NYU

Spins Dynamics in Nanomagnets

Andrew D. Kent

Department of Physics, New York University

Lecture 1

Outline

I. Magnetic Interactions

- *–Exchange, Anisotropy and Dipolar Interactions*
- *–Zeeman Interaction*

II. Micromagnetic Energy

- *–Energy, Field and Length Scales*
- *–Examples of Magnetic Domain Structure*

III. Magnetic Nanostructures

- *–Single Domain Model*
- *–Experiments on Individual (classical) Nanomagnets*
- *–Thermal Activation and Quantum Tunneling of Magnetization*

IV. Classical Magnetization Dynamics

- *–Landau-Lifshitz-Gilbert Equation*

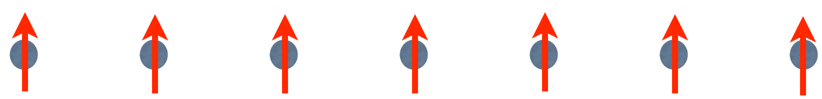
References

Magnetic Interactions

- Exchange
  - Coulomb Interactions + Pauli Exclusion Principle

locks spins together

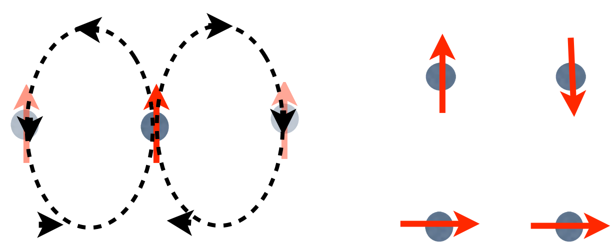
- Magnetocrystalline Anisotropy
  - Spin-orbit interactions



preferred direction in space

- Magnetic Dipole Interactions
  - Magnetic field associated with a magnetic moment

non-local



Magnetic Interactions

Microscopic | Continuum

- Exchange

$$H_{\text{exc}} = J \sum_{<ij>} \vec{S}_i \cdot \vec{S}_j \qquad E_{\text{exc}} = A\left(|\nabla m_x|^2 + |\nabla m_y|^2 + |\nabla m_z|^2\right)$$

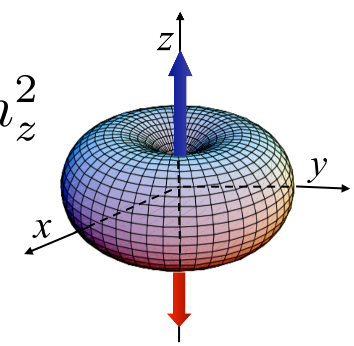
$J < 0$ Ferromagnetic interactions

$$A = -JS^2 c/a$$

$A \simeq kT_c/a$ a=lattice constant
c(lattice): c=1(sc), 2(bcc),4 (fcc)

- Anisotropy

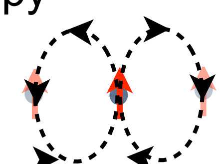
$$H_{\text{anis}} = -d \sum_i S_{iz}^2 \qquad E_{\text{anis}} = -K m_z^2$$



$d > 0$ Easy axis anisotropy

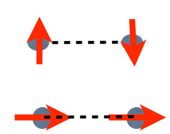
$d < 0$ Easy plane type anisotropy

- Dipolar Interactions



$$H_{ij} = \frac{\mu_0}{4\pi r^3}\left(3(\vec{m}_i \cdot \hat{r}_{ij})(\vec{m}_j \cdot \hat{r}_{ij}) - \vec{m}_i \cdot \vec{m}_j\right)$$

$$\vec{m} = \gamma \vec{S} \qquad \gamma = g\mu_B/\hbar$$



Magnetostatic Energy

$$\vec{H}_d = -\tilde{D}\vec{m}$$

sample

$$E_{\text{ms}} = -\frac{\mu_0}{2} M_s \vec{m} \cdot \vec{H}_d$$

all space

$$E_{\text{ms}} = \frac{\mu_0}{2} H_d^2$$

Magnetic Interactions

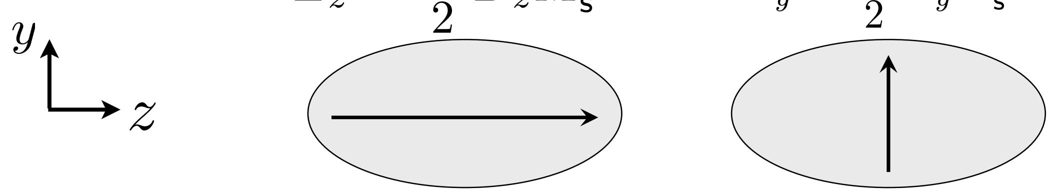
- Zeeman Energy

$$H_{\mathrm{z}} = g\mu_B \sum_i \vec{S}_i \cdot \vec{H}_e \qquad\qquad E = -\mu_0 \vec{M} \cdot \vec{H}_e$$

Magnetostatic Energy

May sometimes be approximated by a *local* contribution to the energy

$$E_z = \frac{\mu_0}{2} D_z M_{\mathrm{s}}^2 \qquad\qquad E_y = \frac{\mu_0}{2} D_y M_{\mathrm{s}}^2$$



$$E_{\mathrm{ms}} = \frac{\mu_0}{2}(D_z - D_y) M_{\mathrm{s}}^2 m_z^2$$

Thin film

$$D_z = 1,\ D_x = D_y = 0$$

Infinite Cylinder

$$D_z = 0,\ D_x = D_y = 1/2$$

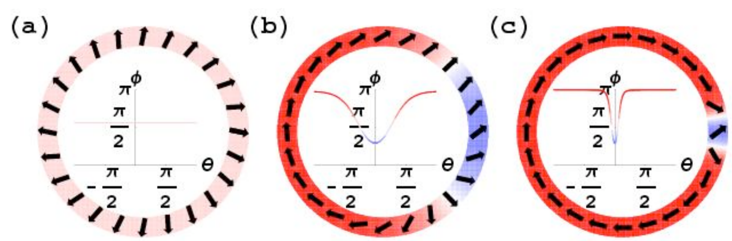
Sphere

$$D_x = D_y = D_z = 1/3$$

<u>Examples</u>:

1) single domain particles
2) thin films with in-plane magnetization

Analytic solutions for the micromagnetic energy, saddle states, rate of thermally activated reversal, etc. are then possible.



