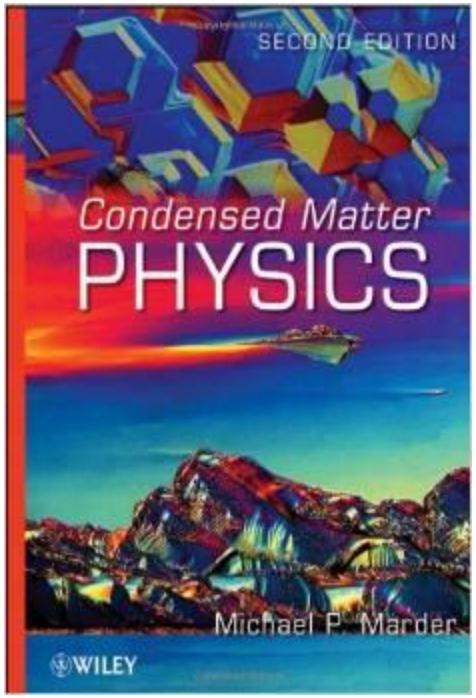
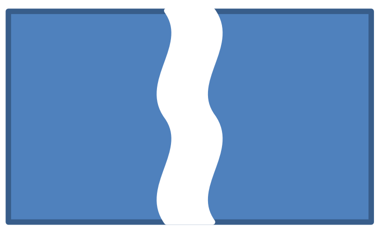
Magnetism to Spintronics

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

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



為什麼(大部分)磁鐵打破後會相斥?



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

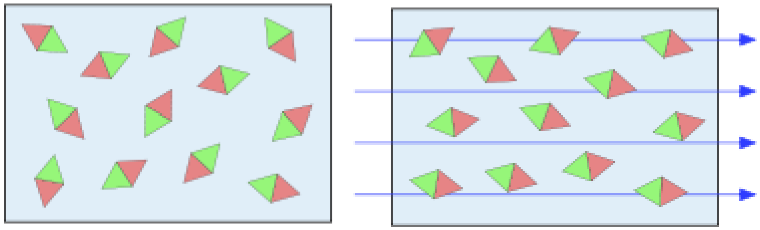
Magnetism

- 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)

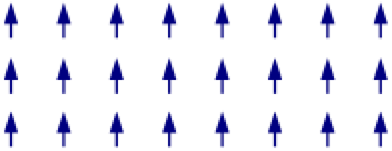
物質的磁性分類

巨觀：　順磁性
Paramagnetism

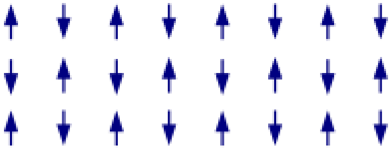


逆磁性
diamagnetism

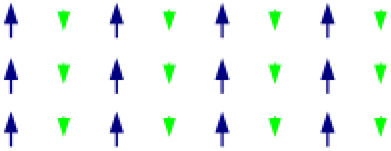
微觀：　鐵磁性
Ferromagnetism

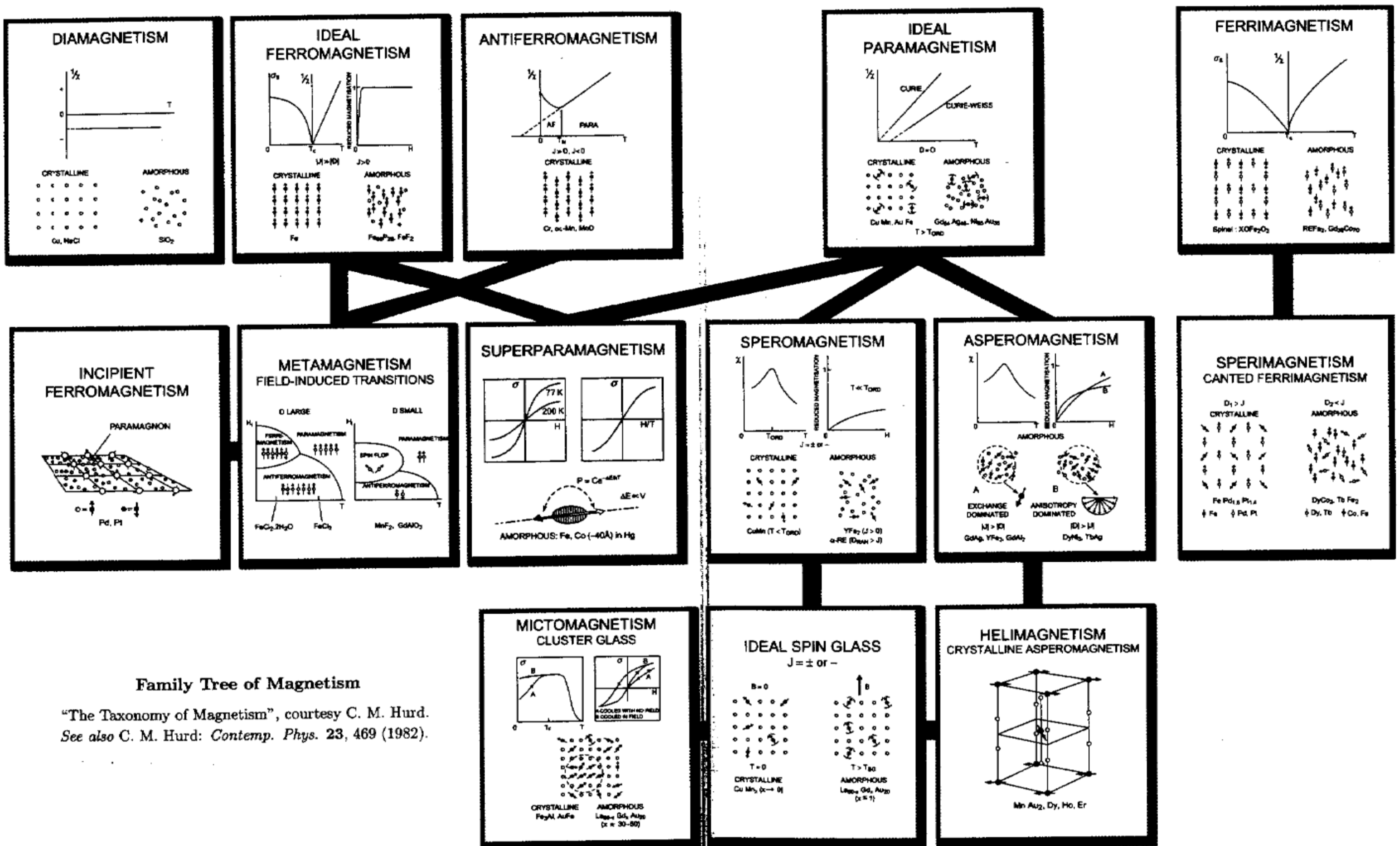


反鐵磁性
Antiferromagnetism



亞鐵磁性
Ferrimagnetism





Family Tree of Magnetism

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

- 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
  - Jahn-Teller effect
  - Paramagnetic susceptibility of conduction electrons

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

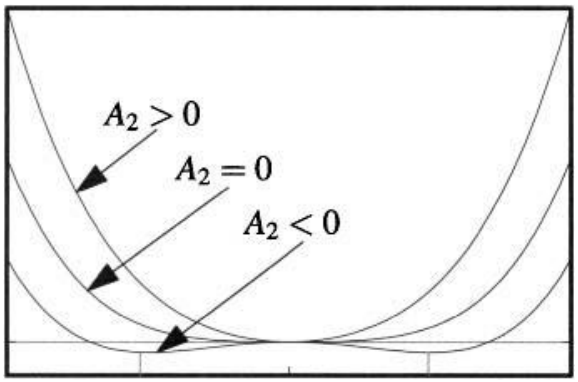
    two-electron system spin-independent Schrodinger equation
  - Type of exchange: direct exchange, super exchange, indirect exchange, itinerant exchange
  - Spin Hamiltonian and Heisenberg model
  - Molecular-field (mean-field) approximation

Critical phenomena

Universality. Divergences near the critical point are identical in a variety of apparently different physical systems and also in a collection of simple models.
Scaling. The key to understanding the critical point lies in understanding the relationship between systems of different sizes. Formal development of this idea led to the *renormalization group* of Wilson (1975).

Landau Free Energy

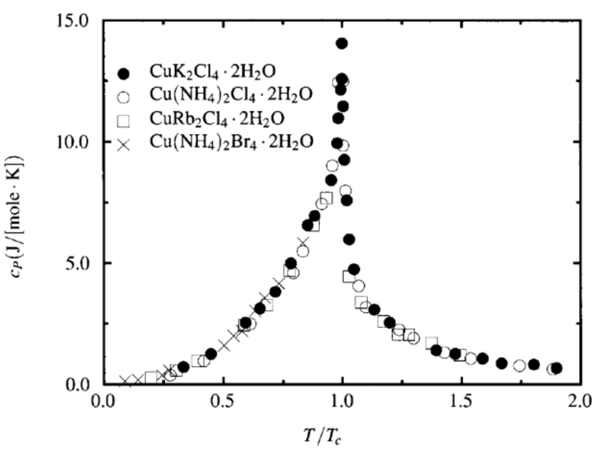
$\mathcal{F}$



$$\mathcal{F}(M, T) = A_0(T) + A_2(T)M^2 + A_4(T)M^4 + HM.$$

$$t \equiv \frac{T - T_C}{T_C}$$

$$\mathcal{F} = a_2 t M^2 + a_4 M^4 + HM.$$



Molar heat capacities of four ferromagnetic copper salts versus scaled temperature T/T_c. [Source Jongh and Miedema (1974).]

Correspondence between Liquids and Magnets

- ***Specific Heat***— α
- ***Magnetization and Density***— β
- ***Compressibility and** Susceptibility*— γ
- ***Critical Isotherm***— δ
- ***Correlation Length*** — ν
- ***Power-Law Decay at Critical Point***— η

Summary of critical exponents, showing correspondence between fluid-gas systems, magnetic systems, and the three-dimensional Ising model.

