely used model for the magnetization of single-domain ferromagnets. It is a simple example of magnetic hysteresis and is useful for modeling small magnetic particles





$$E = K_u V \sin^2(\phi - \theta) - \mu_0 M_s V H \cos\phi,$$

where K_u is the uniaxial anisotropy parameter, V is the volume of the magnet, M_s is the saturation magnetization.

Ferromagnetic domains

- competition between exchange, anisotropy, and magnetic energies.
- Bloch wall: rotation out of the plane of the two spins
- Neel wall: rotation within the plane of the two spins

For a 180° Bloch wall rotated in N+1 atomic planes $N\Delta E_{ex} = N(JS^2\left(\frac{\pi}{N}\right)^2)$

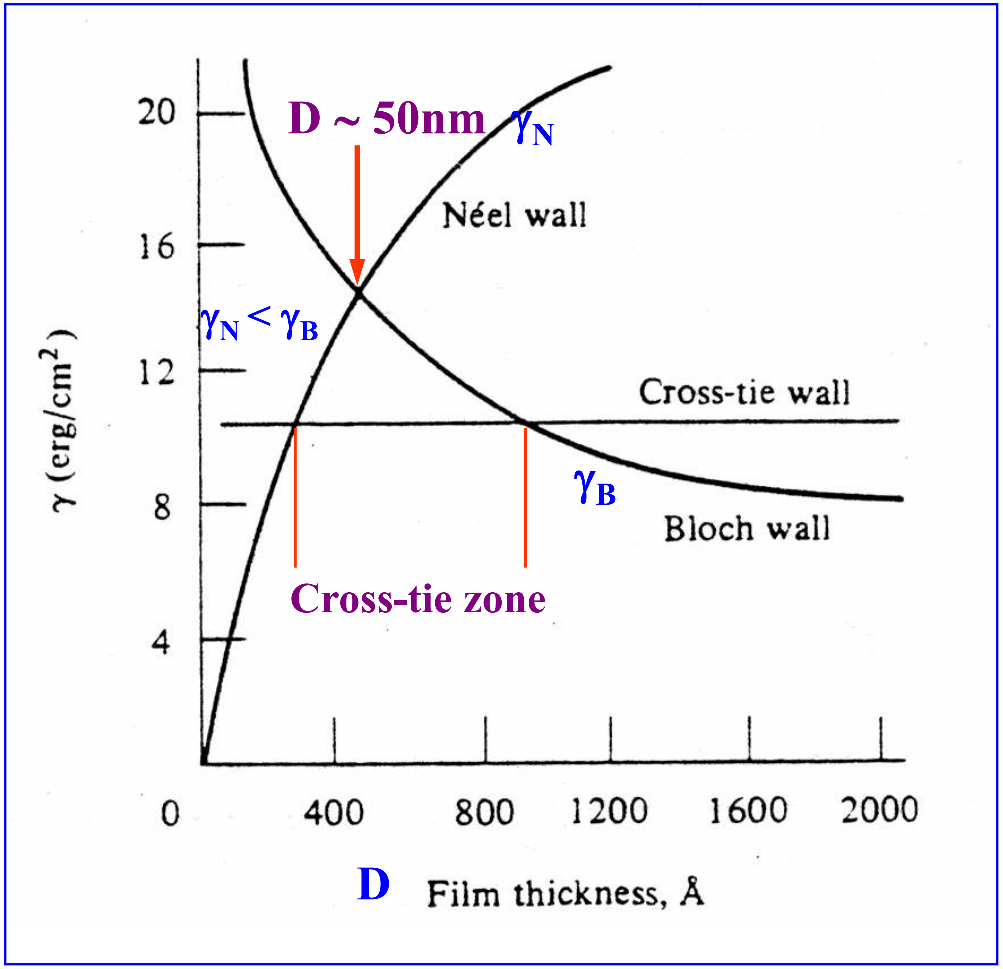
Wall energy density $\sigma_w = \sigma_{ex} + \sigma_{anis} \approx JS^2\pi^2/(Na^2) + KNa$ a : lattice constant

