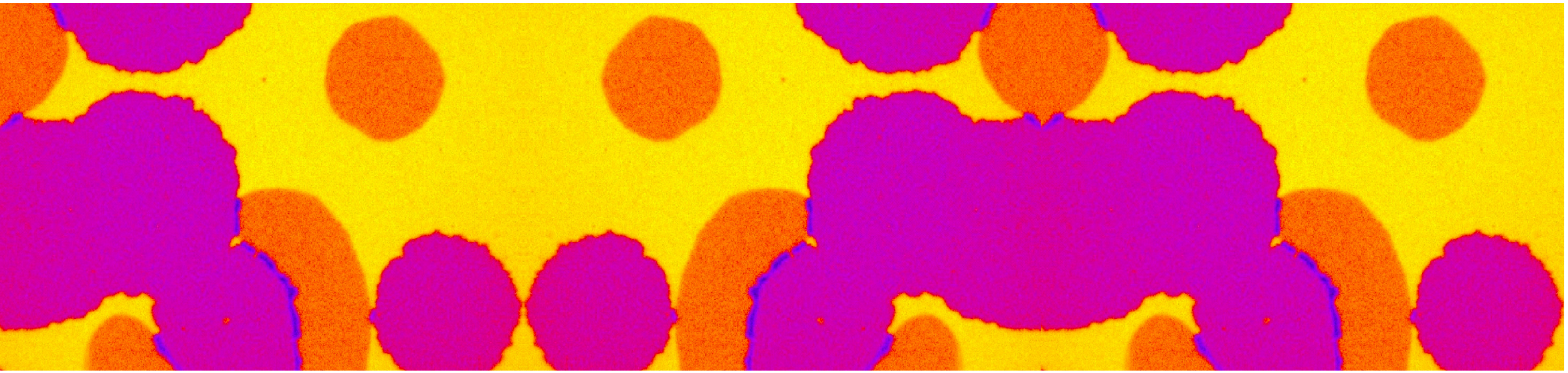
Magnetism and Magnetic Switching

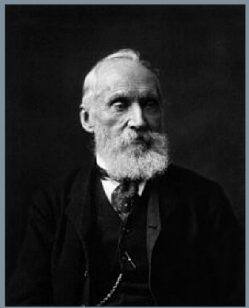
Robert Stamps

SUPA-School of Physics and Astronomy
University of Glasgow



University of Glasgow

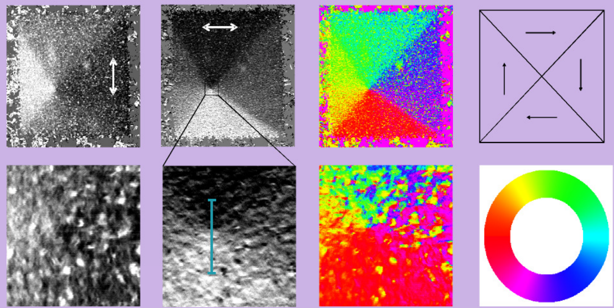
William Thomson (Kelvin)



James Watt

William Rankine

Kelvin Nanocharacterisation Centre



Standard mode: < **100 pm**
Lorentz mode: < **2 nm**

Materials & Condensed Matter Physics

Magnetic Nanostructures
Theory and Modelling
Functional Materials
Electron Microscopy

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THE ROYAL SOCIETY

SUPA

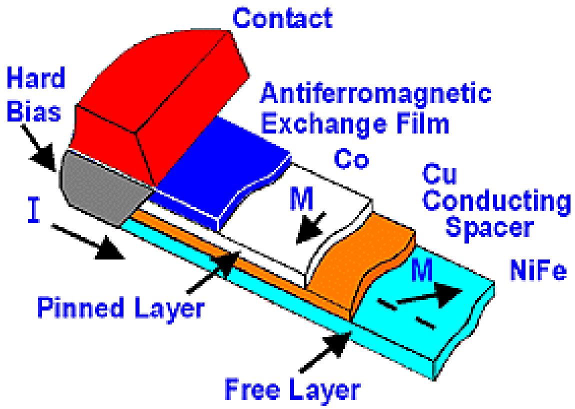
A story from modern magnetism:
The Incredible Shrinking Disk

Instead of this:
(1980)

A story from modern magnetism:
The Incredible Shrinking Disk

We have this:
(10^3 greater capacity)

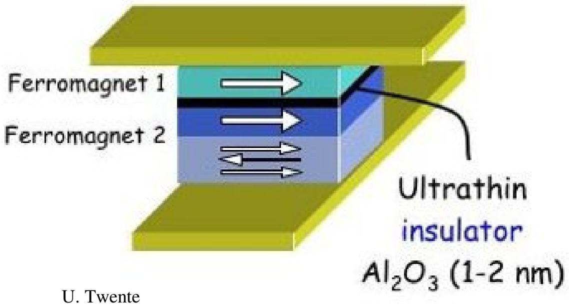
Size and Sensitivity



The physics of GMR **sensors** allow 10 to 100 times sensitivity over previous sensors. Greater sensitivity means ability to read data at higher densities.