Exponent	Fluid	Magnet	Mean Field Theory	Experiment	3d Ising
α	$C_V \sim \|t\|^{-\alpha}$	$C_V \sim \|t\|^{-\alpha}$	discontinuity	0.11–0.12	0.110
β	$\Delta n \sim \|t\|^{\beta}$	$M \sim \|t\|^{\beta}$	$\frac{1}{2}$	0.35–0.37	0.325
γ	$K_T \sim \|t\|^{-\gamma}$	$\chi \sim \|t\|^{-\gamma}$	1	1.21–1.35	1.241
δ	$P \sim \|\Delta n\|^{\delta}$	$\|H\| \sim \|M\|^{\delta}$	3	4.0–4.6	4.82
ν	$\xi \sim \|t\|^{-\nu}$	$\xi \sim \|t\|^{-\nu}$		0.61–0.64	0.63
η	$g(r) \sim r^{-1-\eta}$	$g(r) \sim r^{-1-\eta}$		0.02–0.06	0.032

Source: Vicentini-Missoni (1972) p. 67, Cummins (1971), p. 417, and Goldenfeld (1992) p. 384.

Relations Among Exponents

$$\alpha + 2\beta + \gamma = 2 \qquad (2-\eta)\nu = \gamma$$

$$\delta = 1 + \frac{\gamma}{\beta} \qquad 2 - \alpha = 3\nu$$

- # 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.

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

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

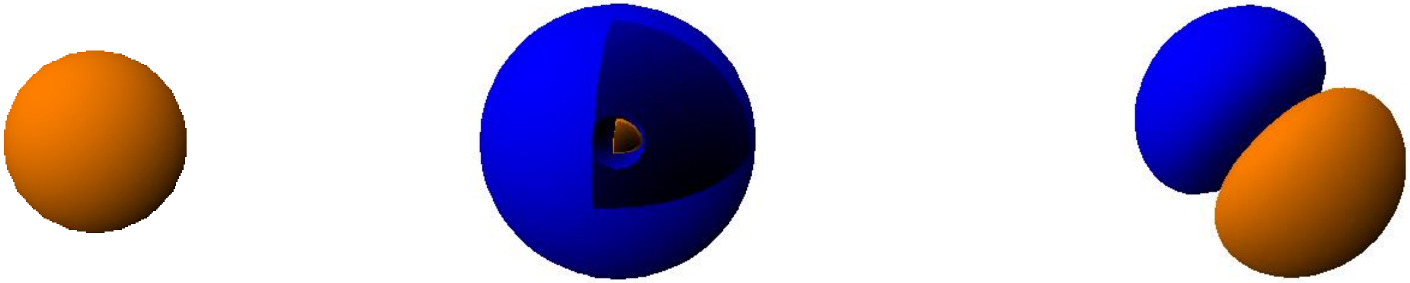
$$\left.\frac{\partial\mathcal{E}}{\partial\Delta}\right|_{\mathcal{E}_F} = \Delta D(\mathcal{E}_F) - \frac{J}{4n}D(\mathcal{E}_F)^2\Delta$$

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

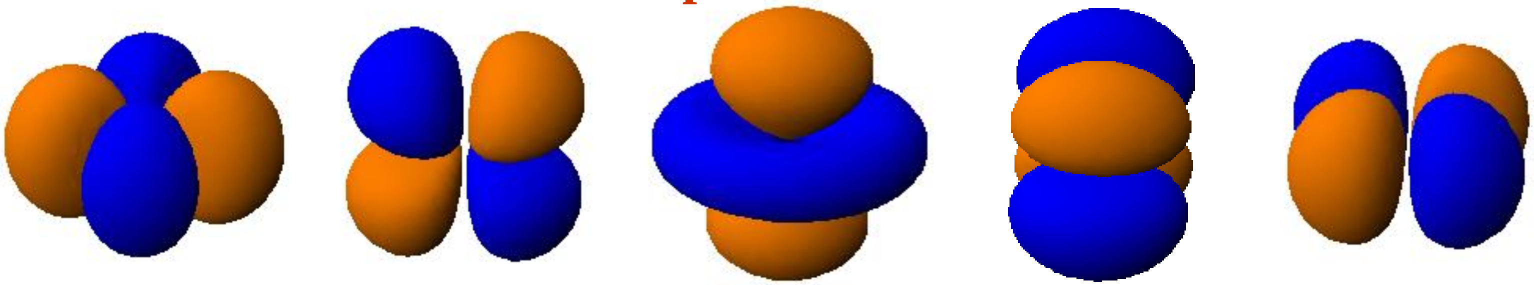
3d transition metals:

Mn atom has 5 d ↑ electrons   Bulk Mn is NOT magnetic

s, p electron orbital



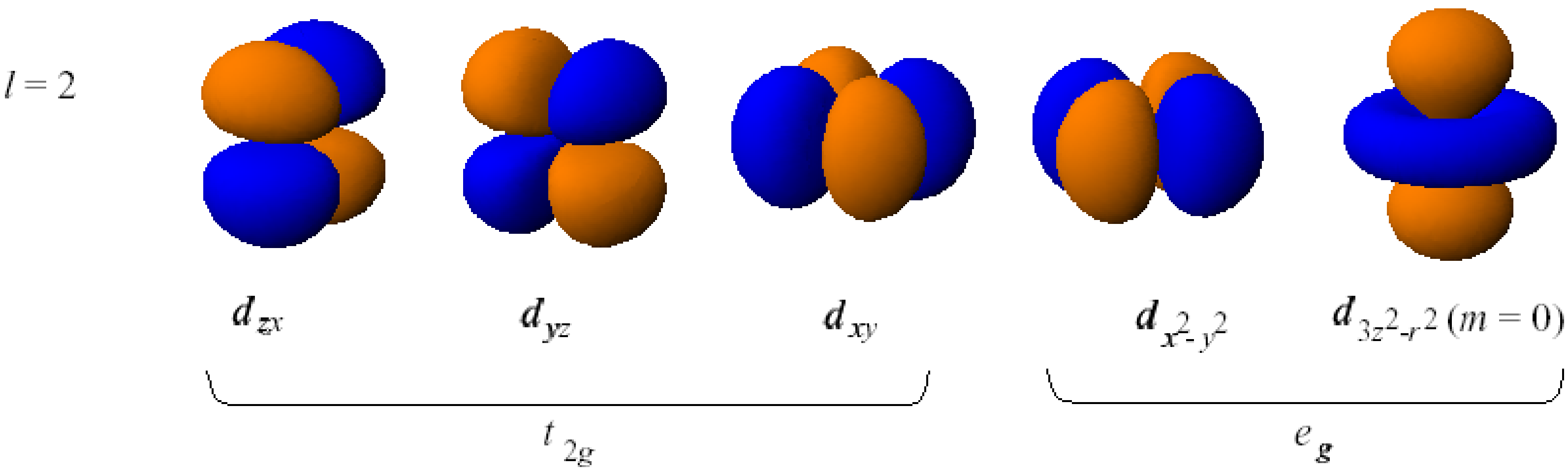
3d electron distribution in real space



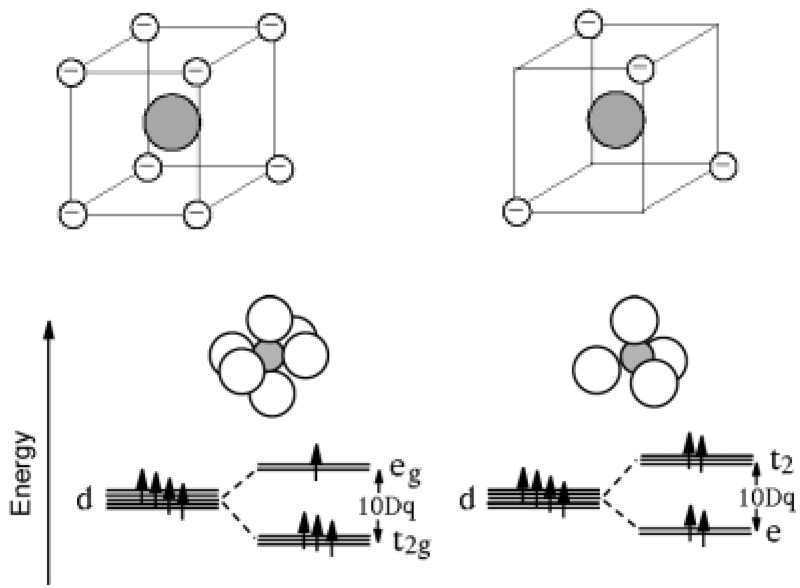
Co atom has 5 d ↑electrons and 2 d ↓ electrons
Bulk Co is magnetic.