$\partial\sigma_w/\partial N \equiv 0,$ $N = \sqrt{[JS^2\pi^2/(Ka^3)]} \approx 300$ in Fe

$\sigma_w = 2\pi\sqrt{KJS^2/a} \approx$ 1 erg/cm^2 in Fe

Wall width $Na = \pi\sqrt{JS^2/Ka} \equiv \pi\sqrt{\frac{A}{K}}$, $A = JS^2/a$ Exchange stiffness constant

Domain wall energy γ versus thickness D of $Ni_{80}Fe_{20}$ thin films



$\gamma_N < \gamma_B \sim 50nm$

Thick films have Bloch walls
Thin films have Neel walls

Cross-tie walls show up in between.

A=10^{-6} erg/cm

K=1500 erg/cm^3

Further reference: Antonio DeSimone, Hans Knupfer, and Felix Otto, Calculus of Variations 27, 233–253 (2006) 2-d stability of the Neel wall

Magnetic Resonance

- Nuclear Magnetic Resonance (NMR)
  - Line width
  - Hyperfine Splitting, Knight Shift
  - Nuclear Quadrupole Resonance (NQR)
- Ferromagnetic Resonance (FMR)
  - Shape Effect
  - Spin Wave resonance (SWR)
- Antiferromagnetic Resonance (AFMR)
- Electron Paramagnetic Resonance (EPR or ESR)
  - Exchange narrowing
  - Zero-field Splitting
- Maser

What we can learn:

- From absorption fine structure ➔ electronic structure of single defects
- From changes in linewidth ➔ relative motion of the spin to the surroundings
- From resonance frequency ➔ internal magnetic field
- Collective spin excitations

FMR

Equation of motion of a magnetic moment $\boldsymbol{\mu}$ in an external field B_0

$$\frac{\hbar d\boldsymbol{I}}{dt} = \boldsymbol{\mu} \times \boldsymbol{B} \qquad \boldsymbol{\mu} = \gamma\hbar\boldsymbol{I} \qquad \frac{d\boldsymbol{\mu}}{dt} = \gamma\boldsymbol{\mu} \times \boldsymbol{B} \qquad \frac{d\boldsymbol{M}}{dt} = \gamma\boldsymbol{M} \times \boldsymbol{B}$$

Shape effect:

internal magnetic field

Landau-Lifshitz-Gilbert (LLG) equation

$$\boxed{\frac{d\boldsymbol{M}}{dt} = -\gamma\boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}} + \alpha\boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}}$$

$$B_x^i = B_x^0 - N_x M_x \qquad B_y^i = B_y^0 - N_y M_y \qquad B_z^i = B_z^0 - N_z M_z$$

$$\frac{dM_x}{dt} = \gamma\left(M_y B_z^i - M_z B_y^i\right) = \gamma[B_0 + \left(N_y - N_z\right)M]M_y$$

$$\frac{dM_y}{dt} = \gamma[M(-N_x M_x) - M_x(B_0 - N_z M)] = -\gamma[B_0 + (N_x - N_z)M]M_x$$

To first order $\frac{dM_z}{dt} = 0 \qquad M_z = M$

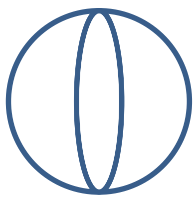
$$\begin{vmatrix} i\omega & \gamma[B_0 + \left(N_y - N_z\right)M] \\ -\gamma[B_0 + (N_x - N_z)M] & i\omega \end{vmatrix} = 0$$

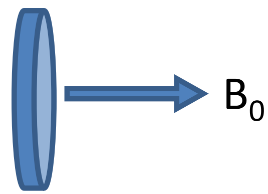
$$\omega_0^2 = \gamma^2[B_0 + \left(N_y - N_z\right)M][B_0 + (N_x - N_z)M]$$