Martens, Stein, ADK, PRB 2006
Chaves, ADK, Stein, PRB 2009

Micromagnetic Energy

$$E[\mathbf{m}(\mathbf{r})] = A\int_{\Omega} |\nabla \mathbf{m}|^2 \, d^3r - K\int_{\Omega} m_z^2 \, d^3r - \mu_0 M_s \int_{\Omega} \mathbf{H}_{\mathrm{e}} \cdot \mathbf{m} \, d^3r + \frac{\mu_0}{2}\int_{\mathbf{R}^3} |\nabla U|^2 \, d^3r$$

Exchange Anisotropy Zeeman Magnetostatic

$\Omega \equiv$ ferromagnet

$$E[\mathbf{m}(\mathbf{r})] = \frac{\mu_0 l_{\text{ex}}^2}{2}\int_{\Omega} |\nabla \mathbf{m}|^2 \, d^3r - K\int_{\Omega} m_z^2 \, d^3r - \mu_0 M_s \int_{\Omega} \mathbf{H}_{\mathrm{e}} \cdot \mathbf{m} \, d^3r + \frac{\mu_0}{2}\int_{\mathbf{R}^3} |\nabla U|^2 \, d^3r$$

Exchange length $l_{\text{ex}} = \sqrt{2A/(\mu_0 M_s^2)}$

Domain wall width $\lambda = \sqrt{2A/K}$

Anisotropy/Magnetostatic $Q = \dfrac{2K}{\mu_0 M_s^2}$

$$|\nabla \mathbf{m}|^2 \equiv |\nabla m_x|^2 + |\nabla m_y|^2 + |\nabla m_z|^2$$

Magnetostatic Potential

$$\mathbf{H} = -\nabla U$$

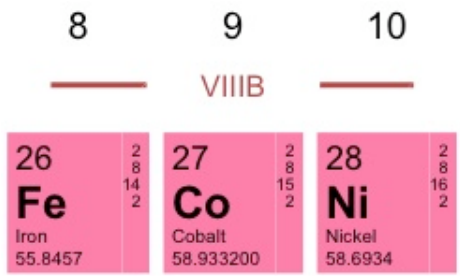
$$\nabla^2 U = \nabla \cdot \mathbf{M}$$

+ boundary conditions

$$U_{\text{in}} = U_{\text{out}} \qquad \frac{\partial U_{\text{in}}}{\partial n} - \frac{\partial U_{\text{out}}}{\partial n} = \mathbf{M} \cdot \hat{n}$$

Energy, Field and Length Scales

Elemental transition metal ferromagnets



[Ar].$3d^6.4s^2$.$3d^7.4s^2$.$3d^8.4s^2$

Partially filled 3d shell

- Exchange ~1000 K, 100 T
  Curie Temperature
- Anisotropy ~10 K, 0.01 to 10 T
- Dipolar Interactions ~1 K, mT

Exchange length $l_{\text{ex}} = \sqrt{2A/(\mu_0 M_s^2)}$ ~ 4 nm

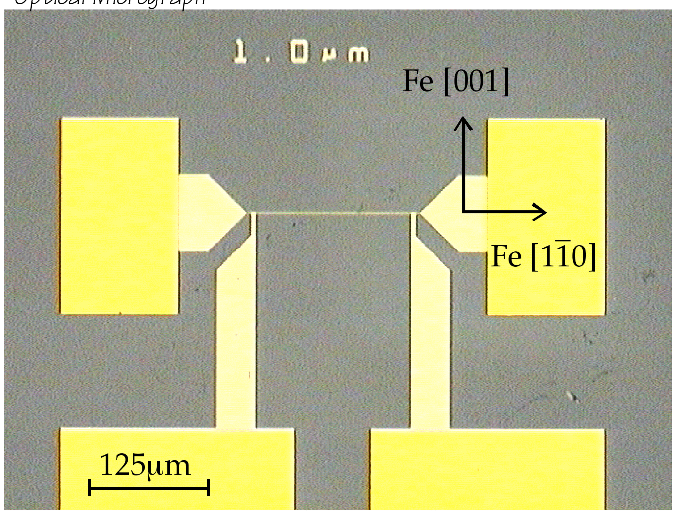
Domain wall width $\lambda = \sqrt{2A/K}$ ~ 5 to 100 nm

Examples

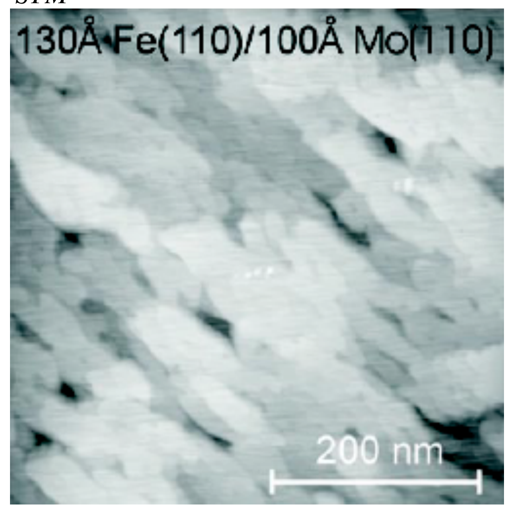
- Competing interactions lead to the formation of magnetic domains: exchange, anisotropy and magnetostatic