Orbital viewer

d orbitals

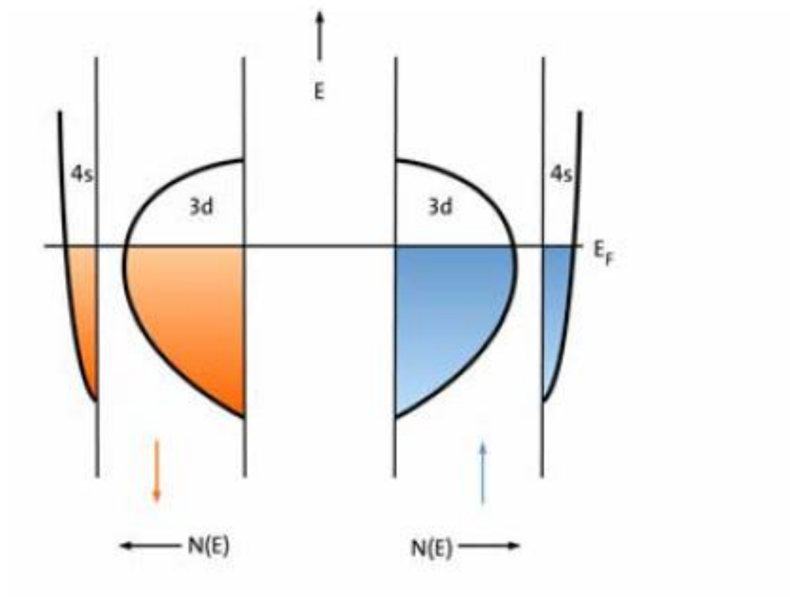


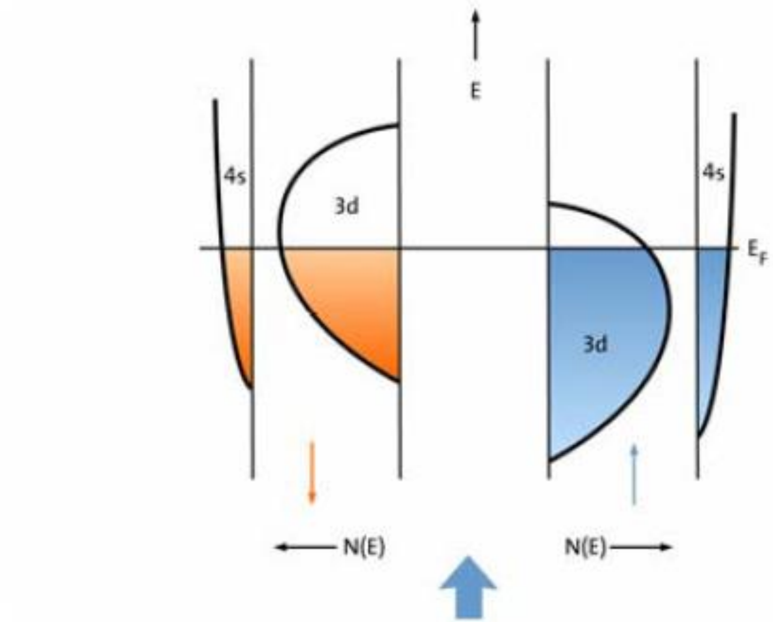
Crystal-field splitting



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.





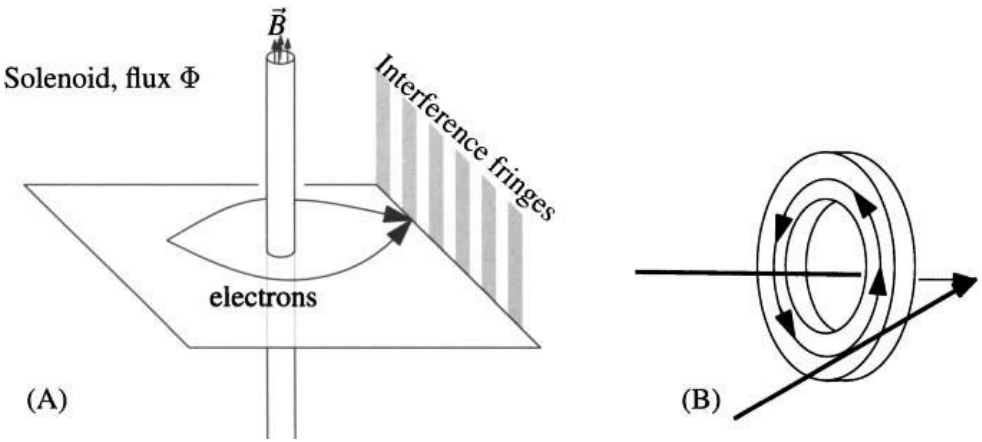
For the non-magnetic state there are identical density of states for the two spins.

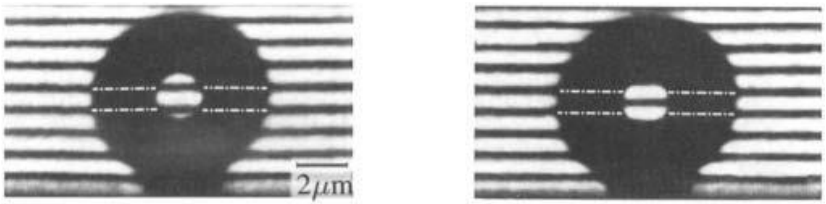
For a ferromagnetic state, $N\uparrow > N\downarrow$. The polarization is indicated by the thick blue arrow.

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

Berry Phase

Aharonov-Bohm Effect



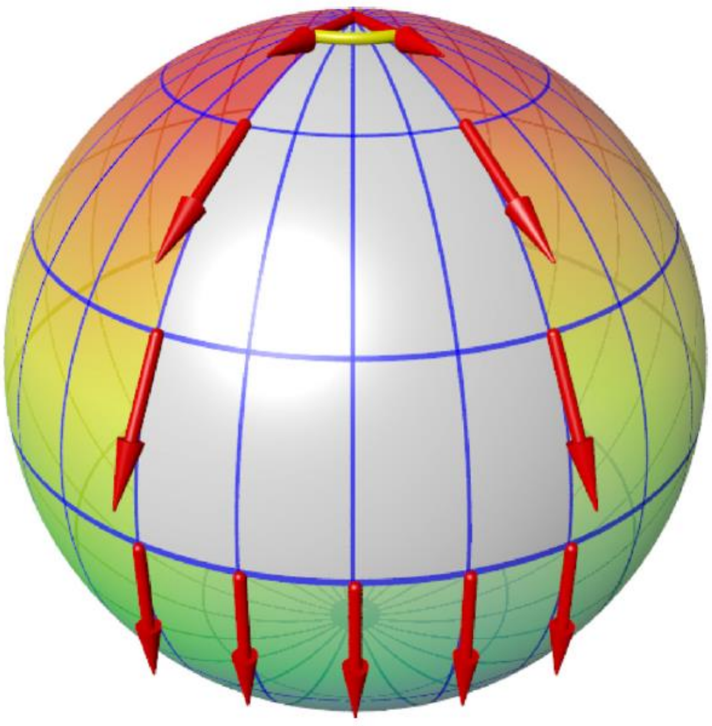


Electrons traveling around a flux tube suffer a phase change and can interfere with themselves even if they only travel through regions where B = 0.
(B) An open flux tube is not experimentally realizable, but a small toroidal magnet with no flux leakage can be constructed instead.

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.

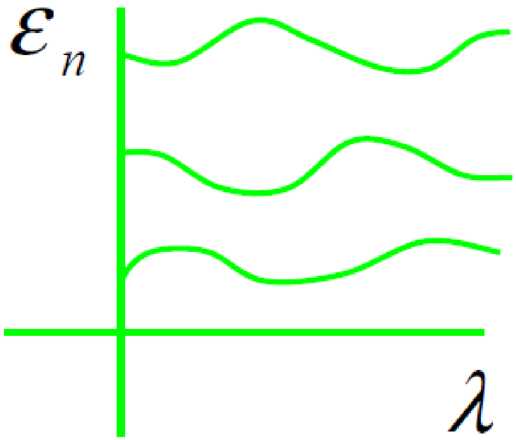
Real-space Berry phases: Skyrmion soccer (invited)
Karin Everschor-Sitte and Matthias Sitte
Journal of Applied Physics **115**, 172602 (2014); doi: 10.1063/1.4870695

Berry phase formalism for intrinsic Hall effects

From Prof. Guo Guang-Yu

Berry phase

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

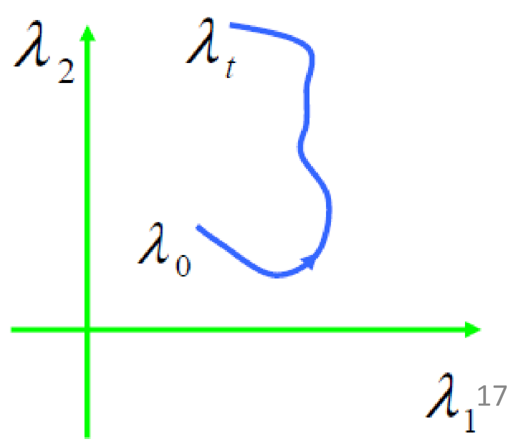


Parameter dependent system:

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

Adiabatic theorem:

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



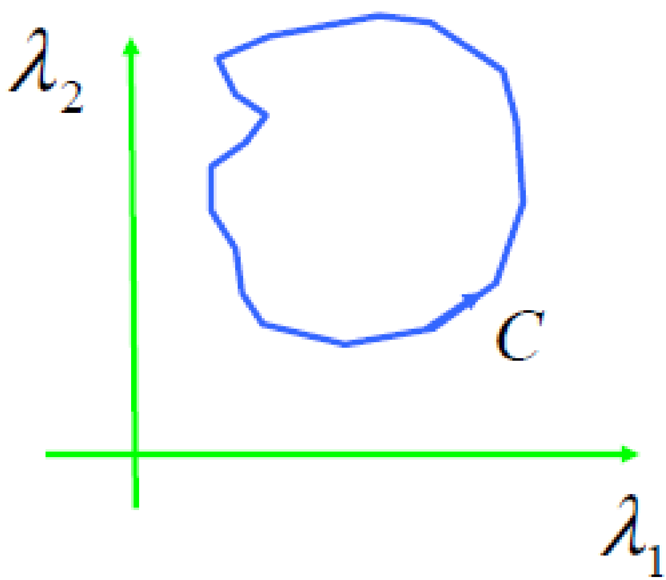
Geometric phase:

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

Well defined for a closed path

From Prof. Guo Guang-Yu

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



Stokes theorem

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

Berry Curvature

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

Analogies

From Prof. Guo Guang-Yu

Berry curvature	Magnetic field
$\Omega(\vec{\lambda})$	$B(\vec{r})$
Berry connection	Vector potential
$\langle\psi\vert i\frac{\partial}{\partial\lambda}\vert\psi\rangle$	$A(\vec{r})$
Geometric phase	Aharonov-Bohm phase
$\oint d\lambda\,\langle\psi\vert i\frac{\partial}{\partial\lambda}\vert\psi\rangle = \iint d^2\lambda\ \Omega(\vec{\lambda})$	$\oint dr\ A(\vec{r}) = \iint d^2r\ B(\vec{r})$
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

Old version [e.g., Aschroft, Mermin, 1976]