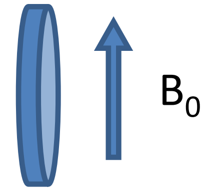
Uniform mode

Uniform mode

Sphere | flat plate with perpendicular field | flat plate with in-plane field







$N_x = N_y = N_z$ $\qquad$ $N_x = N_y = 0 \quad N_z = 4\pi$ $\qquad$ $N_x = N_z = 0 \quad N_y = 4\pi$

$\omega_0 = \gamma\, B_0$ $\qquad$ $\omega_0 = \gamma\,(B_0 - 4\pi M)$ $\qquad$ $\omega_0 = \gamma\,[B_0(B_0 + 4\pi M)]^{1/2}$

Spin wave resonance; Magnons

Consider a one-dimensional spin chain with only nearest-neighbor interactions.

$U = -2J \sum \vec{S_i} \cdot \vec{S_j}$ We can derive $\hbar\omega = 4JS(1 - \cos ka)$

When $ka << 1$ $\qquad \hbar\omega \cong (2JSa^2)k^2$

flat plate with perpendicular field $\qquad \omega_0 = \gamma\,(B_0 - 4\pi M) + Dk^2$

Quantization of (uniform mode) spin waves, then consider the thermal excitation of Mannons, leads to Bloch $T^{3/2}$ law. $\qquad \Delta M / M(0) \propto T^{3/2}$

AFMR

Spin wave resonance; Antiferromagnetic Magnons

Consider a one-dimensional antiferromangetic spin chain with only nearest-neighbor interactions. Treat sublattice A with up spin S and sublattice B with down spin –S, J<0.

$U = -2J\sum \vec{S_i}\cdot\vec{S_j}$ We can derive $\hbar\omega = -4JS|\sin ka|$

When *ka* << 1 $\hbar\omega \cong (-4JS)|ka|$

AFMR

exchange plus anisotropy fields on the two sublattices

$\boldsymbol{B}_1 = -\lambda\boldsymbol{M}_2 + B_A\hat{\boldsymbol{z}}$ on $\mathbf{M}_1$ $\boldsymbol{B}_2 = -\lambda\boldsymbol{M}_1 - B_A\hat{\boldsymbol{z}}$ on $\mathbf{M}_2$

$M_1^z \equiv M$ $M_2^z \equiv -M$ $M_1^+ \equiv M_1^x + iM_1^y$ $M_2^+ \equiv M_2^x + iM_2^y$ $B_E \equiv \lambda M$

$$\frac{dM_1^+}{dt} = -i\gamma[M_1^+(B_A+B_E) + M_2^+B_E]$$

$$\frac{dM_2^+}{dt} = -i\gamma[M_2^+(B_A+B_E) + M_1^+B_E]$$

$$\begin{vmatrix}\gamma(B_A+B_E)-\omega & \gamma B_E \\ B_E & \gamma(B_A+B_E)+\omega\end{vmatrix} = 0$$