(110) Fe Thin Films

Optical Micrograph



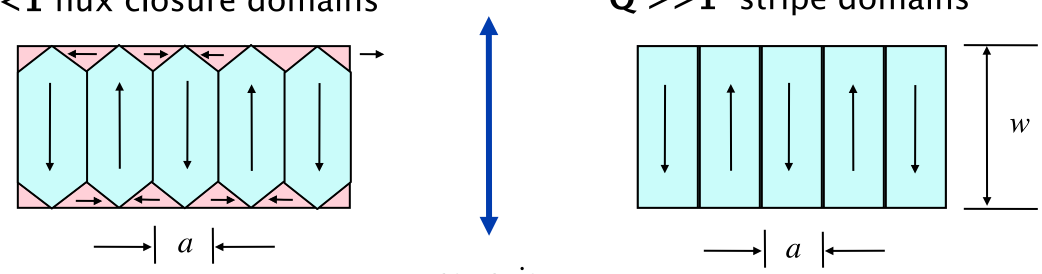
STM



$$Q = \frac{2K}{\mu_0 M_s^2}$$

Q <<1 flux closure domains

Q >>1 stripe domains



easy axis

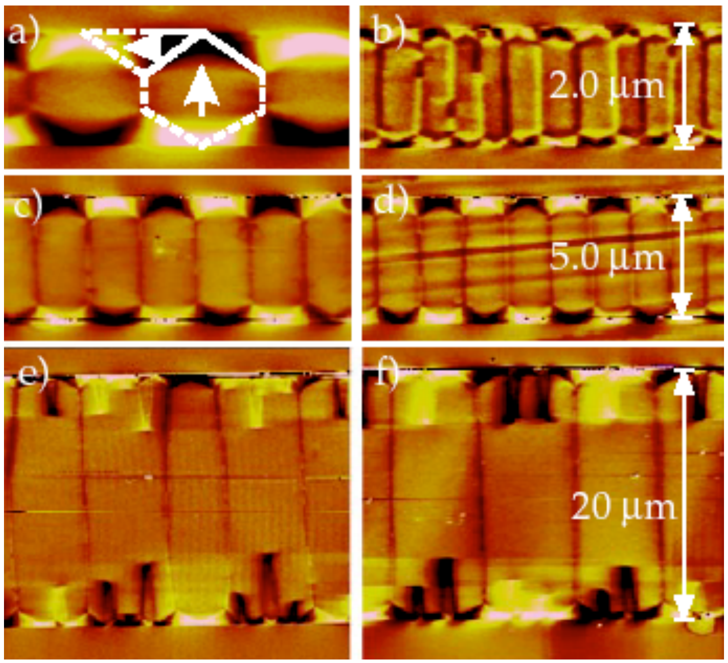
film thickness t

Examples

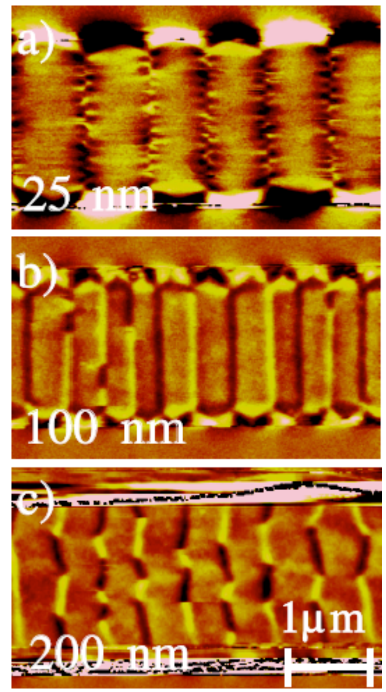
•Domain configurations as function of:
- Linewidth
- Magnetic history