From Prof. Guo Guang-Yu

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

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

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

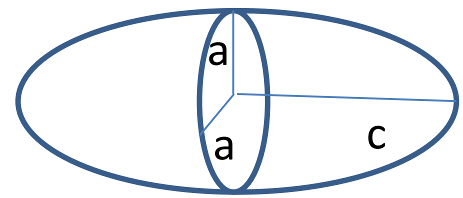
For an ellipsoid $D_x + D_y + D_z = 1$ (SI units) $D_x + D_y + D_z = 4\pi$ (cgs units)

Solution for Spheroid $a = b \neq c$

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

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

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

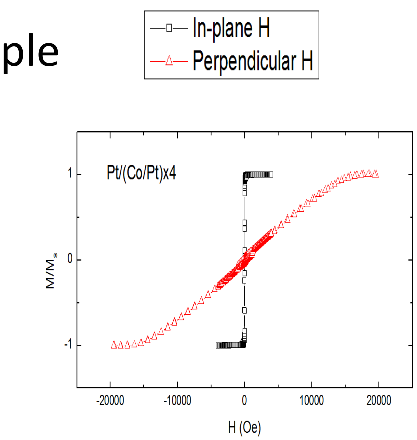


Limiting case r >> 1 (long rod)

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

$$D_a = D_b = 2\pi$$

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

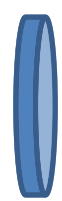


2. Oblate Spheroid (pancake shape) $c/a = r < 1$; $a = b$

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

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

Limiting case r >> 1 (flat disk)



$$D_c = 4\pi$$

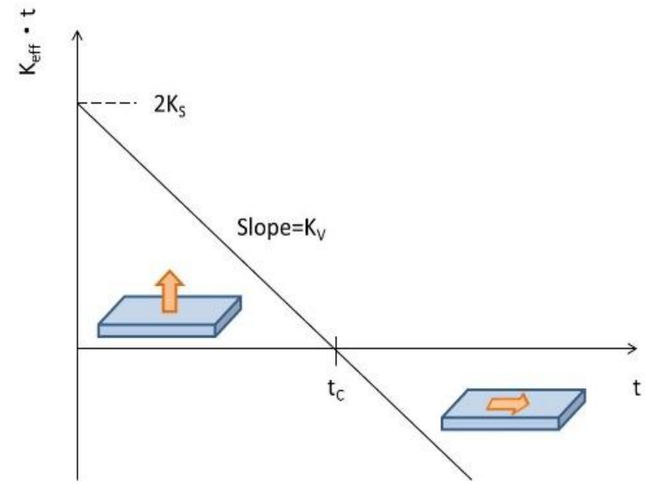
$$D_a = D_b = \pi^2 r \ll 1$$

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

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 $N\Delta E_{ex} = N(JS^2\left(\frac{\pi}{N}\right)^2)$

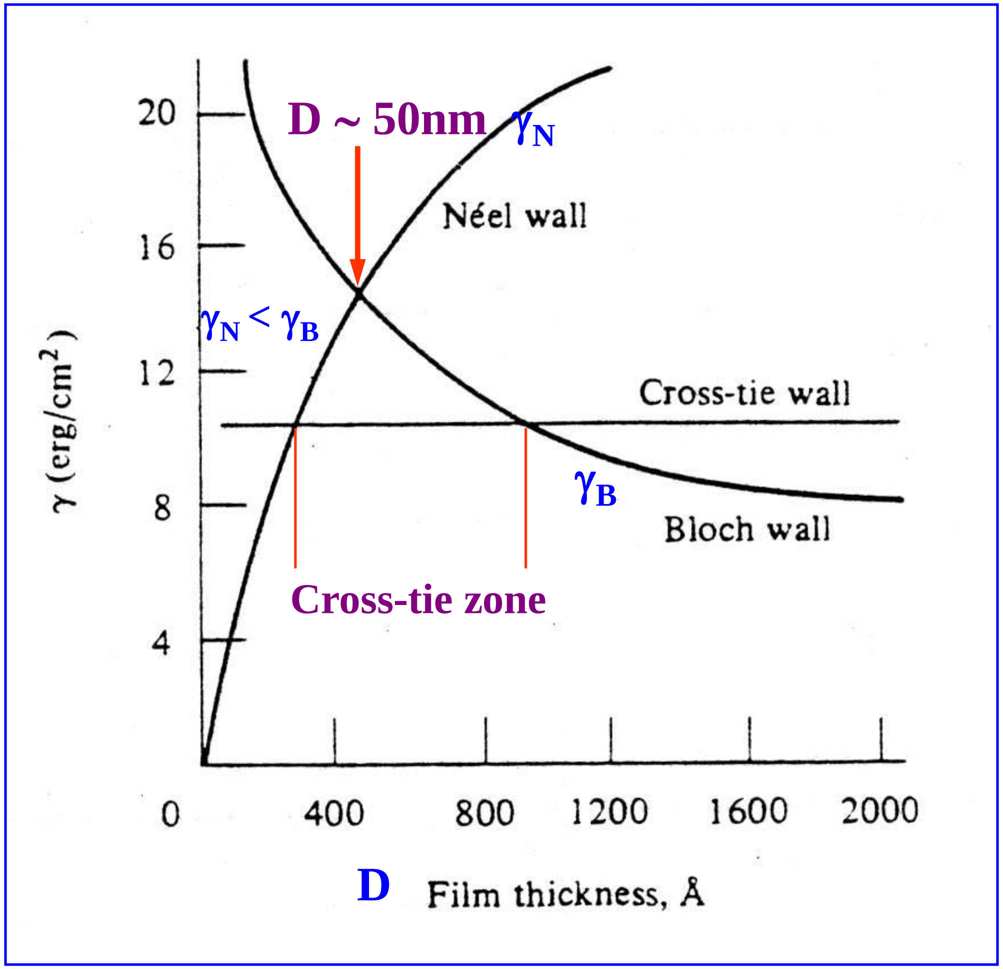
Wall energy density $\sigma_w = \sigma_{ex} + \sigma_{anis} \approx JS^2\pi^2/(Na^2) + KNa$ a : lattice constant

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



$\gamma_N < \gamma_B$ ~ 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

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

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

Landau-Lifshitz-Gilbert (LLG) equation

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

Shape effect:

internal magnetic field

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

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

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

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

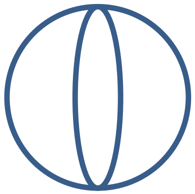
$$\begin{vmatrix} i\omega & \gamma[B_0 + \left(N_y - N_z\right)M] \\ -\gamma[B_0 + (N_x - N_z)M] & i\omega \end{vmatrix} = 0$$

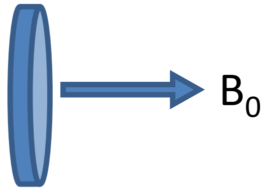
$$\omega_0^2 = \gamma^2[B_0 + \left(N_y - N_z\right)M][B_0 + (N_x - N_z)M]$$

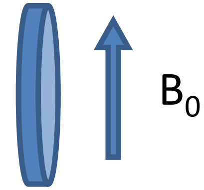
Uniform mode

Uniform mode

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







Sphere: $N_x = N_y = N_z$, $\omega_0 = \gamma\, B_0$

Flat plate with perpendicular field: $N_x = N_y = 0 \quad N_z = 4\pi$, $\omega_0 = \gamma\, (B_0 - 4\pi M)$

Flat plate with in-plane field: $N_x = N_z = 0 \quad N_y = 4\pi$, $\omega_0 = \gamma\, [B_0(B_0 + 4\pi M)]^{1/2}$

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

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

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

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 $ka \ll 1$ $\hbar\omega \cong (-4JS)|ka|$

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 $\mathbf{M}_2$

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

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

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

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

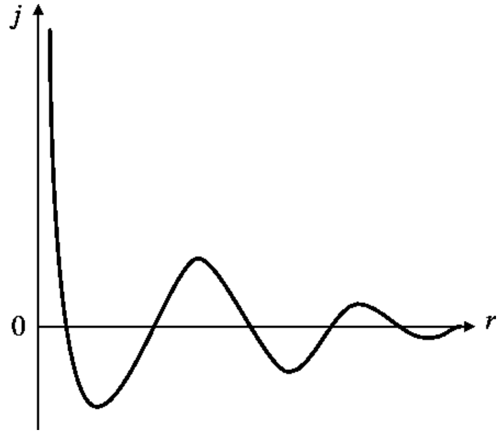
$\omega_0^2 = \gamma^2 B_A(B_A + 2B_E)$ Uniform mode

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

RKKY (*Ruderman-Kittel-Kasuya-Yosida*) interaction



coupling coefficient

$$j\left(\boldsymbol{R}_l - \boldsymbol{R}_{l'}\right) = 9\pi\left(\frac{j^2}{\epsilon_F}\right) F\left(2k_F\left|\boldsymbol{R}_l - \boldsymbol{R}_{l'}\right|\right)$$

$$F(x) = \frac{x\cos x - \sin x}{x^4}$$

Magnetic coupling in superlattices

- Long-range incommensurate magnetic order in a Dy-Y multilayer

M. B. Salamon, Shantanu Sinha, J. J. Rhyne, J. E. Cunningham, Ross W. Erwin, Julie Borchers, and C. P. Flynn, Phys. Rev. Lett. **56**, 259 - 262 (1986)

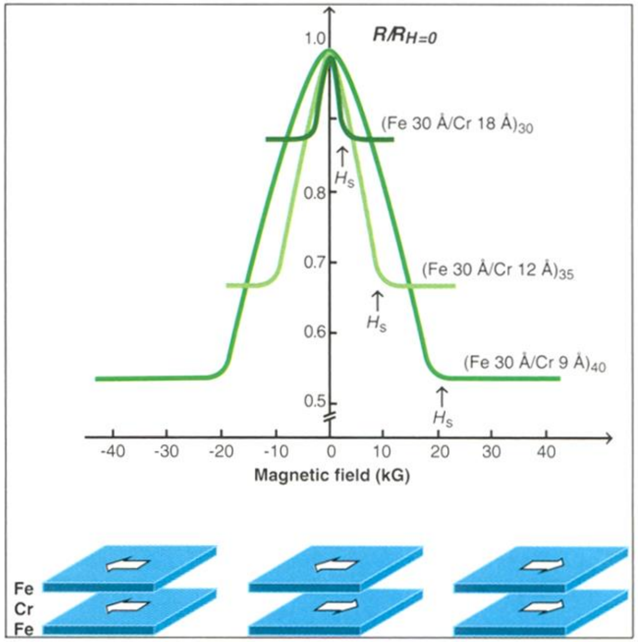
- Observation of a Magnetic Antiphase Domain Structure with Long- Range Order in a Synthetic Gd-Y Superlattice