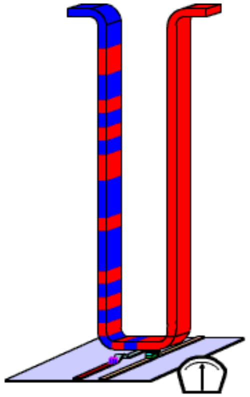
Devices for Tomorrow

Magnetic RAM



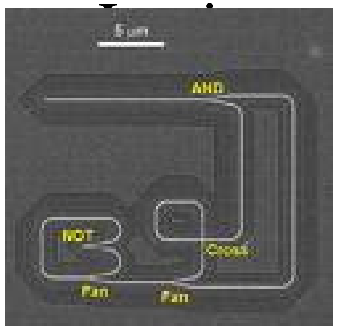
U. Twente

Racetrack Memory

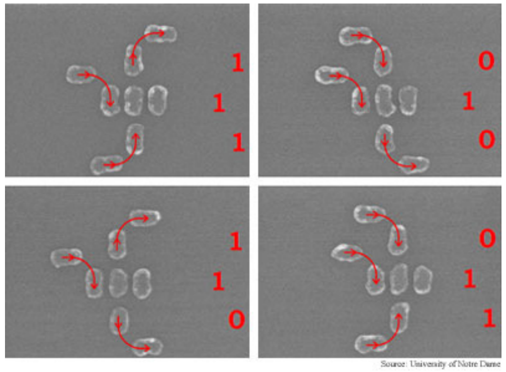


IBM Almaden

Nanomagnetic

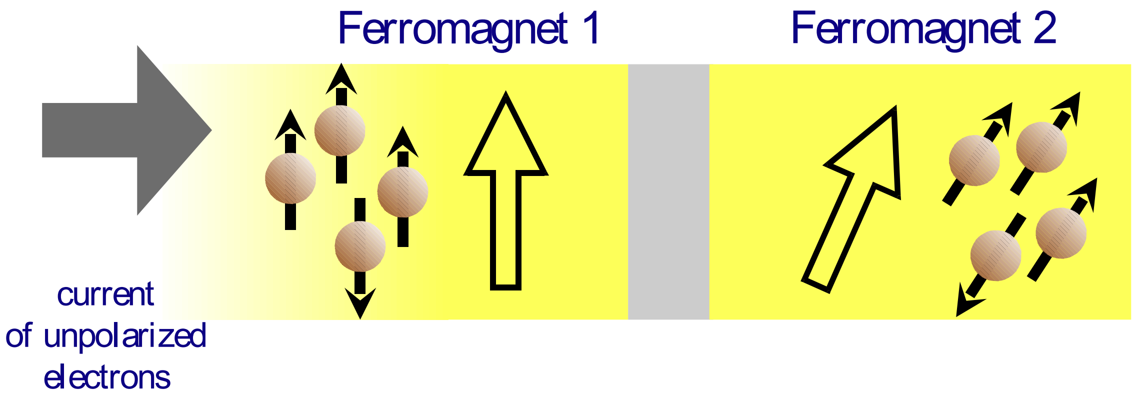


U. Sheffield



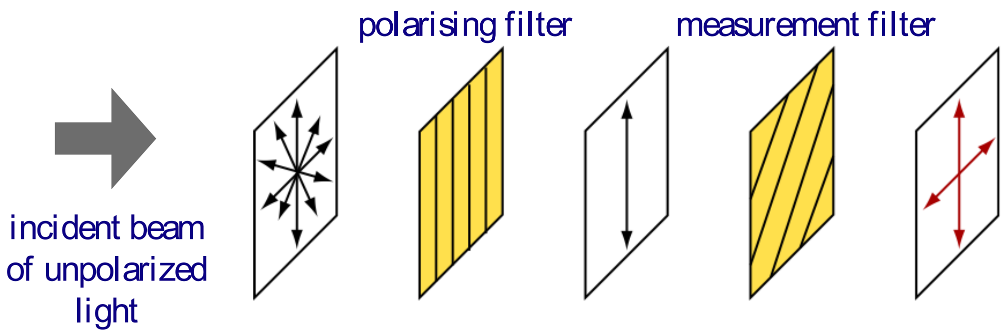
Reversal involves **precessional** magnetic **rotation,** domain wall formation and **domain wall motion**

Spin Torque Transfer & Spin Currents



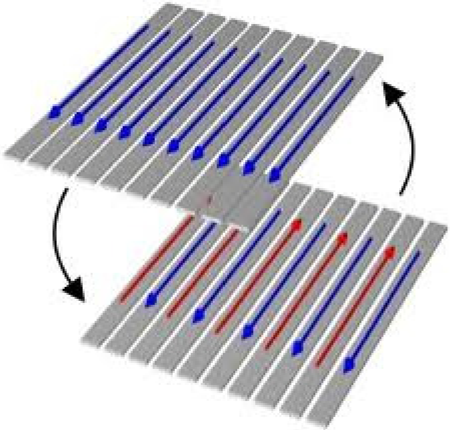
Spin accumulation
and torque transfer

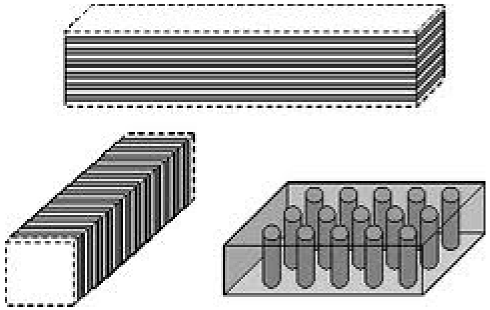
Optical analogy:



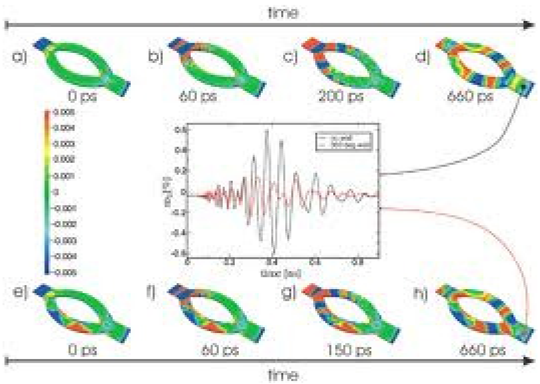
Magnonics

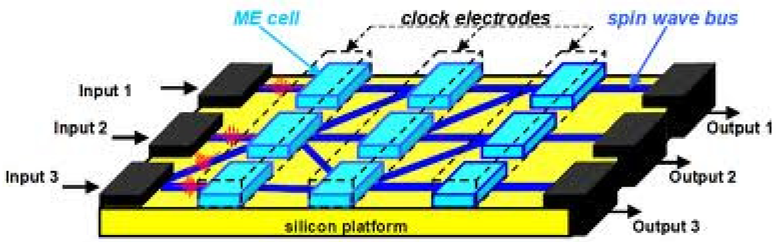
Control GHz properties with patterned magnetic films:





Spinwave based logic:





Outline:

- **Starting points: Magnetic moment and exchange**
  - Electrostatics and exchange energy
  - Magnetic ordering and mechanisms for exchange

- **Magnetisation dynamics**
  - Torque equations and effective fields
  - Precessional dynamics
  - Switching

- **Spin waves**
  - Correlated precession

Starting Point 1: Magnetic Moment

Spin and orbital **angular momentum**:

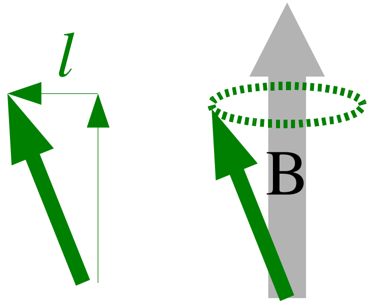
$$\hbar \boldsymbol{J} = \hbar(\boldsymbol{S} + \boldsymbol{L}) \qquad\qquad \mu = \gamma(\hbar \boldsymbol{J})$$

Gyromagnetic ratio γ: $$\gamma = -g\frac{\mu_B}{\hbar}$$

Energy and **precession**:

$$U = -\mu \cdot \boldsymbol{B} \qquad\qquad \Gamma = \frac{d}{dt}\boldsymbol{L} = \mu \times \boldsymbol{B}$$

$$\boldsymbol{L} = \boldsymbol{L_o} + \boldsymbol{l}\, e^{-i\omega_L t}$$

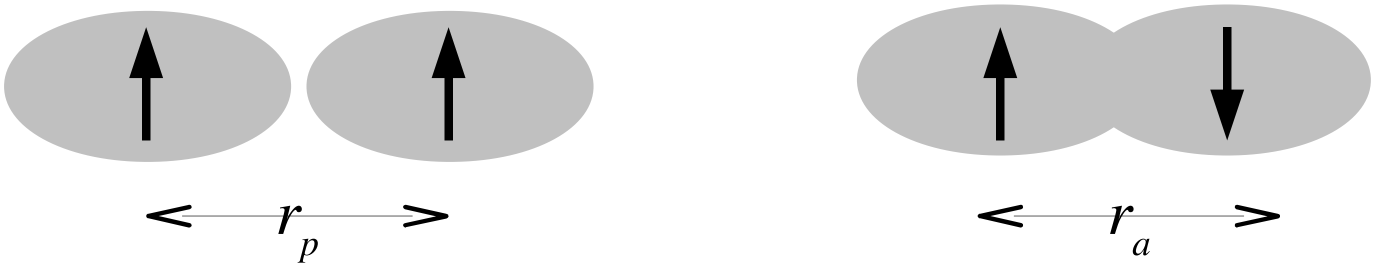


Larmor precession

$$\omega_L = \frac{\mu_B}{\hbar} B$$

Concept: Exchange Energy

Pauli exclusion **separates** like spins:



Can be **energetically favourable**: *suppose* parallel alignment results in a small change in average separation. Then *if*:

$$\left.\begin{array}{lcl} \langle r_a \rangle \sim 0.3\,nm & \Rightarrow & \dfrac{e^2}{r_a} \sim 4.8\,eV \\ \langle r_p \rangle \sim 0.31\,nm & \Rightarrow & \dfrac{e^2}{r_p} \sim 4.75\,eV \end{array}\right\} E_{\uparrow\uparrow} - E_{\uparrow\downarrow} = 0.05\,eV\,(580\,K)$$

… equivalent field: $\dfrac{E_{\uparrow\uparrow} - E_{\uparrow\downarrow}}{\mu_B} = 870\,T$

Example: Direct Exchange

Electrons on two **neighbouring atoms**:

$$H = \frac{p_1^2}{2\mathrm{m}} + \frac{p_2^2}{2\mathrm{m}} + \underbrace{\frac{e^2}{|\boldsymbol{R}_a - \boldsymbol{R}_b|}}_{\textit{core-core}} \underbrace{- \frac{e^2}{|\boldsymbol{r}_1 - \boldsymbol{r}_a|} - \frac{e^2}{|\boldsymbol{r}_2 - \boldsymbol{r}_b|}}_{\textit{intra-atomic}} + \underbrace{\frac{e^2}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|}}_{\textit{inter-atomic}}$$

Assume know solutions for **isolated orbitals** with energy E on atoms a and b.