H=0

After transverse saturation *After longitudinal saturation*



Domain wall structure vs film thickness



Neel-cross-tie walls

(Asymmetric) Bloch walls

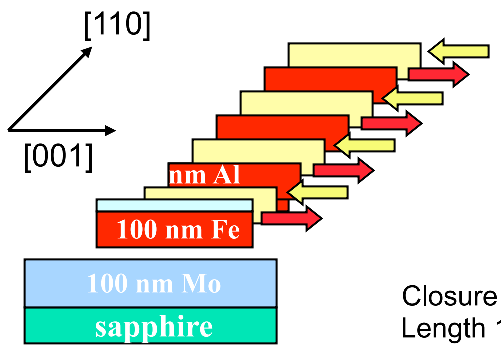
Canted Bloch walls

ADK, et al., J. Phys.: condens. Matter 13 (2001), R461-R488

Examples

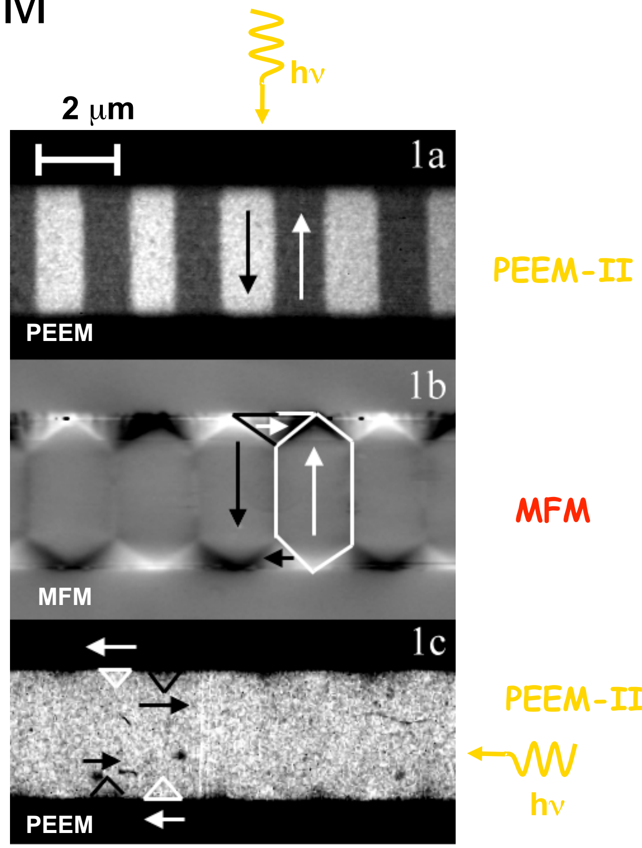
Photoelectron emission microscopy--PEEM

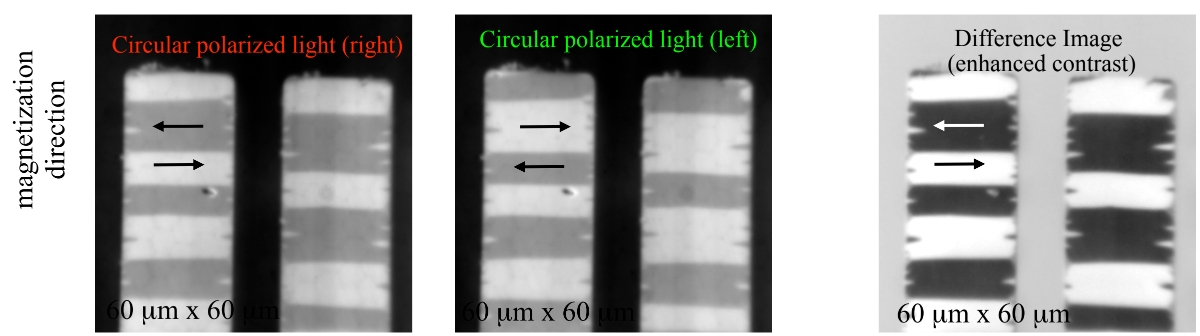
Fe(110) Wire on Mo (110)/[Al_2O_3]



Closure Domain
Length 1500 nm

Observed: 800 nm





Ni/Co (111) Single Crystalline Superlattices

Magneto-optical images

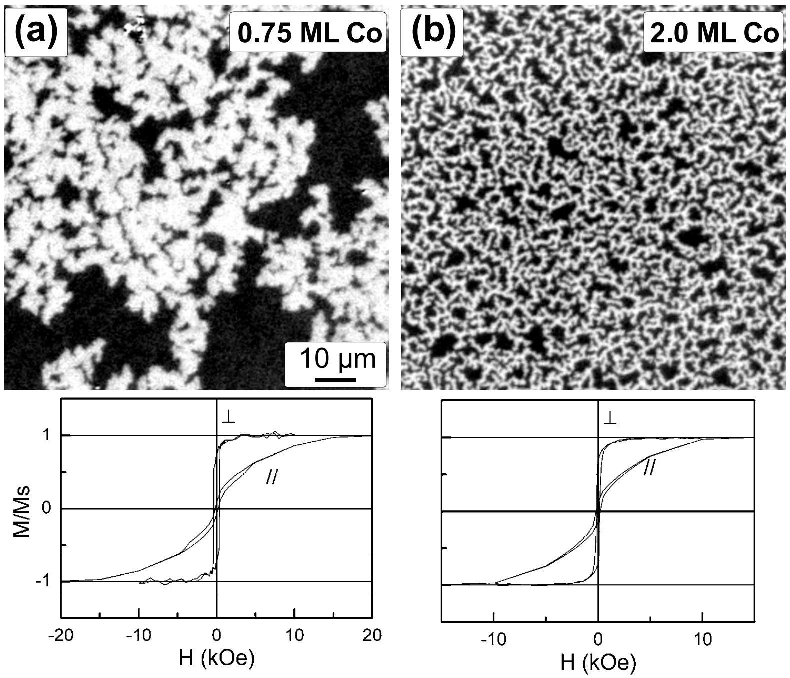
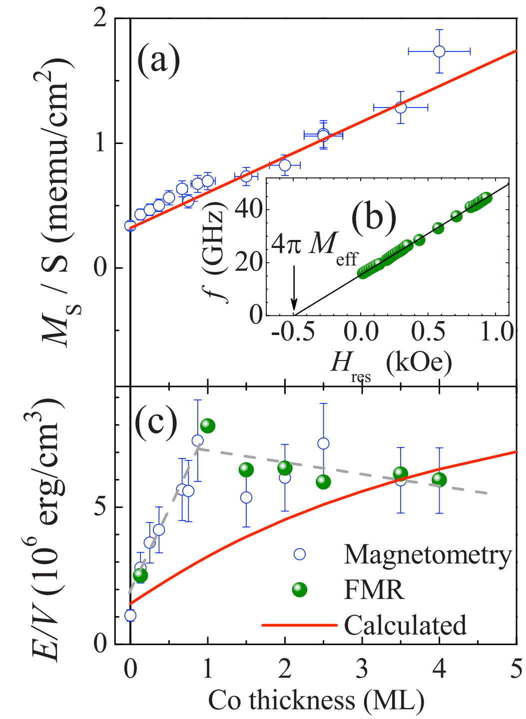


FIG. 2. (top) Kerr images obtained during magnetization reversal close to the coercive field for a (a) SL with Co coverage equal to 0.75 ML and (b) for a SL with Co coverage equal to 2 ML. (bottom) Corresponding hysteresis loops measured by SQUID on these samples.



sapphire substrate/bcc V (110)/fcc Au (111)-10/fcc (111)×$\{Ni_3/Co_x\}_{10}$/Au

FIG. 3. (Color online) Data for a series of SLs with 3 ML of Ni, Co coverage varying from 0 to 4 ML, repeated ten times. (a) Saturation magnetization per unit surface area versus Co layer thickness from magnetometry (open circles) compared to the calculated value assuming magnetization value of the bulk Co and Ni–(solid line) (b) Frequency dependence of the resonance field for the multilayer film with 2.5 ML Co. The *x*-intercept gives the perpendicular anisotropy constant. (c) Energy density (Perpendicular magnetocrystalline anisotropy constant and demagnetization energy density) vs Co layer thickness. The anisotropy constant is deduced from magnetometry (open circles) and FMR measurements (full circles). The dash lines are guide to the eyes. The demagnetization energy density (full line) is calculated assuming magnetization value of the bulk Co and Ni.