$\omega_0^2 = \gamma^2 B_A(B_A+2B_E)$ Uniform mode

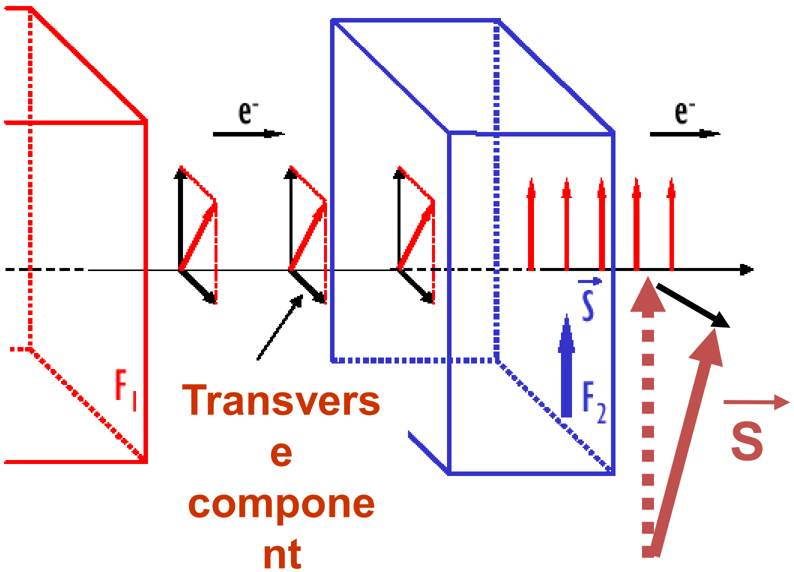
Spintronics

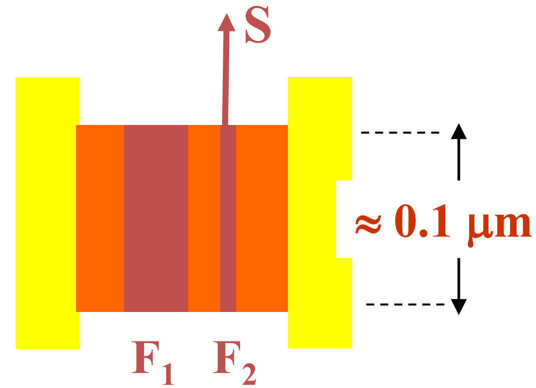
Electronics with electron spin as an extra degree of freedom
Generate, inject, process, and detect spin currents

- Generation: ferromagnetic materials, spin Hall effect, spin pumping effect etc.
- Injection: interfaces, heterogeneous structures, tunnel junctions
- Process: spin transfer torque
- Detection: Giant Magnetoresistance, Tunneling MR
- Historically, from magnetic coupling to transport phenomena

important materials: CoFe, CoFeB, Cu, Ru, IrMn, PtMn, MgO, Al2O3, Pt, Ta

Spin Transfer Torque





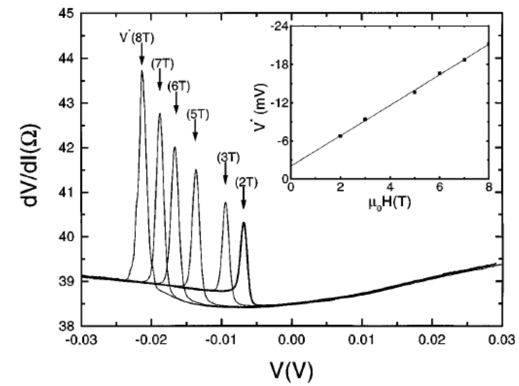


FIG. 1. The point contact $dV/dI(V)$ spectra for a series of magnetic fields (2, 3, 5, 6, 7, and 8 T) revealing an upward step and a corresponding peak in dV/dI at a certain negative bias voltage $V^*(H)$. The inset shows that $V^*(H)$ increases linearly with the applied magnetic field H.

Tsoi et al. PRL **61**, 2472 (1998)

The transverse spin component is lost by the conduction electrons, transferred to the global spin of the $\vec{S}$

$$\dot{\boldsymbol{S}}_{1,2} = (I_e g/e)\hat{\boldsymbol{s}}_{1,2} \times (\hat{\boldsymbol{s}}_1 \times \hat{\boldsymbol{s}}_2)$$