C. F. Majkrzak, J. W. Cable, J. Kwo, M. Hong, D. B. McWhan, Y. Yafet, and J. V. Waszczak,C. Vettier, Phys. Rev. Lett. **56**, 2700 - 2703 (1986)

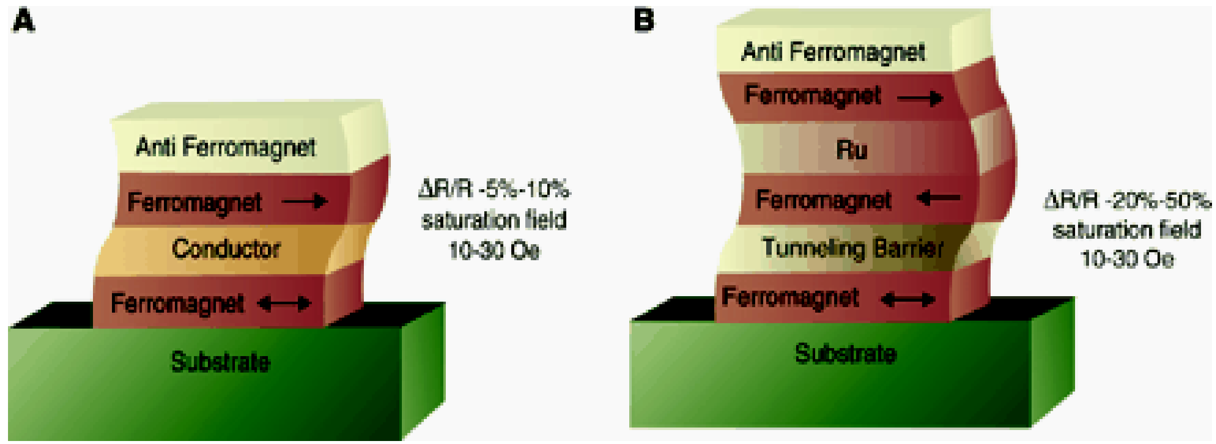
- Layered Magnetic Structures: Evidence for Antiferromagnetic Coupling of Fe Layers across Cr Interlayers

P. Grünberg, R. Schreiber, Y. Pang, M. B. Brodsky, and H. Sowers, Phys. Rev. Lett. **57**, 2442 - 2445 (1986)

Giant Magnetoresistance
Tunneling Magnetoresistance



Discovery of Giant MR -- Two-current model combines with magnetic coupling in multilayers



Spin-dependent transport structures. (A) Spin valve. (B) Magnetic tunnel junction. (from Science)

Moodera's group, PRL **74**, 3273 (1995)

Fert's group, PRL **61**, 2472 (1988)

Miyazaki's group, JMMM **139**, L231(1995)

Valet and Fert model of (CPP-)GMR

Based on the Boltzmann equation

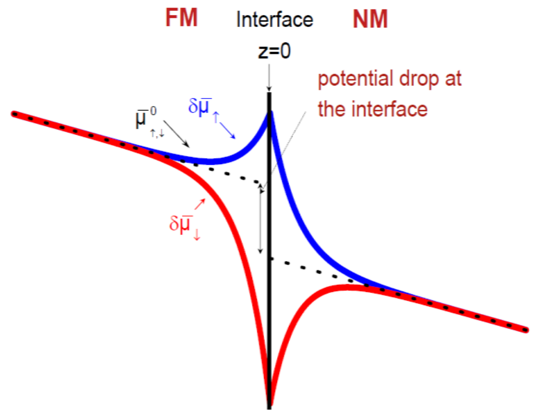
A semi-classical model with spin taken into consideration

$$j_{+(-)} = \frac{1}{e\rho_{+(-)}} \frac{\partial \mu_{+(-)}}{\partial x}$$

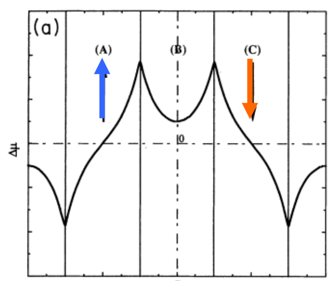
$$j_+ + j_- = j_e$$

$$\frac{\partial (j_+ - j_-)}{\partial x} = \frac{2eN(E_F)\Delta\mu}{\tau_{sf}}$$

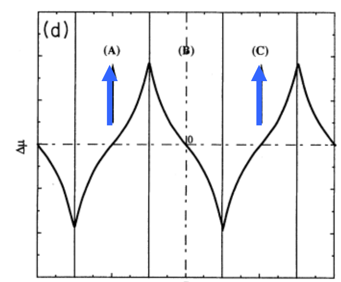
$$\frac{\partial^2 \mu_{+(-)}}{\partial z^2} = \frac{\mu_{+(-)}}{l_{sf}^2} \qquad l_{sf}^F = \left[\lambda_{sf}^F / 3(\lambda_\uparrow^{-1} + \lambda_\downarrow^{-1})\right]^{1/2}, \quad l_{sf}^N = \left[\lambda_{sf}^N \lambda / 6\right]^{1/2}$$



Δμ for antiparallel aligned multilayers



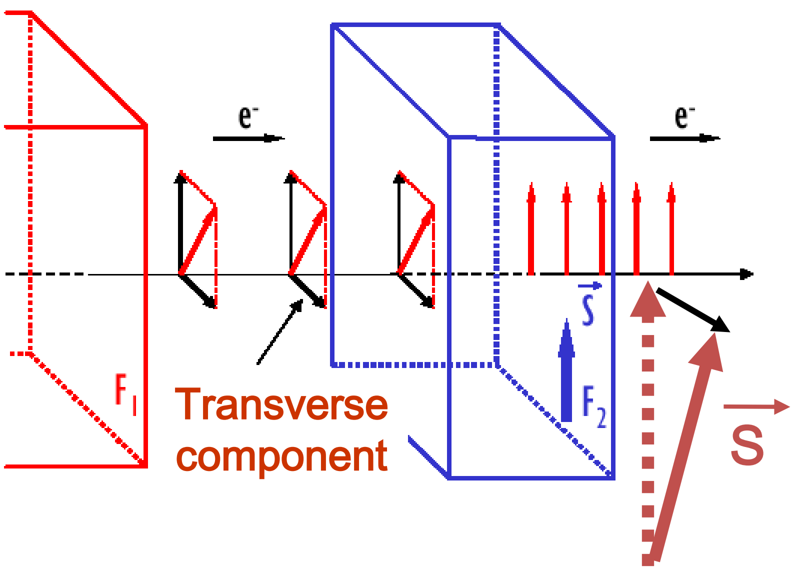
Δμ for parallel aligned multilayers

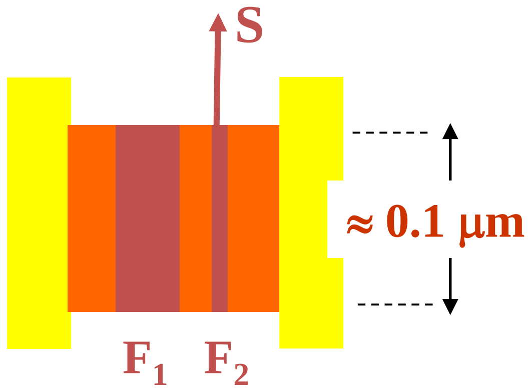


Spin imbalance induced charge accumulation at the interface is important

Spin diffusion length, instead of mean free path, is the dominant physical length scale

Spin Transfer Torque





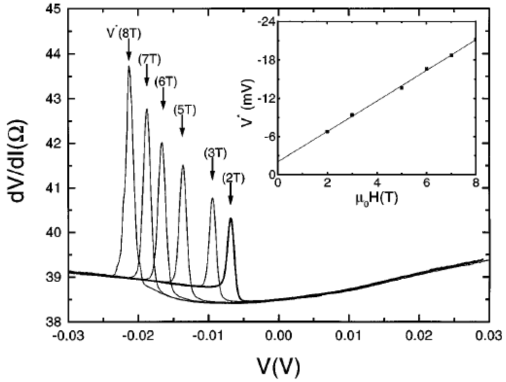


FIG. 1. The point contact $dV/dI(V)$ spectra for a series of magnetic fields (2, 3, 5, 6, 7, and 8 T) revealing an upward step and a corresponding peak in dV/dI at a certain negative bias voltage $V^*(H)$. The inset shows that $V^*(H)$ increases linearly with the applied magnetic field H.