S. Girod et al. APL 2009

Magnetic Nanostructures

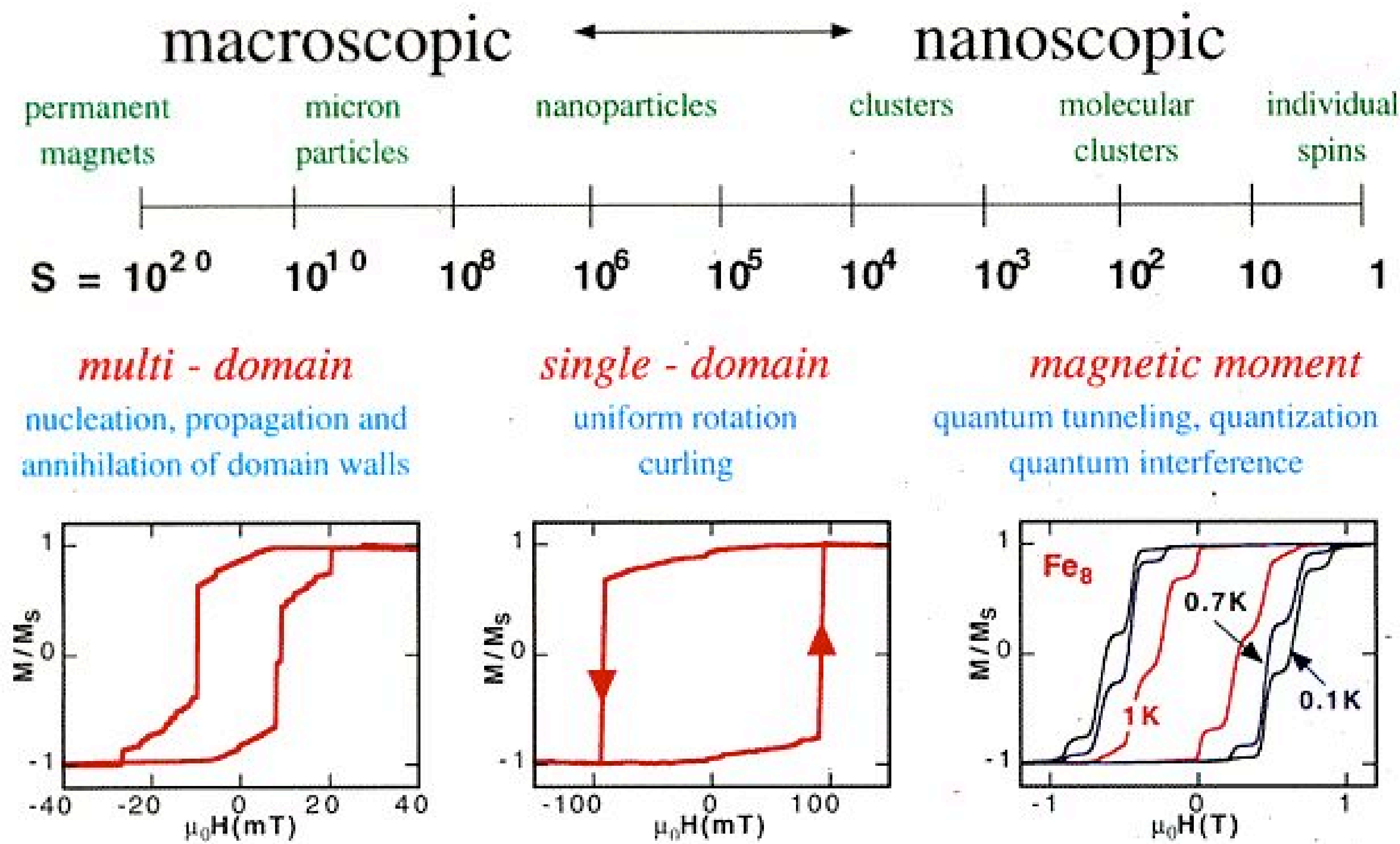
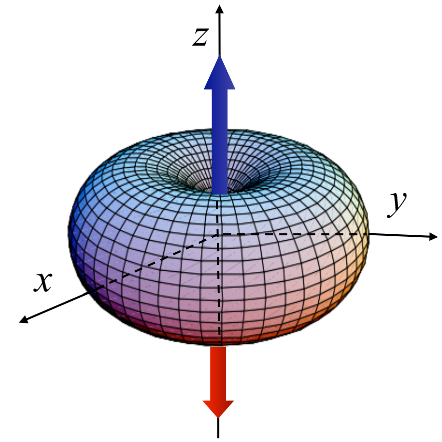


Image from, W. Wernsdorfer, Advances in Chemical Physics 2001 and ArXiv:0101104

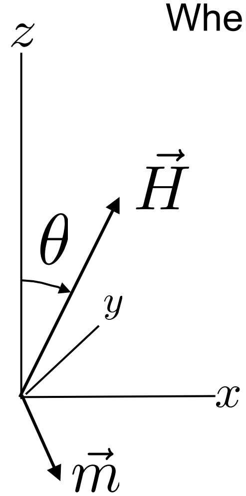
Single Domain Model

Uniform M--no exchange energy

$$E = -Km_z^2 - \mu_0 M_s \vec{m} \cdot \vec{H}$$



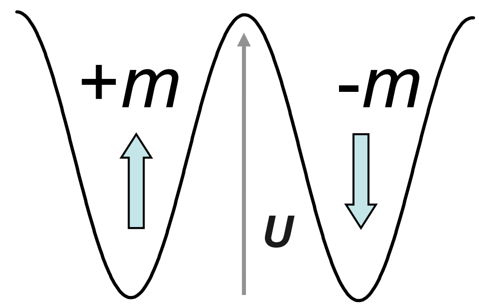
When does the metastable state become unstable?