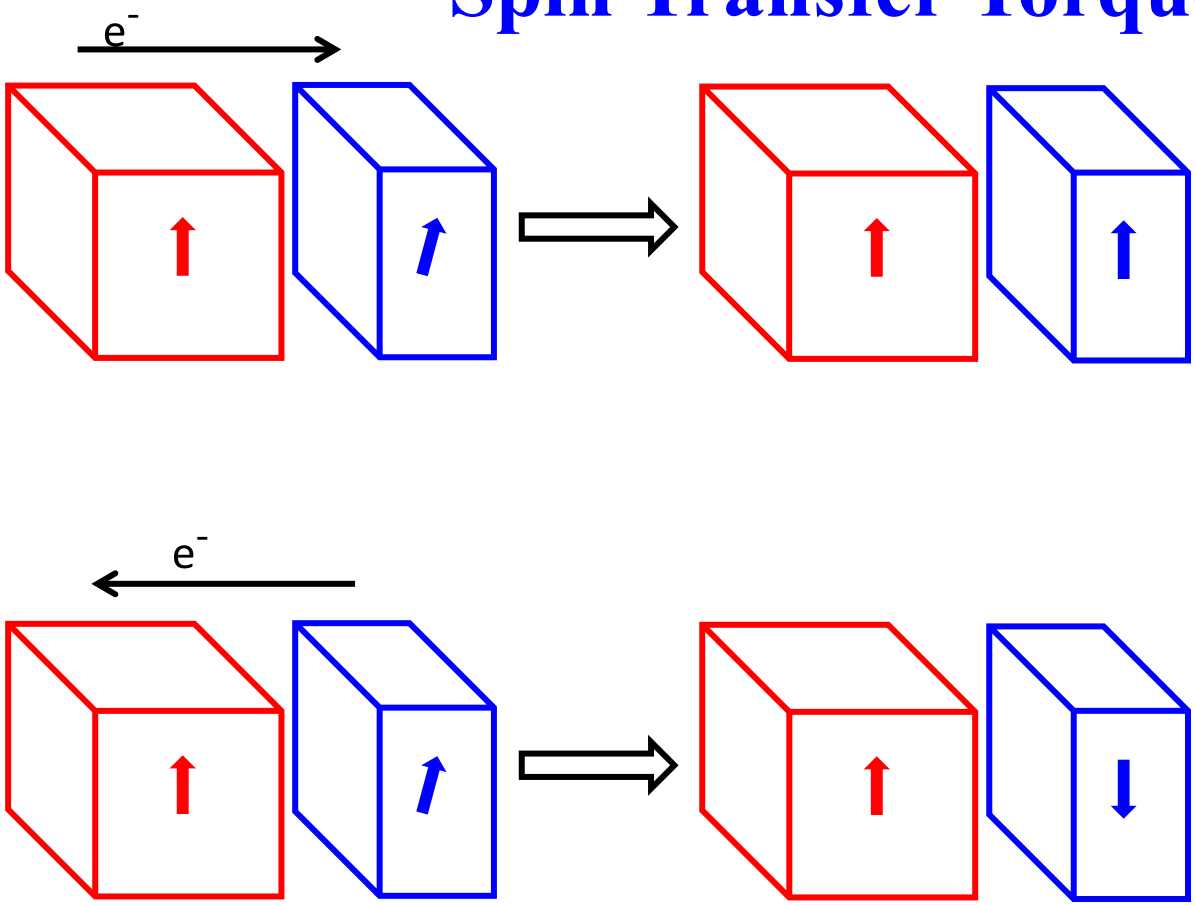
Slonczewski JMMM **159**, L1 (1996)

Modified Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{dm}{dt} = -\gamma m \times H_{eff} + \alpha m \times \frac{dm}{dt} + \frac{\gamma \hbar P I}{2e\mu_0 M_S V}(m \times \sigma \times m)$$

Experimantally determined current density ~10^{10}-10^{12}A/m^2

Spin Transfer Torque



when there is a saturation field, magnetization precession radiates microwave.