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

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

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

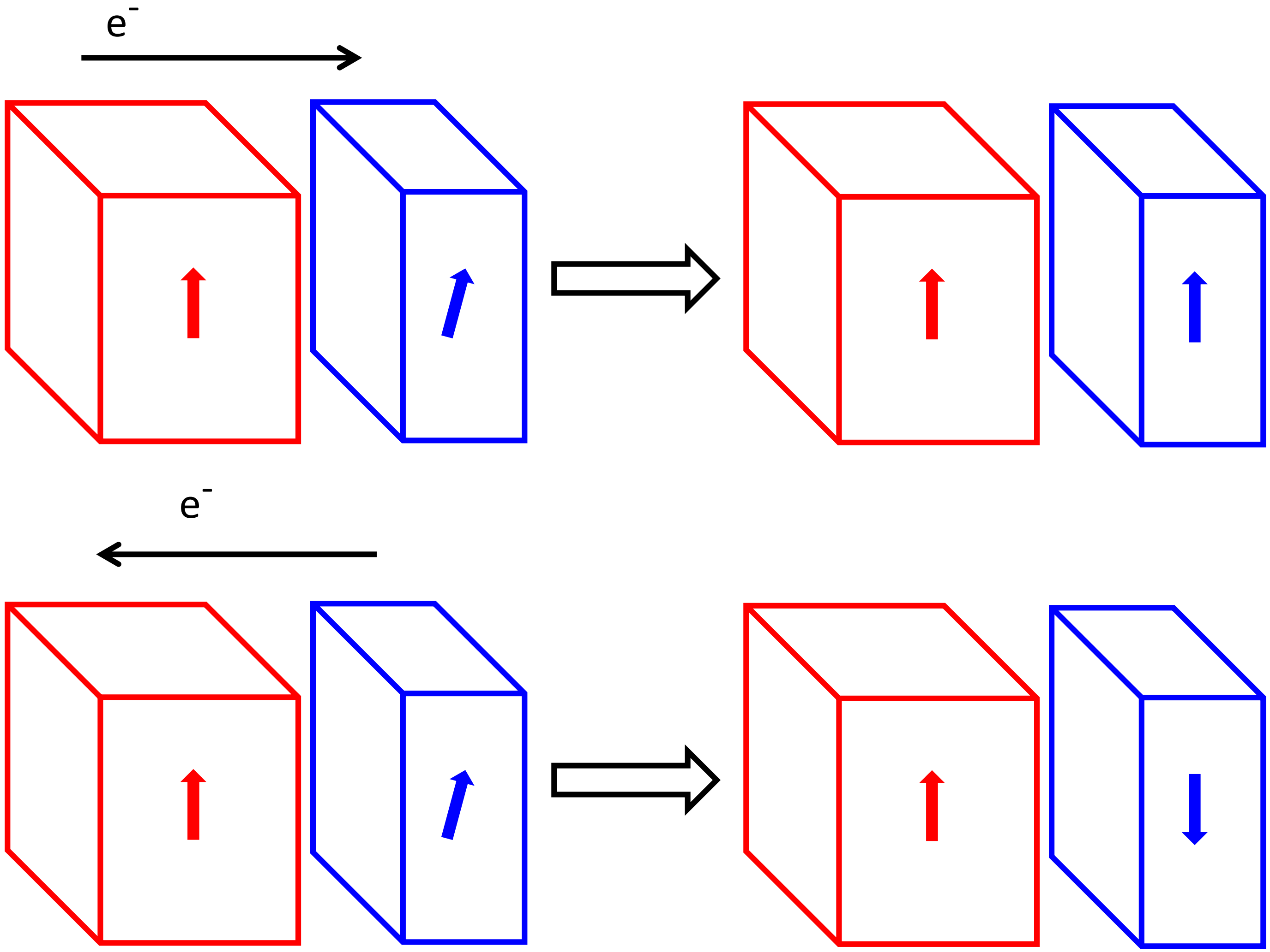
Slonczewski JMMM **159**, L1 (1996)

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



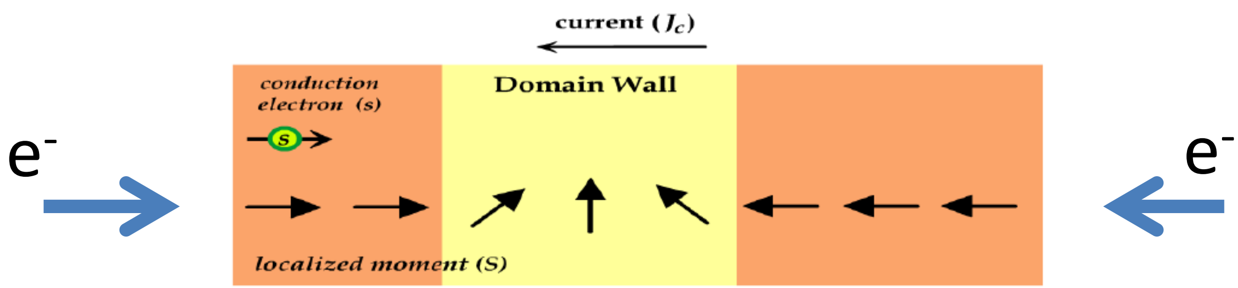
In a trilayer, current direction determines the relative orientation of F_1 and F_2

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



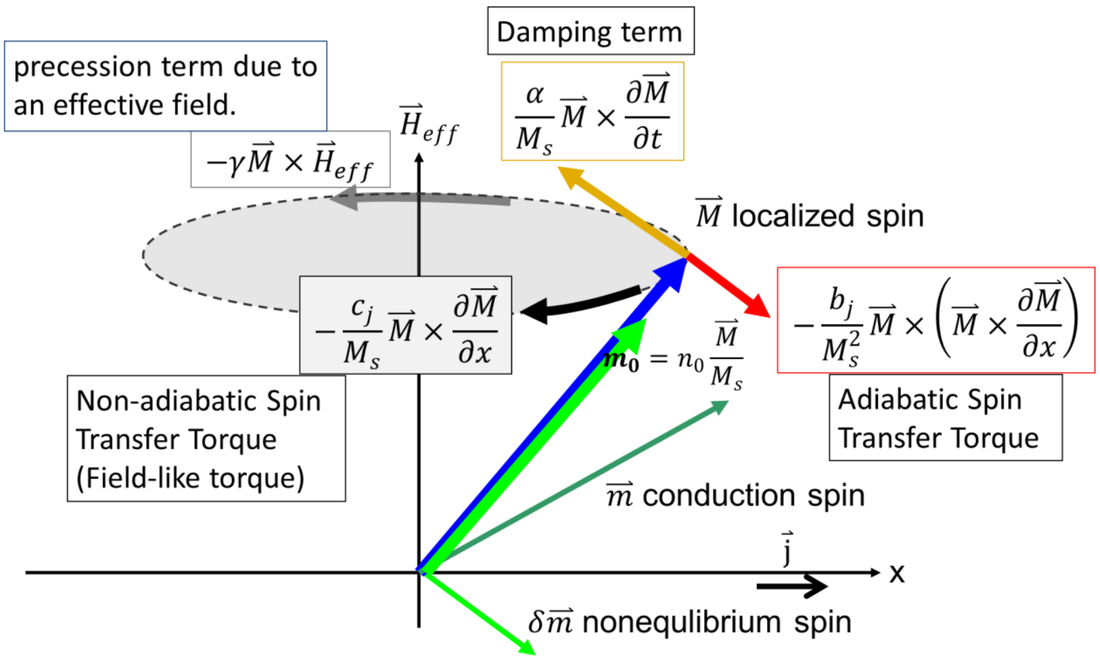
Domain A **Domain B**

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

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



Damping term

Adiabatic Spin Transfer Torque

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

$$b_j, c_j \sim JP/t$$

Precessional term due to an effective field.

Non-adiabatic Spin Transfer Torque

Onsager reciprocity relations

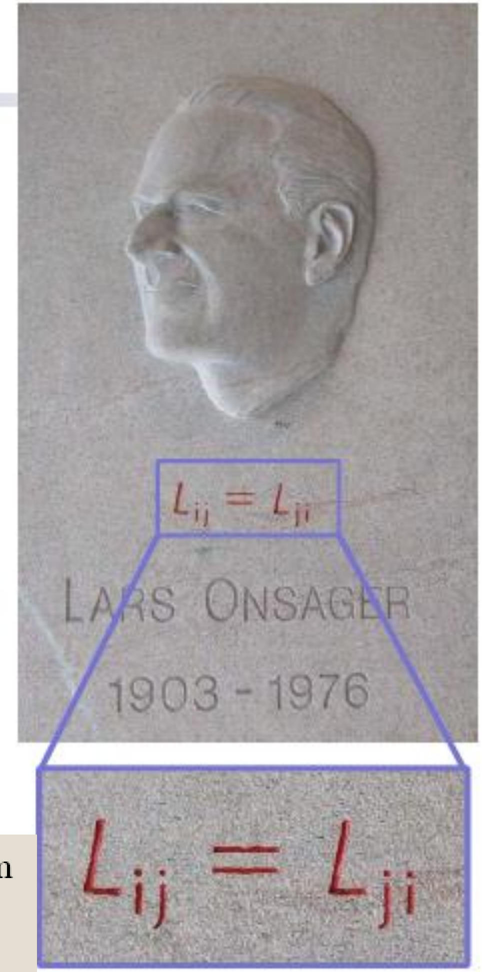
Conjugate variables

X_i	generalized forces
J_i	generalized currents
$J_i = \sum_j L_{ij} X_j$	linear response

i = {mass, charge, spin, energy, ...}

$\dot{S} = \sum_i X_i J_i$	entropy creation rate

$$L_{ij}\left(\mathbf{m}, \mathbf{H}_{ext}\right) = \varepsilon_i \varepsilon_j L_{ji}\left(-\mathbf{m}, -\mathbf{H}_{ext}\right)$$



Equality between certain relations between flows and forces out of equilibrium

Currents can induce magnetization excitations

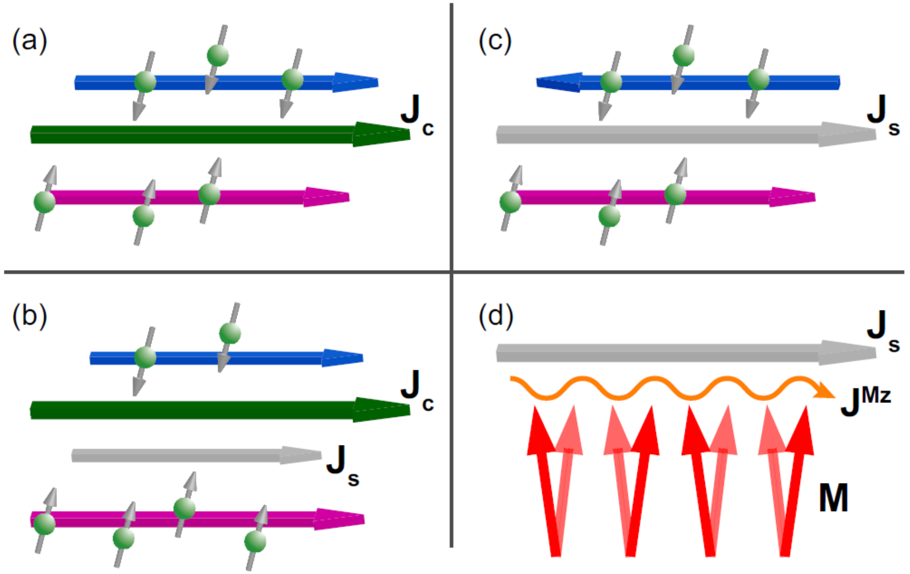
↕

A time-dependent magnetization can induce (charge and spin) currents

Pure Spin Current

-- with no accompanying net charge current

- Theoretically
  - $J_S = \hat{s} \cdot \vec{v} \;\; \rightarrow J_S = \frac{d}{dt}(\hat{s} \cdot \vec{r})$
- Experimentally
  - Spin Hall, Inverse Spin Hall effects
  - Spin Pumping effect
  - Spin Seebeck effect