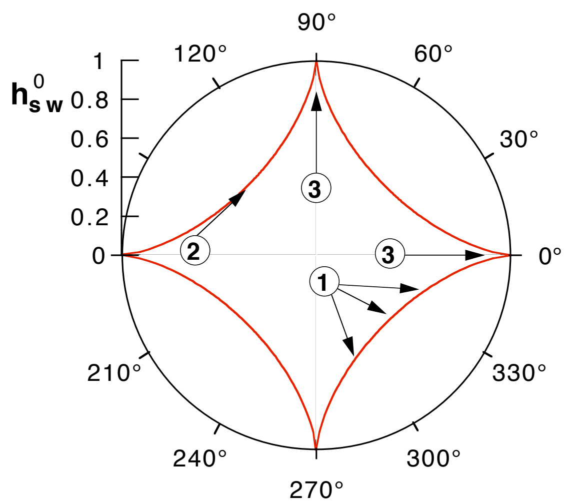


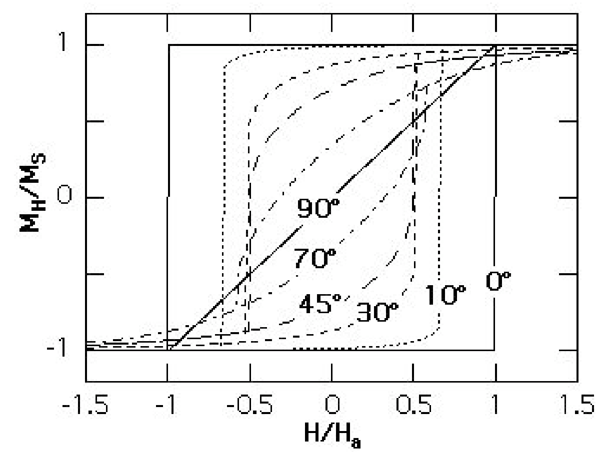
$$h_{\mathrm{sw}}^0 = \frac{H_{\mathrm{sw}}^0}{H_{\mathrm{a}}} = \frac{1}{\left(\sin^{2/3}\theta + \cos^{2/3}\theta\right)^{3/2}}$$

$$H_{\mathrm{a}} = 2K/(\mu_0 M_{\mathrm{S}})$$

$$h_x^{2/3} + h_y^{2/3} = 1$$







also known as the Macrospin or Stoner-Wohlfarth Model

Single Domain Model

Experimental study of an individual Co nanoparticle

Wernsdorfer, et al. 1996

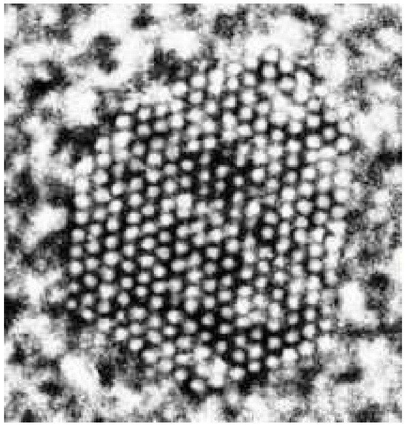


Fig. 2.4 High Resolution Transmission Electron Microscopy observation along a [110] direction of a 3 nm cobalt cluster exhibiting a $f.c.c$–structure.

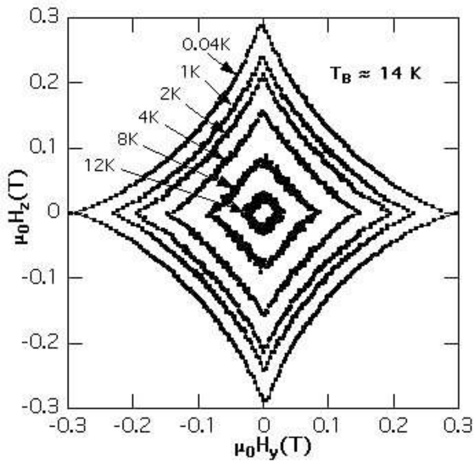


Fig. 3.3 Temperature dependence of the switching field of a 3 nm Co cluster, measured in the plane defined by the easy and medium hard axes ($H_y - H_z$ plane in Fig. 2.6). The data were recorded using the blind mode method (Sect. 1.2.6) with a waiting time of the applied field of $\Delta t = 0.1$s. The scattering of the data is due to stochastic and in good agreement with Eq. 3.10.

Prob, of not switching in a time t:

$$P(t) = e^{-t/\tau}$$

$$\tau = \tau_0 \exp(U/k_B T)$$

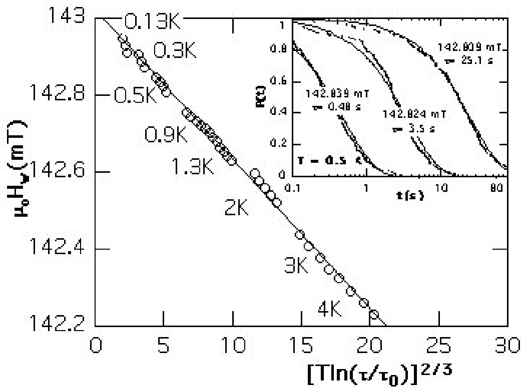


Fig. 3.2 Scaling plot of the mean switching time $\tau(H_w, T)$ for several waiting fields H_w and temperatures (0.1 s $< \tau(H_w, T) <$ 60 s) for a Co nanoparticle. The scaling yields $\tau_0 \approx 3 \times 10^{-9}$s. *Inset:* examples of the probability of not-switching of magnetization as a function of time for different applied fields and at 0.5 K. *Full lines* are data fits with an exponential function: $P(t) = e^{-t/\tau}$