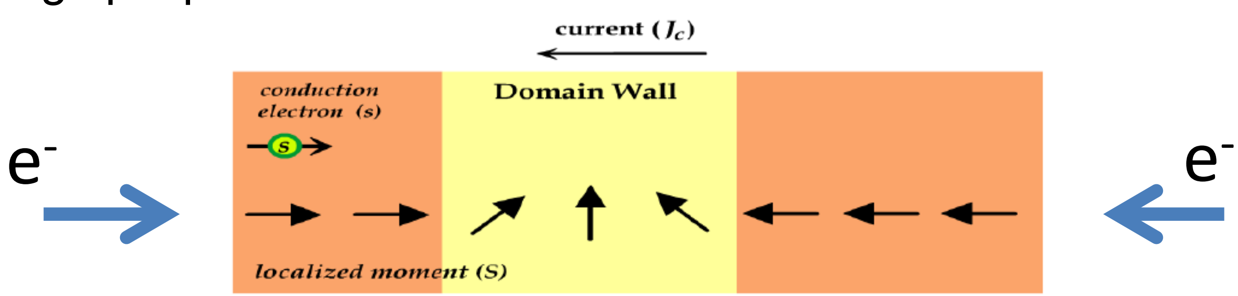
In a trilayer, current direction determines the relative orientation of F_1 and F_2 when $H = 0$

Spin Transfer Torque

Landau-Lifshitz-Gilbert equation with Spin Transfer Torque terms

Current induced domain wall motion

Passing spin polarized current from Domain A to Domain B⇒B switches



Domain A **Domain B**

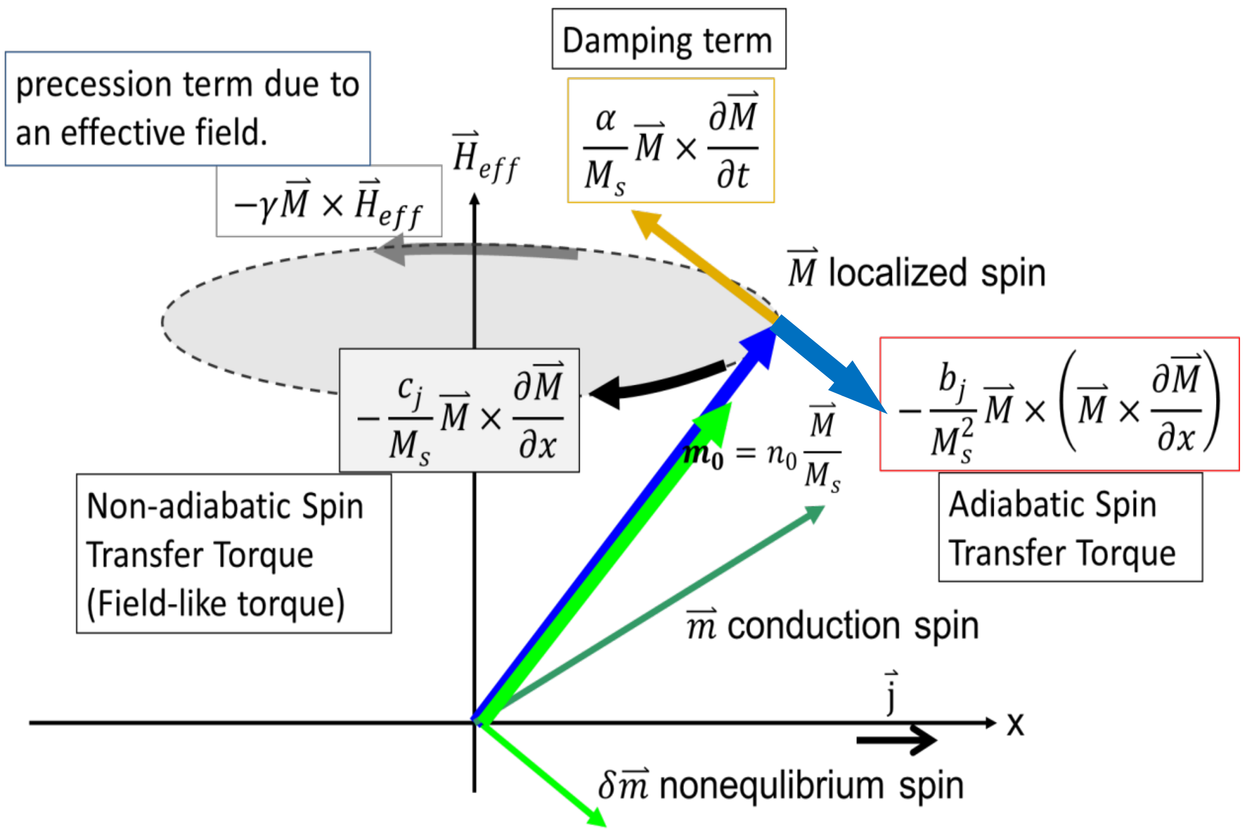
$$\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{M} \times \vec{H}_{eff} + \frac{\alpha}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial t} + \vec{\mathrm{T}}_{STT}$$