Solve two electron problem with **combination of** product orbitals

$$\left.\begin{aligned}\Psi_I &= \phi_a(\boldsymbol{r}_1)\phi_b(\boldsymbol{r}_2)\\ \Psi_{II} &= \phi_a(\boldsymbol{r}_2)\phi_b(\boldsymbol{r}_1)\end{aligned}\right\} \qquad \psi = c_I \Psi_I + c_{II}\Psi_{II}$$

Example: Direct Exchange

Solution involves several **overlap integrals**:

$$V=\iint d\boldsymbol{r_1}\,d\boldsymbol{r_2}\,|\Psi^2_{I,II}|\,e^2\left(\frac{1}{R_{ab}}+\frac{1}{r_{12}}-\frac{1}{r_{ab}}-\frac{1}{r_{1a}}-\frac{1}{r_{2b}}\right)$$

$$U=\iint d\boldsymbol{r_1}\,d\boldsymbol{r_2}\,\Psi^*_I\Psi_{II}\,e^2\left(\frac{1}{R_{ab}}+\frac{1}{r_{12}}-\frac{1}{r_{ab}}-\frac{1}{r_{1a}}-\frac{1}{r_{2b}}\right)$$

$$l=\int d\boldsymbol{r}\,\phi^*_a(\boldsymbol{r})\,\phi_b(\boldsymbol{r})$$

Two electron **wavefunctions**:

space symmetric

$$c_I=c_{II}$$

$$E_+=2E+\frac{V+U}{1+l^2}$$

space anti-symmetric

$$c_I=-c_{II}$$

$$E_-=2E+\frac{V-U}{1-l^2}$$

Example: Direct Exchange

For **Pauli exclusion** require

$$\psi_s \sim \ (\textit{space symmetric})(\textit{spin antisymmetric})$$
$$\psi_a \sim \ (\textit{space antisymmetric})(\textit{spin symmetric})$$

$$\psi_s \to \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$$

spin 0

$$\psi_a \to \underbrace{(\downarrow\downarrow) \quad \frac{1}{\sqrt{2}}(\uparrow\uparrow + \downarrow\downarrow) \quad (\uparrow\uparrow)}_{\textit{spin -1, 0, 1}}$$

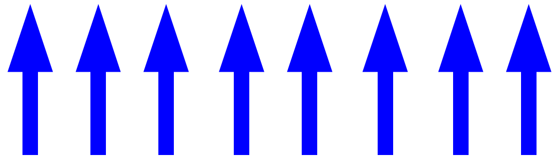
Energy difference determines whether spins prefer **parallel or antiparallel** alignment**:**

$$\boxed{J = E_{-} - E_{+} \sim U\, l^2 - V}$$

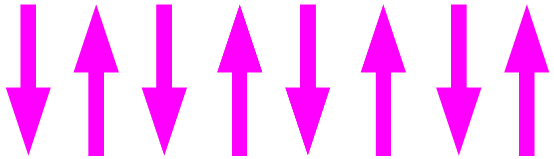
Heitler & London (1927)

Examples of Magnetic Ordering

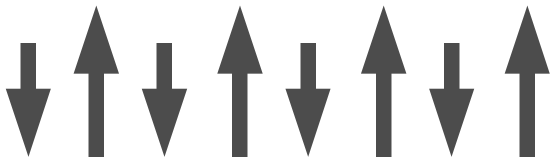
Ferromagnetic:



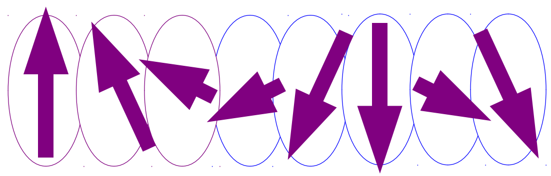
Antiferromagnetic:



Ferrimagnetic:

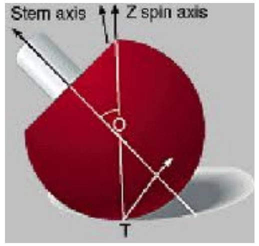


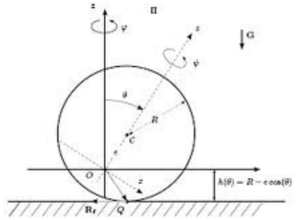
Helical:



Summary I

Bohr and Pauli Study
Angular Momentum





Angular momentum & magnetic moment:

- Defines energy, torque and precession

Exchange: electrostatic repulsion & Pauli exclusion:

- Determines long range order and phase transitions

Starting Point 2: Phenomenology

Relevant energy scales (P. W. Anderson, 1953):

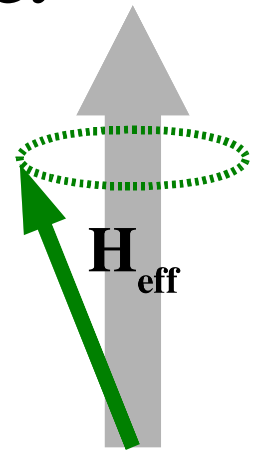
	1 – 10 eV	Atomic Coulomb integrals Hund's rule exchange energy Electronic band widths Energy/state at ε_f
ordering	0.1 – 1.0 eV	Exchange energy splitting
	10^{-2} – 10^{-1} eV	Spin-orbit coupling
spin waves	10^{-4} eV	Magnetic spin-spin coupling Interaction of a spin with 10 kG field
	10^{-6} – 10^{-5} eV	Hyperfine electron-nuclear coupling

Dynamics & Effective Field

Magnetic parameters describe energy & torques:

$$E = -\boldsymbol{m}(\boldsymbol{r},t)\cdot\boldsymbol{H}_{eff}(\boldsymbol{r},t)$$

$$\frac{\partial}{\partial t}\boldsymbol{m}(\boldsymbol{r}) = -\gamma\,\boldsymbol{m}(\boldsymbol{r})\times\boldsymbol{H}_{eff}$$



$$\boldsymbol{H}_{eff} = \boldsymbol{H}_a + \boldsymbol{K}(\boldsymbol{m}(\boldsymbol{r})) + A\nabla^2\boldsymbol{m}(\boldsymbol{r}) - \boldsymbol{h}_{dip}$$

applied field

anisotropy

exchange

Magnetisation & Exchange Parameters

Basic idea: define magnetisation density

$$\hat{\boldsymbol{M}}(\boldsymbol{r}) = g\,\mu_B \Sigma_j \delta(\boldsymbol{r}-\boldsymbol{r}_j)\hat{\boldsymbol{\sigma}}_j$$

Exchange energy must be compatible with symmetry of local atomic environment:

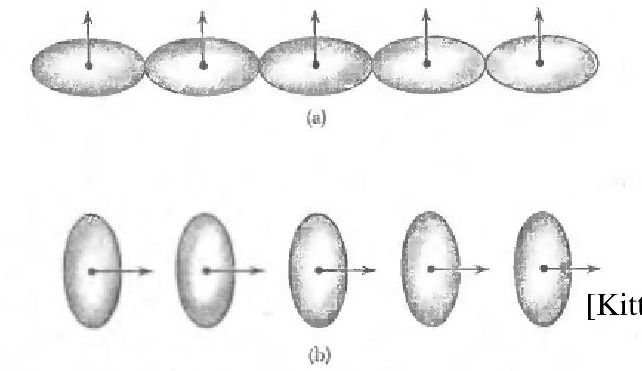
$$E_{ex} = \Sigma_{\alpha k l} C_{kl} \frac{\partial m_\alpha(\boldsymbol{r})}{\partial r_k} \frac{\partial m_\alpha(\boldsymbol{r})}{\partial r_l}$$

Example: **isotropic medium**

$$E_{ex} = A[(\nabla m_x)^2 + (\nabla m_y)^2 + (\nabla m_z)^2]$$

Magnetic Anisotropy Parameter

Local atomic environment affects spin **orientation**:



[Kittel, Introduction to Solid State]

Spin orbit interaction and crystal field effects

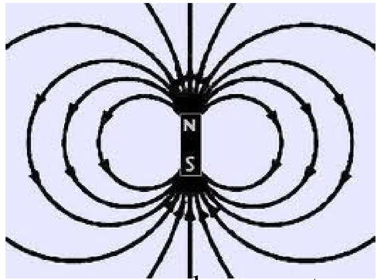
Anisotropy energy and **symmetries**:

- Uniaxial: $E_{ani}(m_z) = E_{ani}(-m_z)$ $\Rightarrow$ $E_{ani} = -K_u^{(1)} m_z^2 - K_u^{(2)} m_z^4 + \ldots$

- Cubic: $E_{ani}(m_x, m_y, m_z) = E_{ani}(-m_x, m_y, m_z)$, etc.

$$\Rightarrow E_{ani} = K_4 (m_x^2 m_y^2 + m_x^2 m_z^2 + m_y^2 m_z^2) + \ldots$$

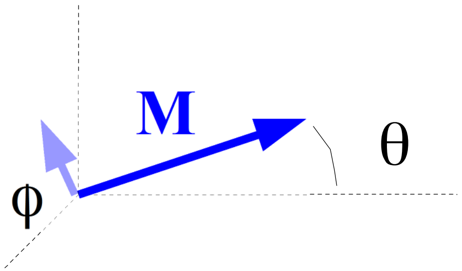
Dipolar Interactions



wondermagnet.com

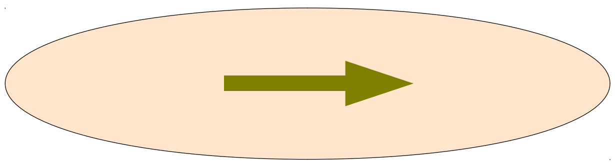
Magnetic moments are **point dipoles**:

$$\boldsymbol{h}_{dip}(\boldsymbol{r}_{ij}) = \frac{1}{2} g^2 \mu_B^2 \sum_{ij} \left(\frac{\boldsymbol{m}(r_i) \cdot \boldsymbol{m}(r_j)}{r_{ij}^3} - 3 \frac{[\boldsymbol{r}_{ij} \cdot \boldsymbol{m}(r_i)][\boldsymbol{r}_{ij} \cdot \boldsymbol{m}(r_j)]}{r_{ij}^5} \right)$$

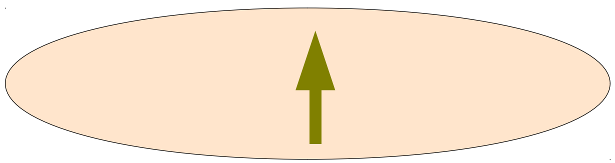


All moments interact **throughout** sample. Sample **shape** contributes to anisotropy. For an ellipsoid:

$$E_{ani} = \frac{M^2 V}{2\mu_o} \left(N_x \sin^2\theta \cos^2\phi + N_y \sin^2\theta \sin^2\phi + N_z \cos^2\theta \right)$$



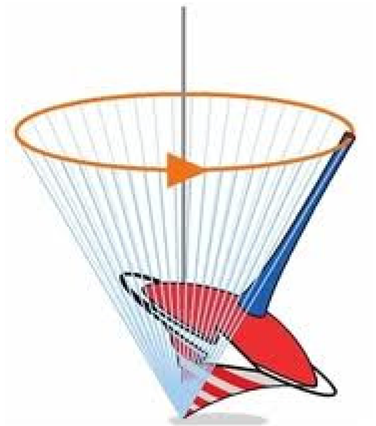
Easy direction



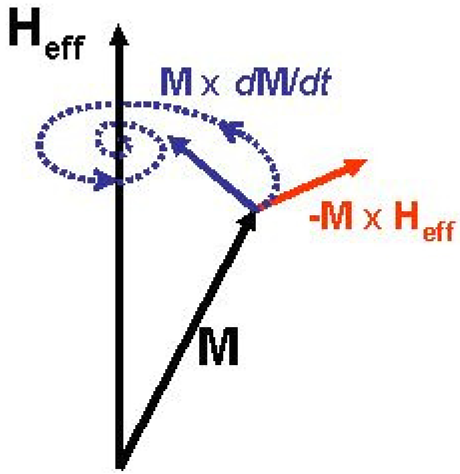
Hard direction

Dissipation

Damping: additional torques



www.medical.siemens.com

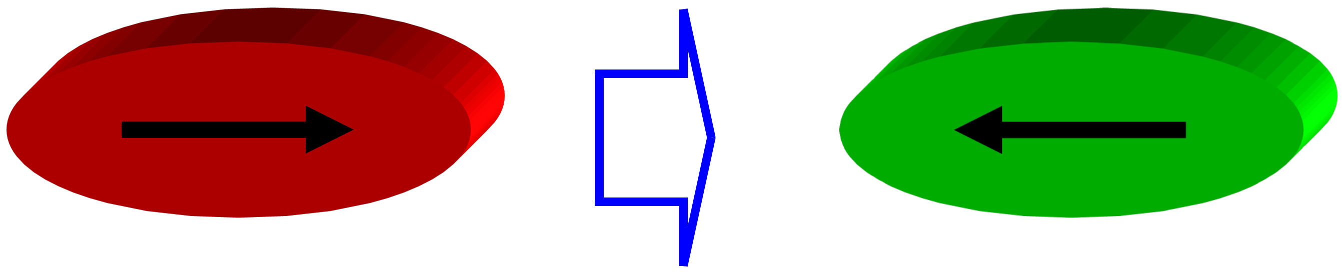


www.ptb.de

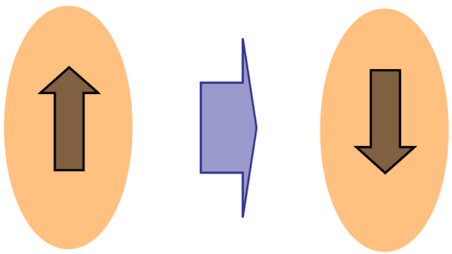
Gilbert damping: Rayleigh dissipation form

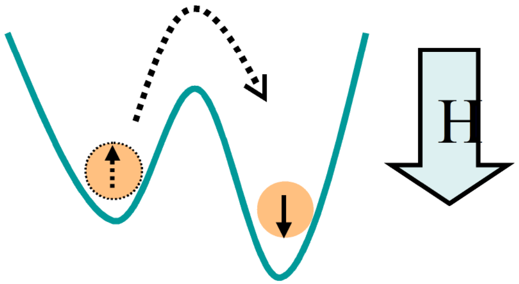
$$\frac{\partial}{\partial t}\boldsymbol{m}(\boldsymbol{r})=\gamma\,\boldsymbol{m}(\boldsymbol{r})\times\boldsymbol{H}_{eff}-\alpha\,\boldsymbol{m}(\boldsymbol{r})\times\frac{\partial\boldsymbol{m}(\boldsymbol{r})}{\partial t}$$