Spin Current

Proper Definition of Spin Current in Spin-Orbit Coupled Systems

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[1]*Institute of Physics and ICQS, Chinese Academy of Sciences, Beijing 100080, People's Republic of China*
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(Received 19 April 2005; revised manuscript received 18 November 2005; published 24 February 2006)

The conventional definition of spin current is incomplete and unphysical in describing spin transport in systems with spin-orbit coupling. A proper and measurable spin current is established in this study, which fits well into the standard framework of near-equilibrium transport theory and has the desirable property to vanish in insulators with localized orbitals. Experimental implications of our theory are discussed.

$$J_S = \hat{s}\cdot\vec{v} \qquad \rightarrow \qquad J_S = \frac{d}{dt}(\hat{s}\cdot\vec{r}) = \hat{s}\cdot\vec{v} + \frac{d}{dt}\hat{s}\cdot\vec{r}$$

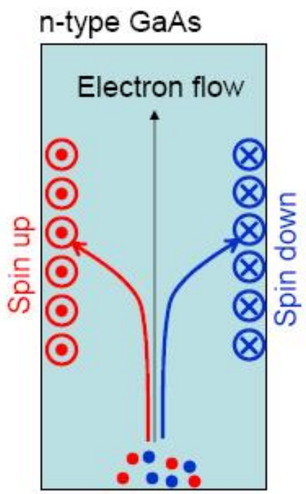
torque dipole term

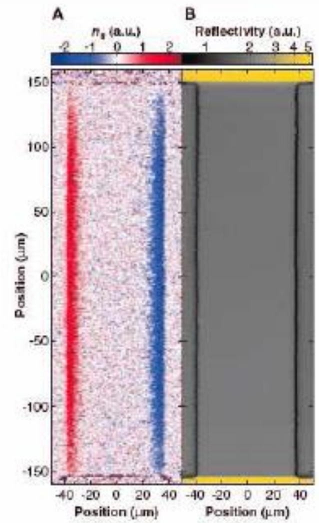
1. spin current is not conserved
2. can even be finite in insulators with localized eigenstates only
3. not in conjugation with any mechanical or thermodynamic force, not fitted into the standard near-equilibrium transport theory

1. spin current conserved
2. vanishes identically in insulators with localized orbitals
3. in conjugation with a force given by the gradient of the Zeeman field or spin-dependent chemical potential

Spin Hall effect

Spin Hall Effect: Electron flow generates transverse spin current





SHE observed in GaAs using Kerr effect to measure spin

Kato et.al. (Awschalom), Science 306, 1910 (2004)

Now observed at room temperature in ZnSe

M. I. Dyakonov and V. I. Perel, *JETP* **13** 467 (1971)

J. E. Hirsch, *Phys. Rev. Lett.* **83** 1834 (1999)

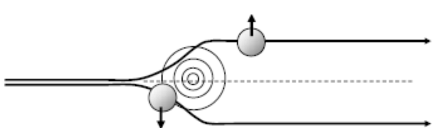
Guo *et al*, PRL **100** 096401 (2008)

Berry curvature

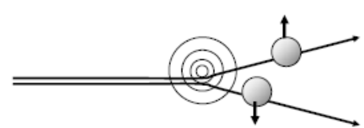
$$\dot{\vec{r}} = \frac{1}{\hbar}\frac{\partial \varepsilon_n(\vec{k})}{\partial \vec{k}} + \frac{e}{\hbar}\vec{E}\times\vec{\Omega}(\vec{k})$$

The Intrinsic SHE is due to topological band structures

The extrinsic SHE is due to asymmetry in electron scattering for up and down spins. – spin dependent probability difference in the electron trajectories



Side jump



Skew scattering

Inverse Spin Hall effect : ISHE

VOLUME 83, NUMBER 9 PHYSICAL REVIEW LETTERS 30 AUGUST 1999

Spin Hall Effect

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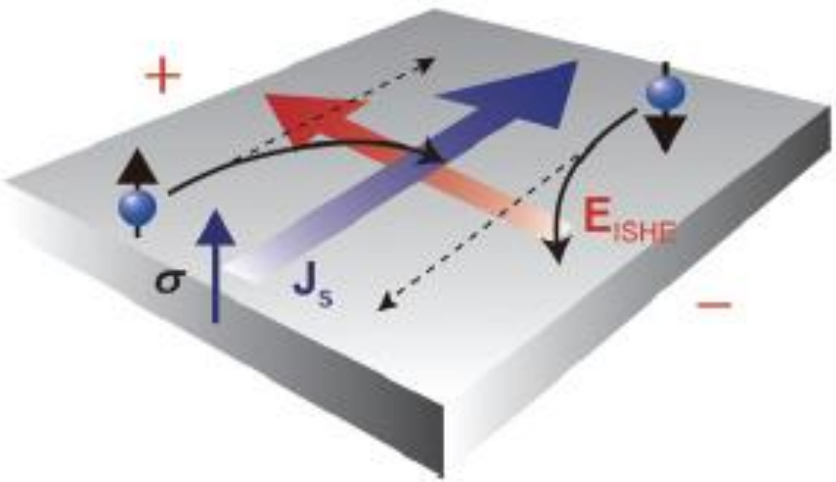
(Received 24 February 1999)

It is proposed that when a charge current circulates in a paramagnetic metal a transverse spin imbalance will be generated, giving rise to a "spin Hall voltage." Similarly, it is proposed that when a spin current circulates a transverse charge imbalance will be generated, giving rise to a Hall voltage, in the absence of charge current and magnetic field. Based on these principles we propose an experiment to generate and detect a spin current in a paramagnetic metal.

ISHE: converts a spin current into an electric voltage



J. Appl. Phys. **109**, 103913 (2011)

SO-coupling bends the two electrons in the same direction → charge accumulation → E_{ISHE}.

$$\mathbf{E}_{\mathrm{ISHE}} \propto \mathbf{J}_s \times \boldsymbol{\sigma}$$

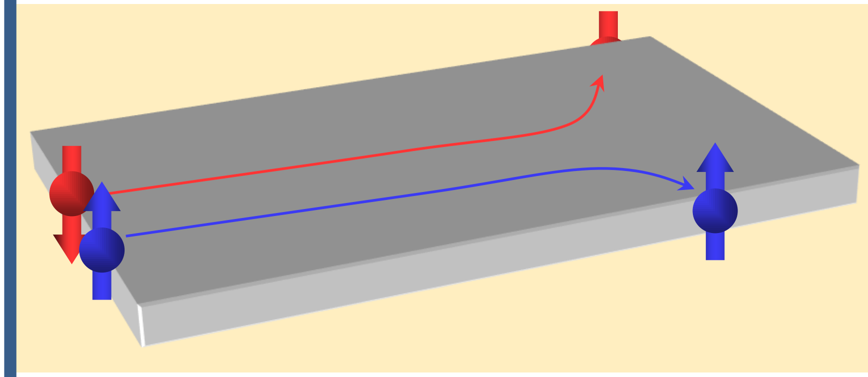
Js : spin current density

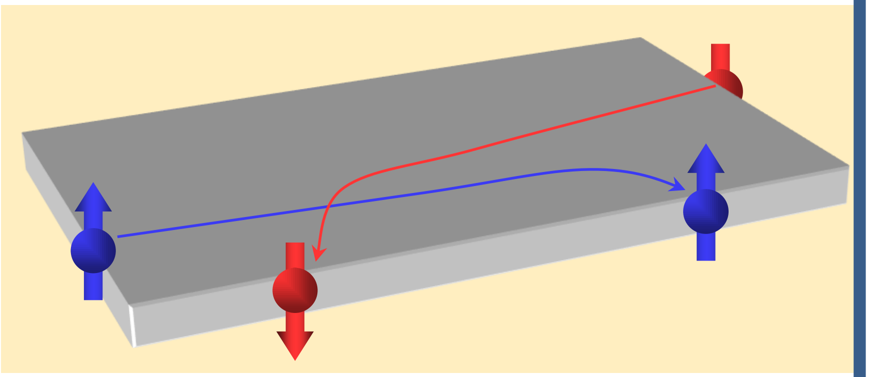
σ : direction of the spin-polarization vector of a spin current.

ISHE: Governed by spin-orbit coupling

SHE vs. ISHE

Spin Hall	Inverse Spin Hall
Charge Current	Spin Current
⇓	⇓
Transverse	Transverse
Spin Imbalance	Charge Imbalance





ISHE : direct & sensitive detection of a spin current !