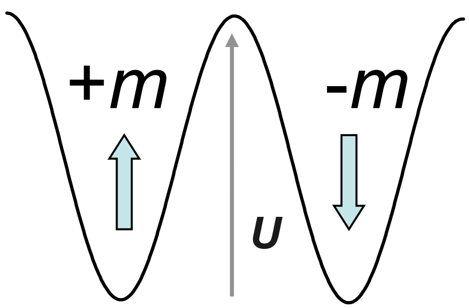
Thermal Activation and Quantum Tunneling

VOLUME 60 22 FEBRUARY 1988 NUMBER 8

Quantum Tunneling of Magnetization in Small Ferromagnetic Particles

E. M. Chudnovsky and L. Gunther
Department of Physics and Astronomy, Tufts University, Medford, Massachusetts 02155
(Received 29 October 1987)

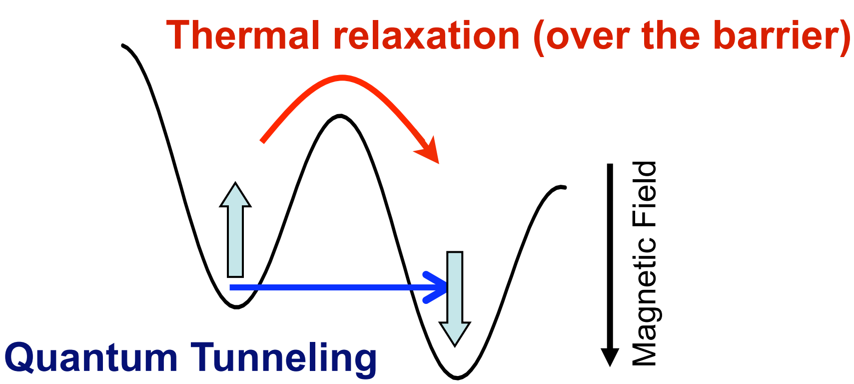
The probability of tunneling of the magnetization in a single-domain particle through an energy barrier between easy directions is calculated for several forms of magnetic anisotropy. Estimated tunneling rates prove to be large enough for observation of the effect with the use of existing experimental techniques.

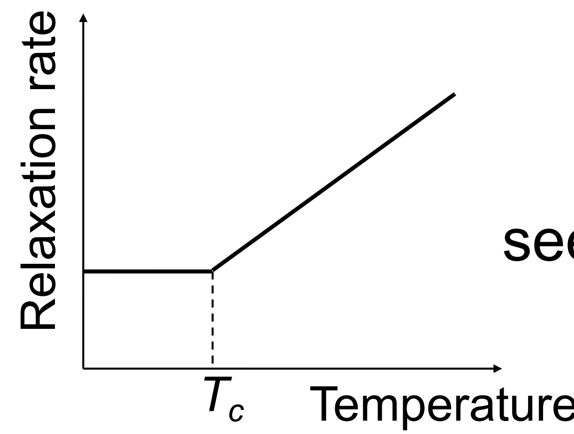


Thermal $\Gamma \sim e^{-U/k_B T}$

Quantum $\Gamma \sim e^{-B(0)} = e^{-U/k_B T_C}$

$$T_c = U/k_B B(0)$$





see lecture 3

also, Enz and Schilling, van Hemmen and Suto (1986)

Classical Magnetization Dynamics

Effective Field $\mu_o \mathbf{H}_{\text{eff}} = -\delta E / \delta \mathbf{M}$

Single Domain Model

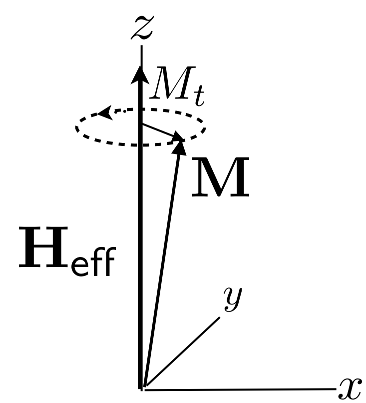
$$E = -K m_z^2 - \mu_0 M_s \vec{m} \cdot \vec{H}$$

$$\vec{H}_{\mathsf{eff}} = \vec{H} + \frac{2K}{M_s} m_z$$

$$\frac{d\vec{L}}{dt} = \text{Torque} = \mu_0 \vec{M} \times \vec{H}_{\mathsf{eff}}$$

$$\vec{M} = -\gamma \vec{L} \qquad \gamma = \left|\frac{g\mu_B}{\hbar}\right| = \frac{g|e|}{2m}$$

$$\frac{d\vec{M}}{dt} = -\gamma \mu_o \vec{M} \times \vec{H}_{\text{eff}}$$



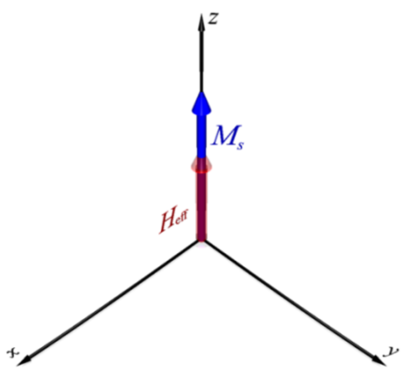
Magnetization Dynamics

Landau Lifshitz Gilbert Equation

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma\mu_o \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s}\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}$$

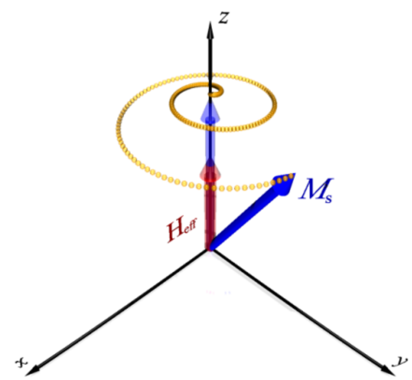
Gyroscopic term	Damping term	Resonance

AT EQUILIBRIUM



$\mathbf{M}$ is aligned with the effective field.