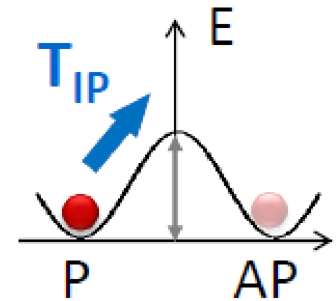
Berger, *JAP* **55**, 1954 (1984)
Tatara *et. al.*, *PRL* **92**, 086601 (2004)
Zhang *et. al.*, *PRL* **93**, 127204 (2004)
Thiaville *et. al.*, *Europhys. Lett*. **69**, 990 (2005)
Stiles *et. al.*, *PRB* **75**, 214423 (2007)

Spin Transfer Torque

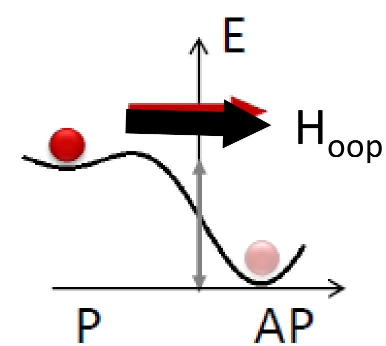
Landau-Lifshitz-Gilbert equation with Spin Transfer Torque terms

$$\frac{\partial \vec{M}}{\partial t} = \boxed{-\gamma \vec{M} \times \vec{H}_{\mathrm{eff}}} + \boxed{\frac{\alpha}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial t}} \boxed{- \frac{b_j}{M_s^2} \vec{M} \times \left(\vec{M} \times \frac{\partial \vec{M}}{\partial x}\right)} \boxed{- \frac{c_j}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial x}} \qquad b_j, c_j \sim JP/t$$





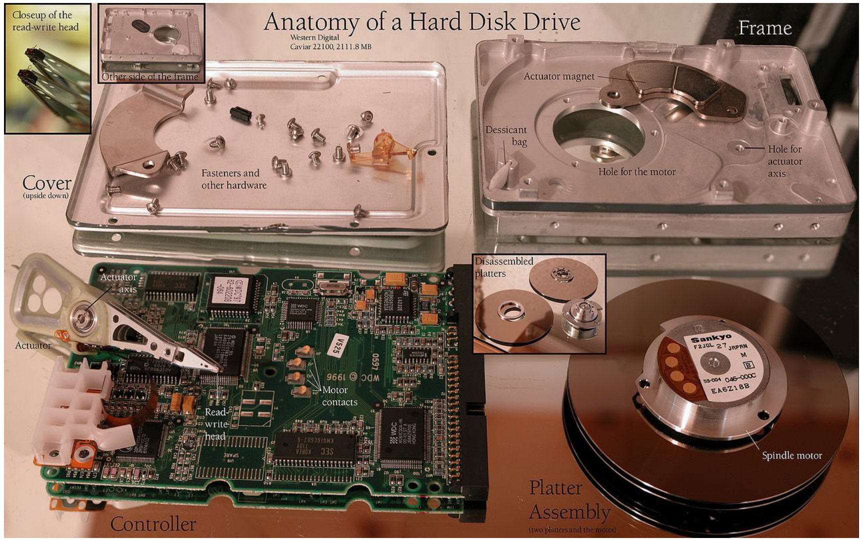
In-plane torque
Anti-damping
Destabilizes M