Magnetic Switching

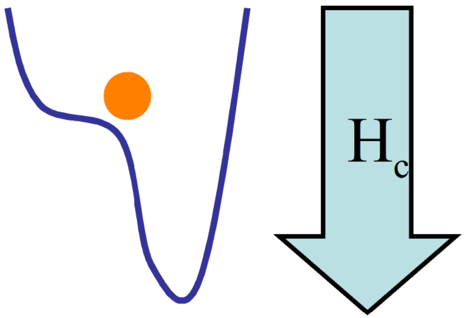


Switching of Single Domain Particles



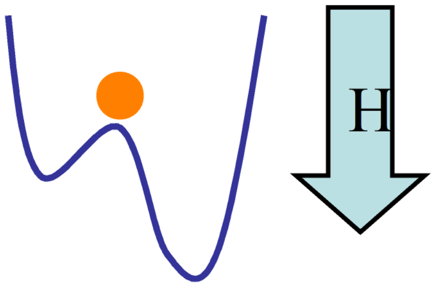


$H \geq H_c$



Dynamics: Precessional reversal

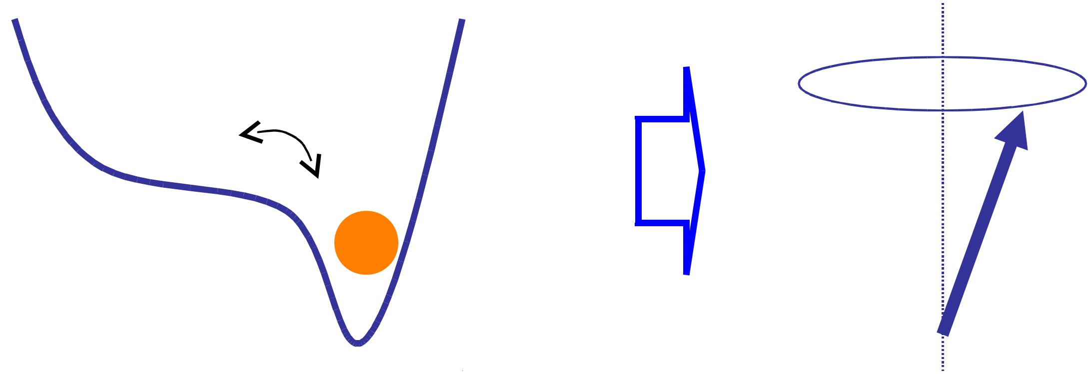
$H < H_c$

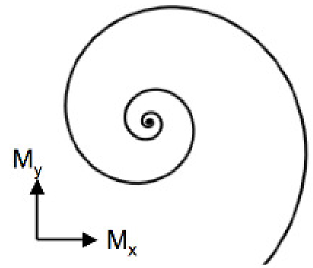


Stability: Thermal activation

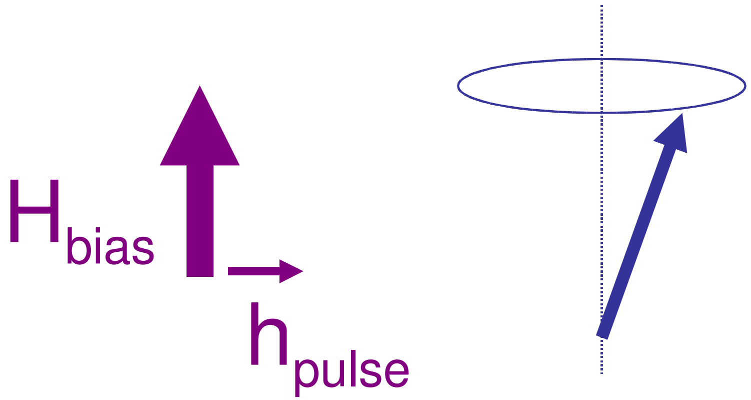
Fast Reversal of Single Particles

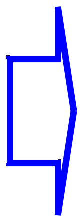
Switching involves **precession + dissipation**:

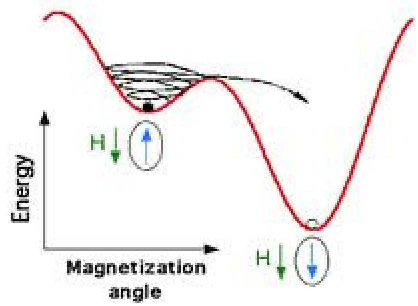




Experiment: Apply pulse, drive reversal





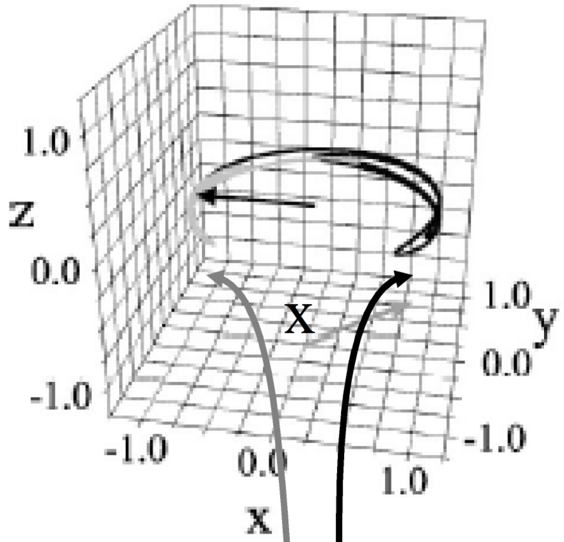


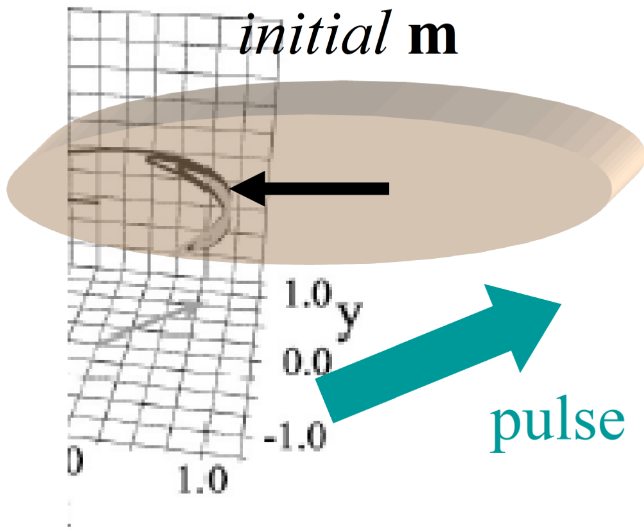
Thirion, et al., Nat. Materials 2003

Bauer, Hillebrands, Stamps, Phys. Rev. B 2000

Reversal: Nonlinearities

Example with pulse: precession with uniaxial e anisotropy first 10 ns

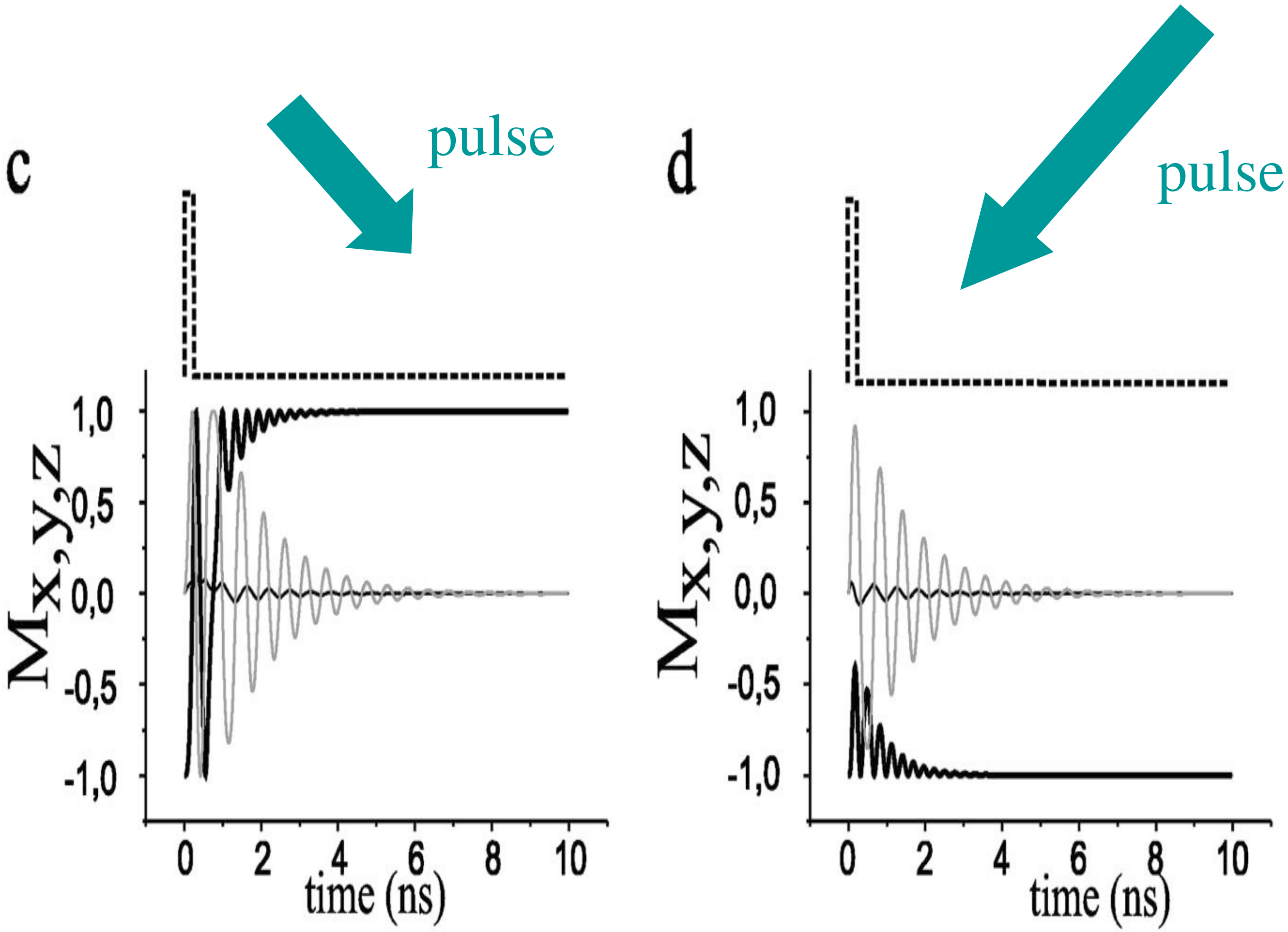




black trajectory = during pulse

gray trajectory = after pulse

Sensitivity To Pulse Orientation



Bauer, Hillebrands, Stamps, Phys. Rev. B 2000

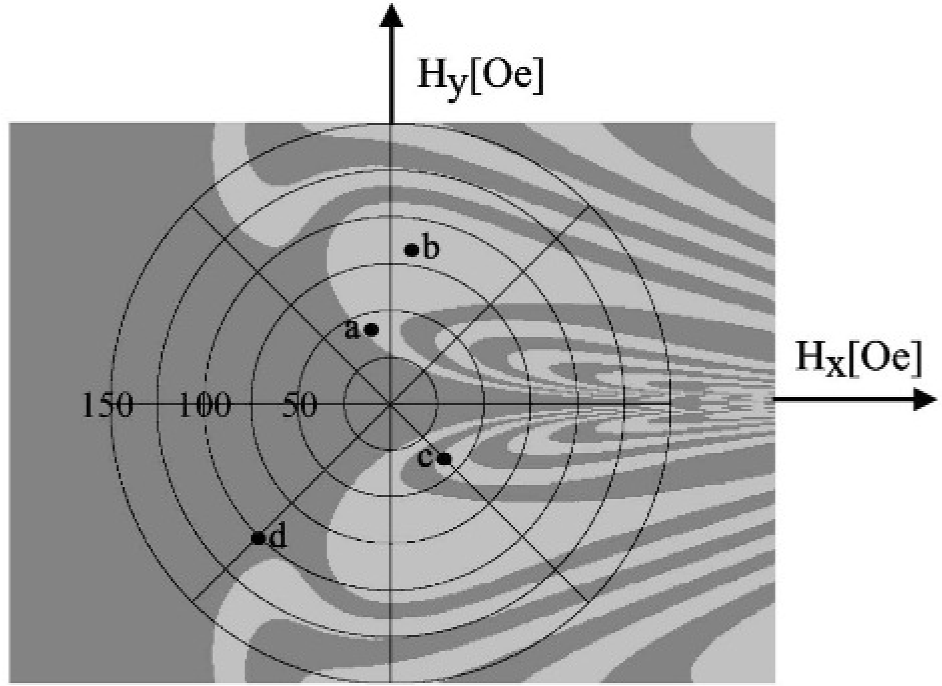
Reversal: Nonlinear Dynamics

Anisotropy creates windows for precessional reversal

- Pulse: 0.25 ns
- Ellipsoidal particle

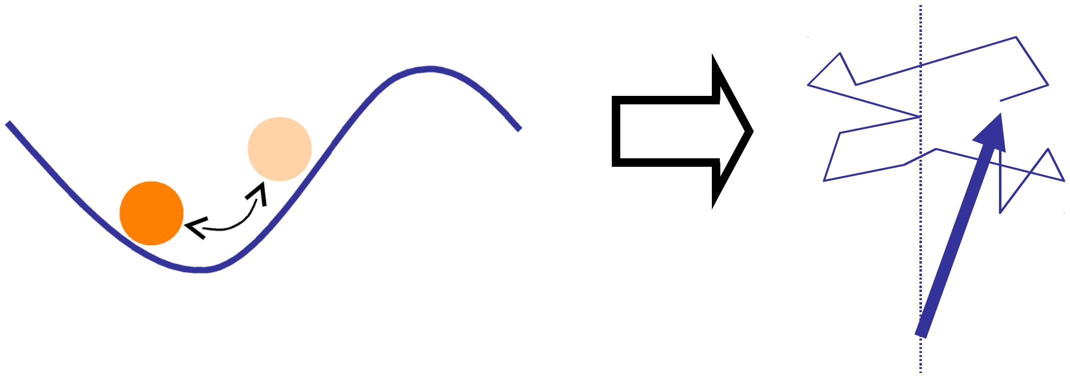
- **Polar plot**: field pulse orientation and strength