Spin Hall Angle

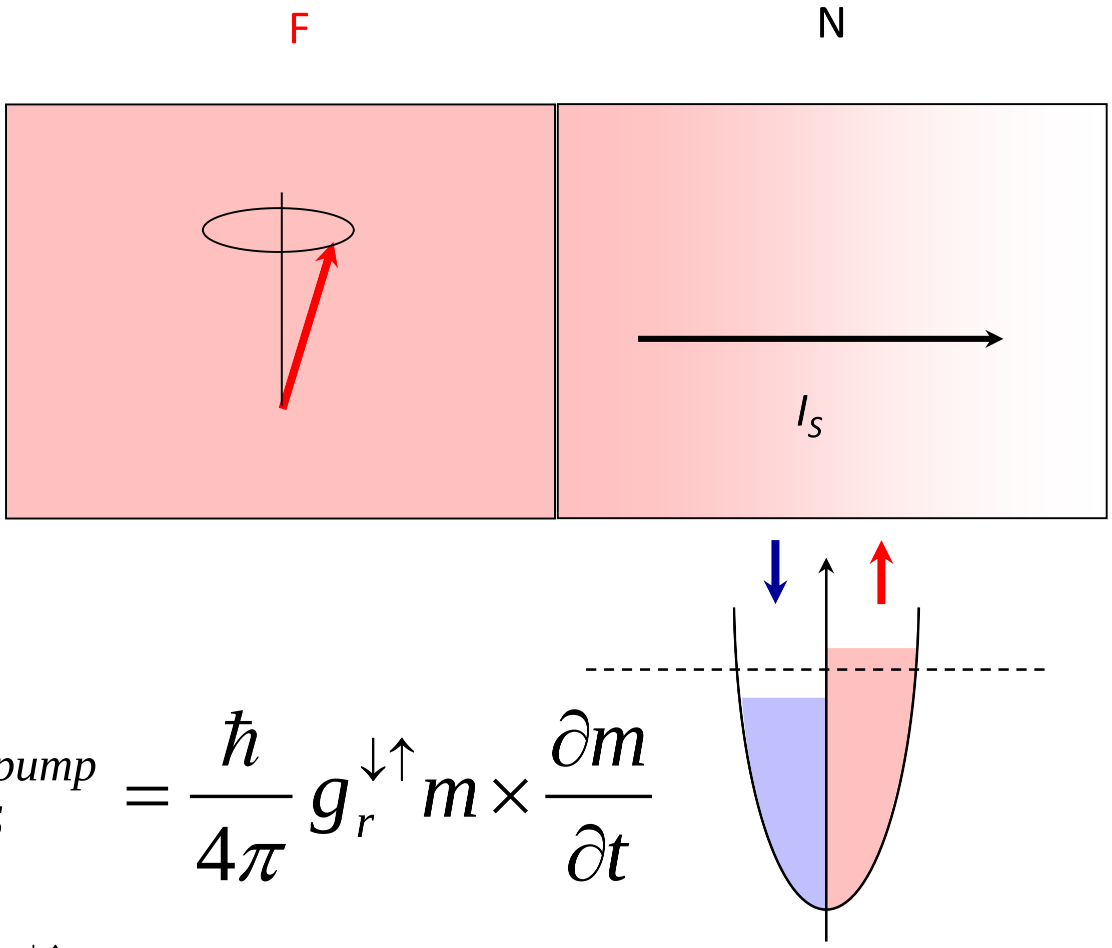
$$\gamma = \frac{\sigma_{SH}}{\sigma_c}$$

$\leftarrow$ spin Hall conductivity

$\leftarrow$ charge conductivity

stronger spin orbit interaction $\Rightarrow$ larger γ

Spin Pumping



- Landau-Lifshitz-Gilbert

$$\dot{\mathbf{m}} = -\gamma \mathbf{m} \times \mathbf{H}_{\mathrm{eff}} + \mathbf{m} \times (\tilde{\alpha} \dot{\mathbf{m}})$$

$$I_S^{pump} = \frac{\hbar}{4\pi} g_r^{\downarrow\uparrow} m \times \frac{\partial m}{\partial t}$$

$g_r^{\downarrow\uparrow}$: spin mixing conductance

Spin accumulation gives rise to spin current in neighboring normal metal

In the FMR condition, the steady magnetization precession in a F is maintained
by balancing the absorption of the applied microwave
and the dissipation of the spin angular momentum --the transfer of angular momentum from the local spins to conduction electrons, which polarizes the conduction-electron spins.

PRL 110, 217602 (2013)

Spin Backflow and ac Voltage Generation by Spin Pumping and the Inverse Spin Hall Effect

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(Received 28 September 2012; published 23 May 2013)

The spin current pumped by a precessing ferromagnet into an adjacent normal metal has a constant polarization component parallel to the precession axis and a rotating one normal to the magnetization. The former is now routinely detected as a dc voltage induced by the inverse spin Hall effect (ISHE). Here we compute ac ISHE voltages much larger than the dc signals for various material combinations and discuss optimal conditions to observe the effect. The backflow of spin is shown to be essential to distill parameters from measured ISHE voltages for both dc and ac configurations.

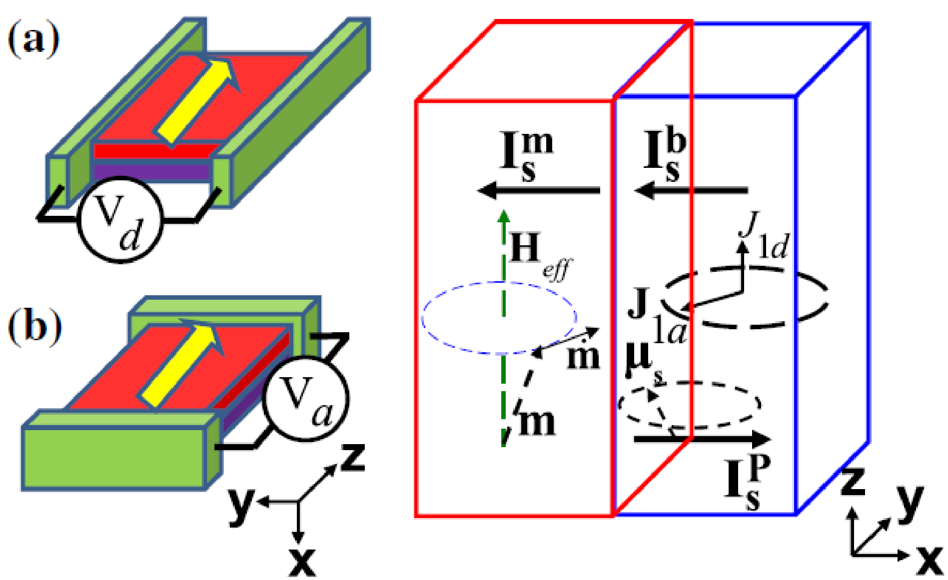
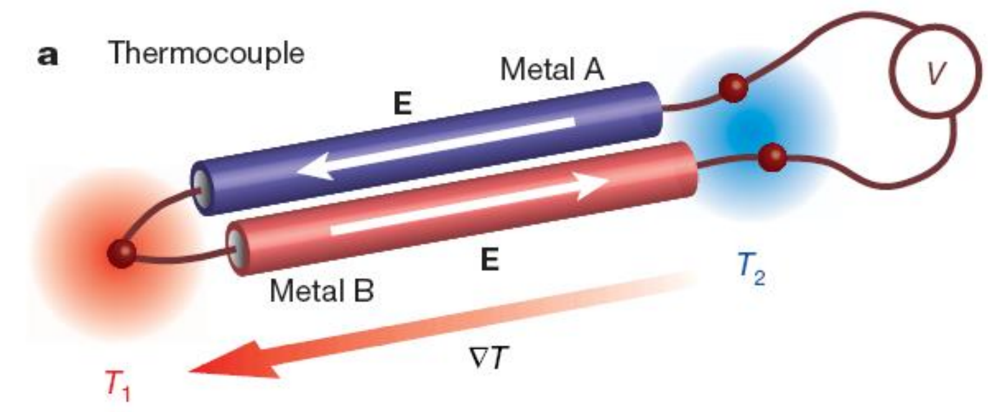
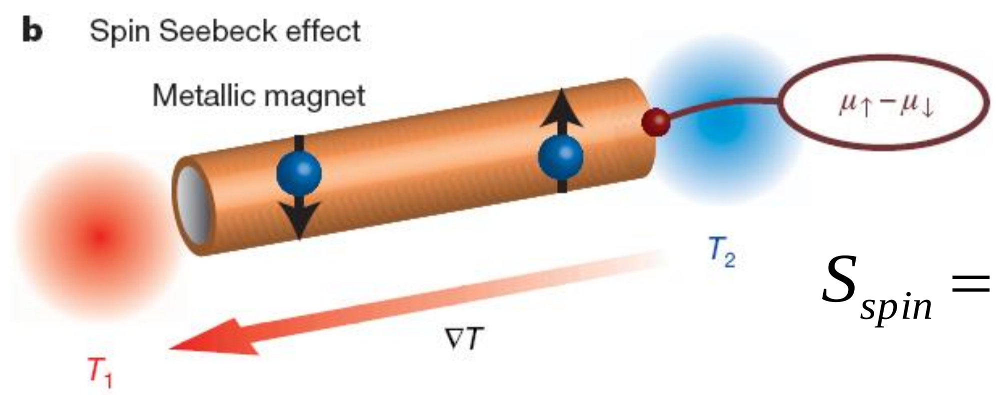


FIG. 1 (color online). Schematic spin battery operated by FMR, for the measurement configurations (a) and (b). The ac (dc) voltage drops along the z (y) direction. The right panel introduces the parameters of the model. The effective field $\mathbf{H}_{\rm eff}$ is the sum of the external field $\mathbf{H}_{\rm ex}$ and the uniaxial field $\mathbf{H}_{\rm un}$, $\mathbf{H}_{\rm ex}$, and $\mathbf{H}_{\rm un}$ point along the z axis. The dc component $J_{1d}(j_{1s}^z)\mathbf{e}_z$ and ac component $\mathbf{J}_{1a}(\mathbf{j}_{1s}^a)$ constitute the spin current $\mathbf{j}_{1s}$.

Spin Seebeck effect



$$\delta V = S\delta T$$



$$\delta V_{spin} = S_{spin}\delta T$$

$$S_{spin} = (1/e)[\partial \mu^c{}_\uparrow / \partial T - \partial \mu^c{}_\downarrow / \partial T]$$

Uchida *et al.*, Nature **455**, 778 (2008)

為什麼(大部分)磁鐵打破後會相斥?