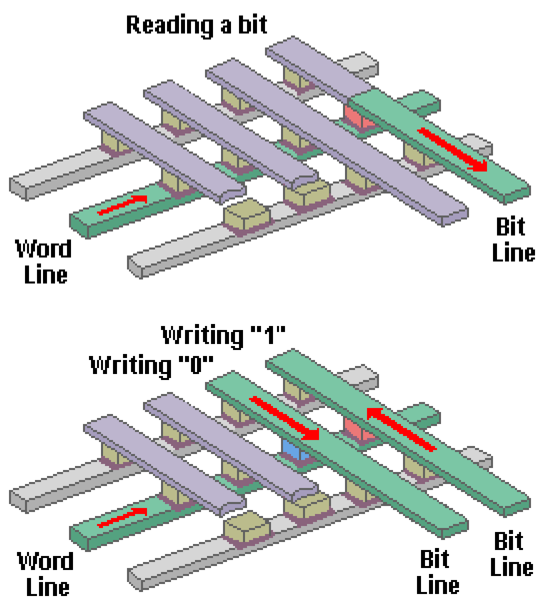
Out-of-plane torque
Field-like torque
Modifies energy barrier

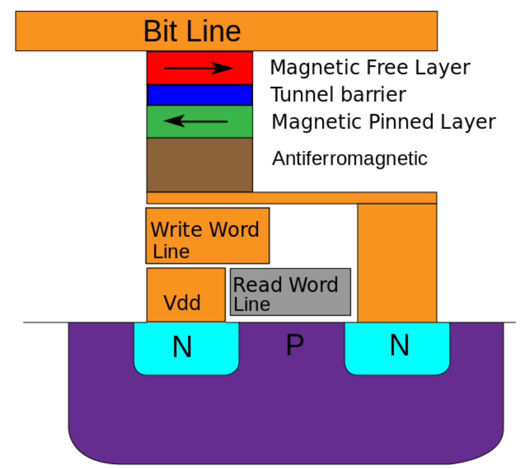
Industrial applications

Read head in hard drives

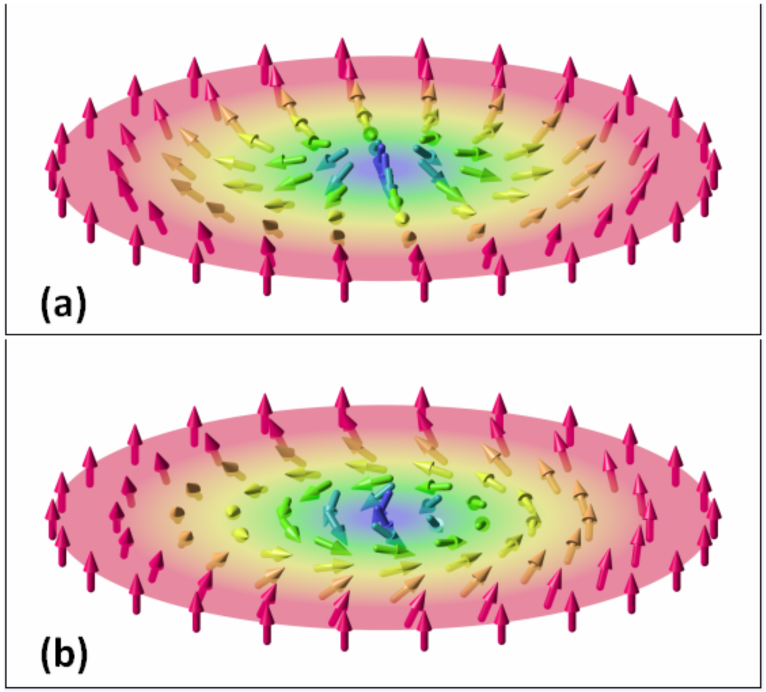


MRAM





Magnetic skyrmions



- Neel
- Bloch

- How to generate
- To detect
- To manipulate

- Magnetic field
- Electric current
- Spin current, spin wave