- **Bright** = switched
- **Dark**   = not switched



Thermal Activation: $H<H_c$

Climbing to the top: fluctuations



Energy transfer between spin system and heat bath

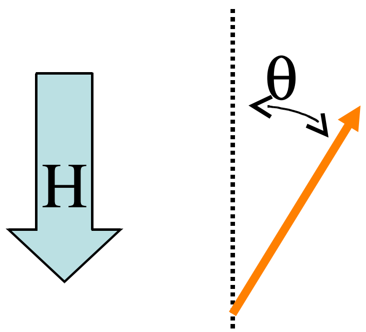
Torque equation of motion: thermal fluctuation 'field'

$$\frac{\partial}{\partial t}\boldsymbol{m}(\boldsymbol{r}) = \gamma\,\boldsymbol{m}(\boldsymbol{r}) \times \boldsymbol{H}_{eff} - \alpha\,\boldsymbol{m}(\boldsymbol{r}) \times \frac{\partial \boldsymbol{m}(\boldsymbol{r})}{\partial t} + \boldsymbol{h}_f$$

random thermal 'driving torque'

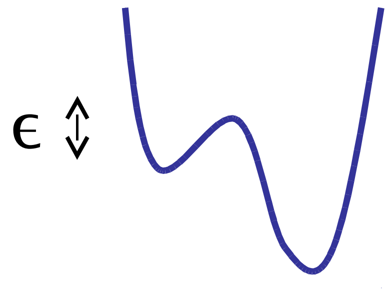
Single Particle Switching: Stoner-Wohlfarth Model

Approximate reversal as pure **relaxation**:



$$E = V\left(-H\,M\cos\theta + K\sin^2\theta\right)$$

$$\epsilon = V\,K + \left[\frac{H\,M}{2K}\right]^2$$

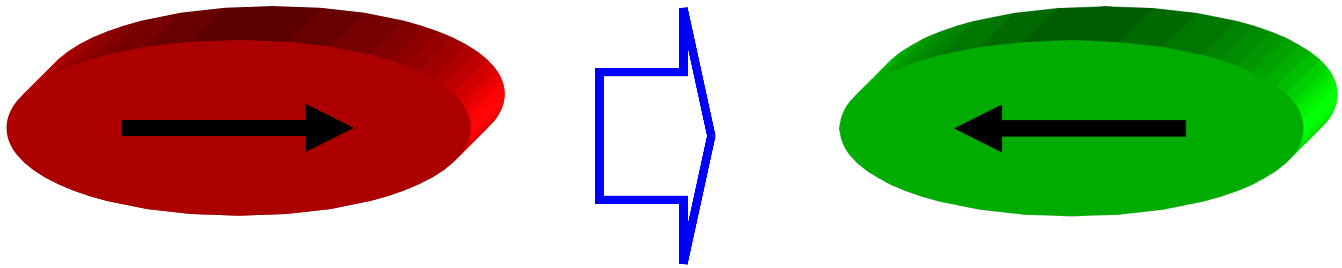


Rate depends on **activation energy** and **attempt frequency**

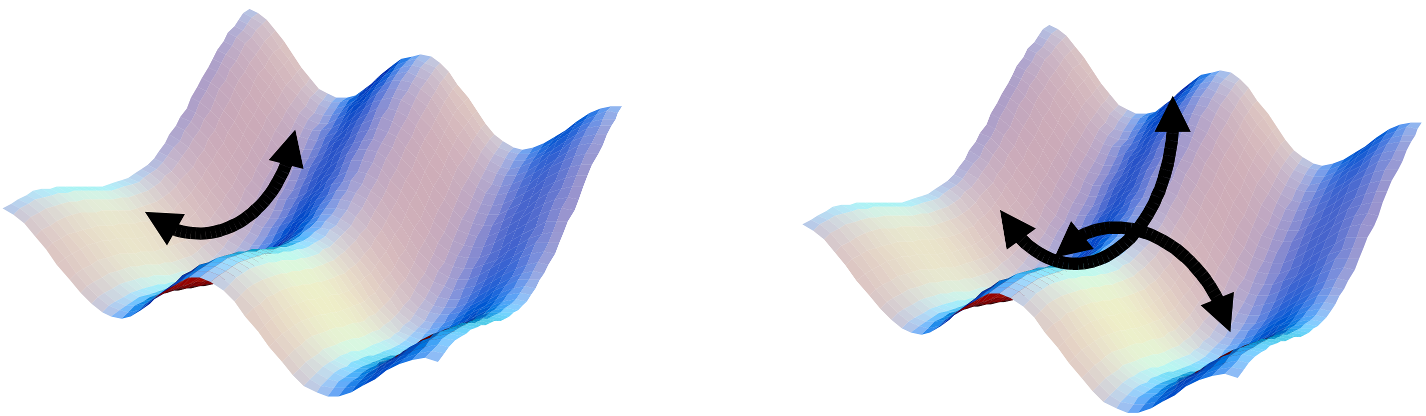
$$\Gamma = \frac{1}{\tau} = f_o \exp\left(-\epsilon / k_B T\right)$$

[Kramers, 1940; Langer, 1969; Büttiker, 1981]

Switching in Elements



Attempt frequency ~ energy landscape **curvatures**

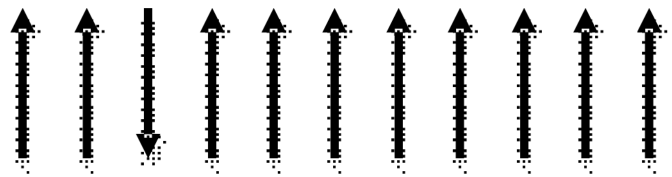


Spin Waves

Fluctuations in Magnetic Density

Energy to reverse one spin in chain: *2 J*

$$H = \sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$



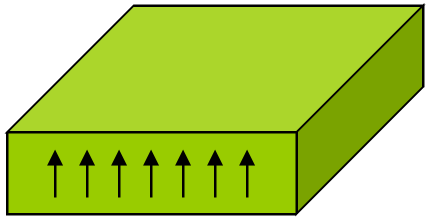
Superposition of ways to flip one spin:

$$|n=1\rangle \;=\; |\uparrow\downarrow\uparrow\uparrow\uparrow\rangle + |\uparrow\uparrow\downarrow\uparrow\uparrow\rangle + |\uparrow\uparrow\uparrow\downarrow\uparrow\rangle + \ldots$$

Spin wave excitation (boson)

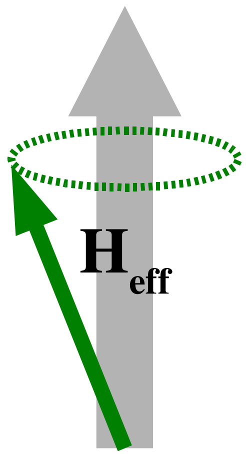
Classical Picture: Correlated Precession

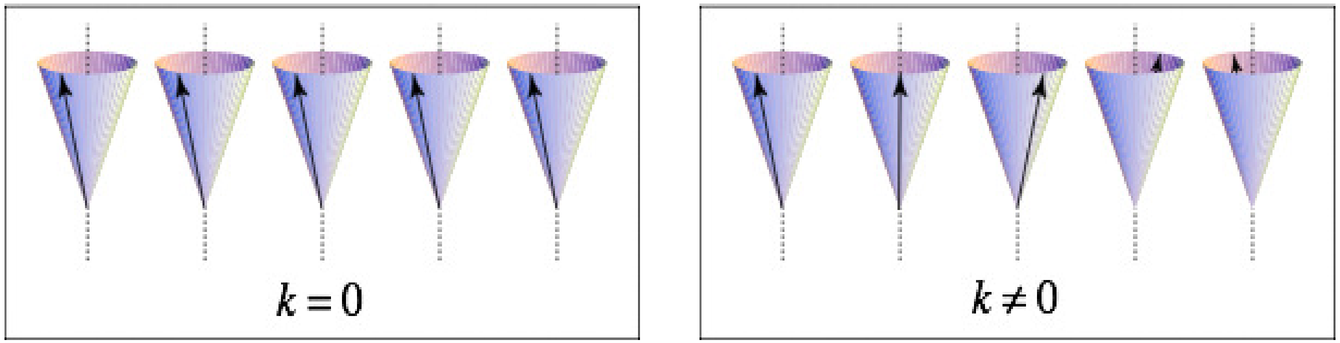
Ground state magnetic orderings:



1) Magnetic moments
2) Exchange coupling

Excitations: Precession dynamics





slide courtesy J-V Kim

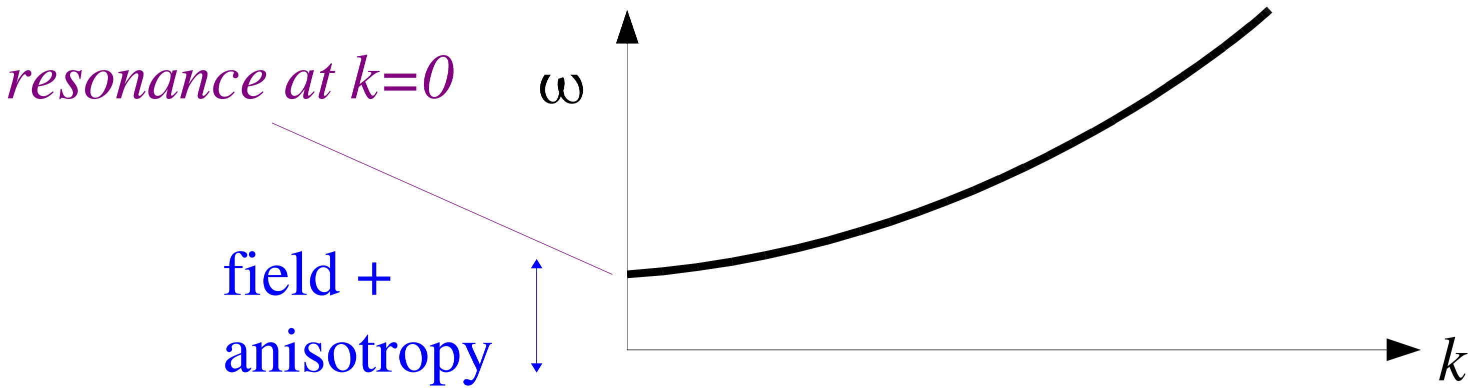
Dispersion: Spinwaves

Contribution from **exchange**:

$$(m_x, m_y) \sim \exp\left(-i\left(\omega t - \boldsymbol{k}\cdot\boldsymbol{r}\right)\right)$$

$$\boldsymbol{H}_{ex} \sim A\nabla^2 \boldsymbol{m}(\boldsymbol{r}) \quad \Rightarrow \quad \boldsymbol{H}_{ex} \sim -Ak^2 \boldsymbol{m}(\boldsymbol{r})$$

$$\boxed{\frac{\omega^2}{\gamma^2} = (H_a + Ak^2)(H_a - 2KM_s + Ak^2)}$$



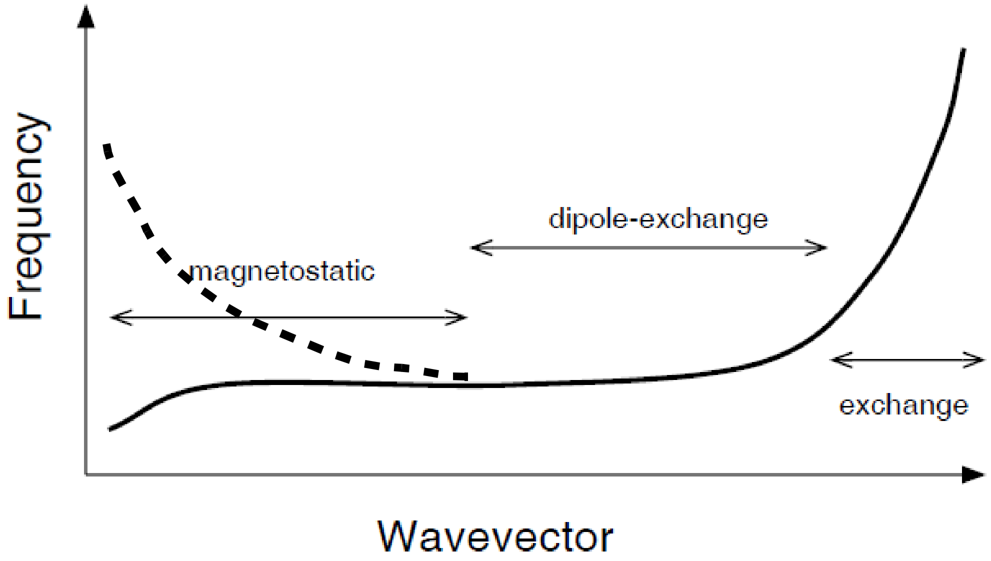
Dispersion: Dipole Exchange Modes

Dipolar: long range nonlocal term

$$\boldsymbol{h}_{dip}(\boldsymbol{r})=\int \boldsymbol{g}(\boldsymbol{r}-\boldsymbol{r}')\boldsymbol{m}(\boldsymbol{r}')\,d\boldsymbol{r}'$$

Shape anisotropies: create effective K terms

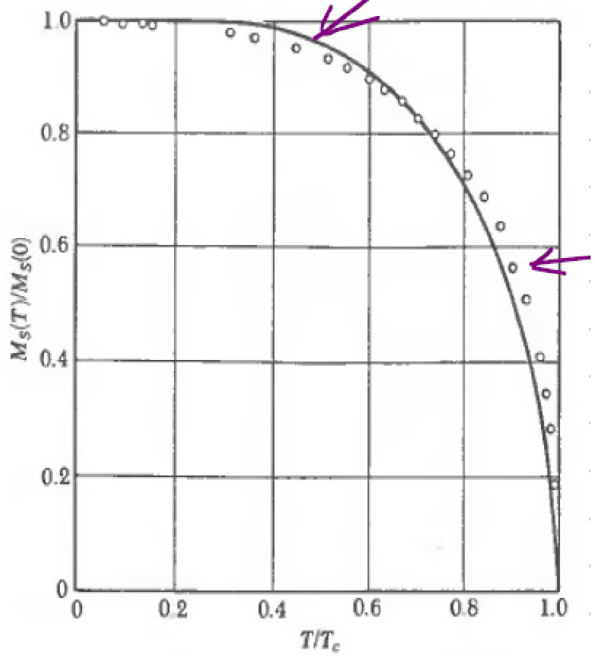
Dynamics: **compete with exchange** at long wavelengths



Thermal Reduction of Magnetisation

$$M_s(0) - M_s(T) \sim \sum_k \langle n_k \rangle \sim T^{3/2}$$

Linear spin waves



Large amplitude fluctuations

[Weiss & Forrer]

Summary II

'Macroscopic' models of magnetic configurations & dynamics

Effective fields: magnetic parameters

Reversal processes: Thermal activation and precession

Spin waves: Fluctuations of magnetisation density

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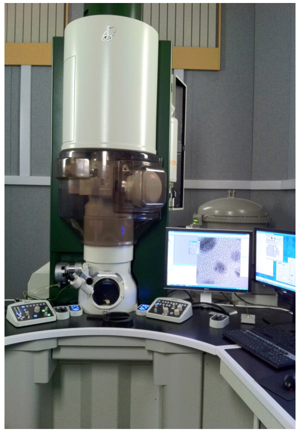
The End

Kelvin Nano-characterisation Centre JEOL Atomic Reolution Microscope



Standard mode: < **100 pm**
Lorentz mode: < **2 nm**
Individual grain Lorentz imaging!

Resolve details of vortex structure:
Field of view: 1 micron (top), 100 nm (bottom)