DISTURBED FROM EQUILIBRIUM

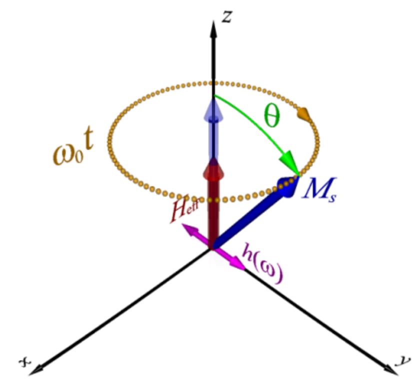


- $\mathbf{M}$ precesses about H_{eff} at the Larmor frequency:

$$\boxed{\omega_0 = \gamma H_{\text{eff}}}$$

- Decrease of the angle of precession due to damping.

DRIVEN PRECESSIONAL MOTION

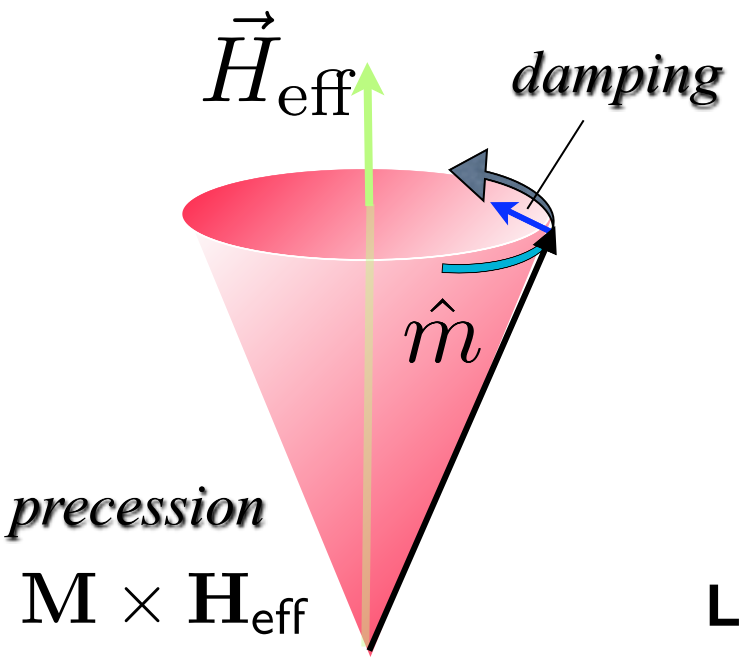


- Maintain the precessional motion with rf field (ω):
- When $\omega=\omega_0$ → θ is max.

FERROMAGNETIC RESONANCE

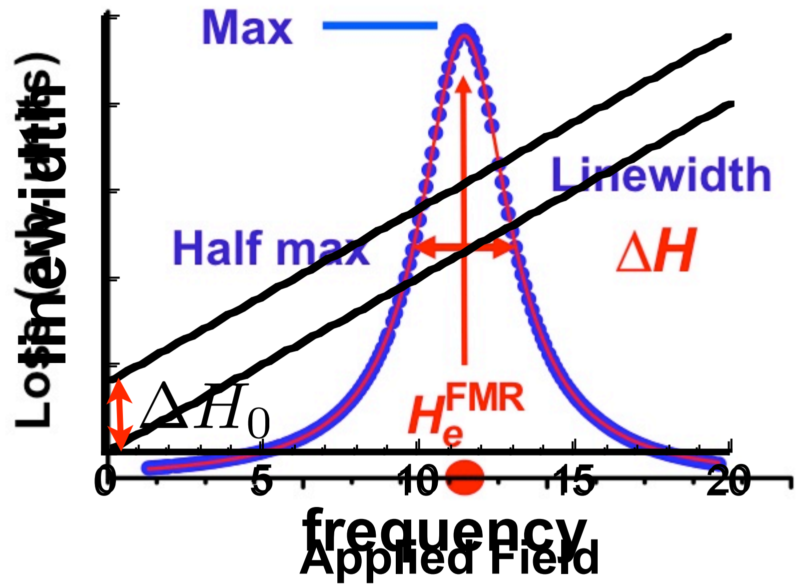
FMR: Landau-Lifshitz-Gilbert Dynamics

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma\mu_o \mathbf{M}\times\mathbf{H}_{\mathrm{eff}} + \frac{\alpha}{M_s}\mathbf{M}\times\frac{\partial \mathbf{M}}{\partial t}$$



$\gamma/2\pi = 28$ GHz/T

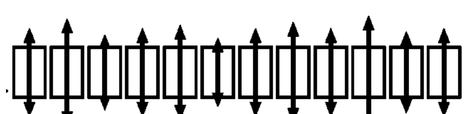
FMR: fixed frequency rf field $\perp$ $\mathbf{H}$



Linewidth: Homogeneous or intrinsic linewidth

$$\boxed{\Delta H = 4\pi\alpha f/(\mu_0\gamma)}$$

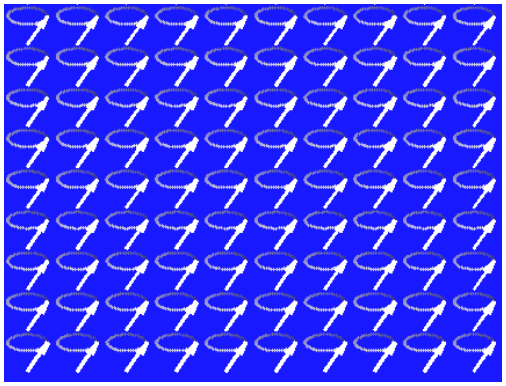
with inhomogeneous broadening



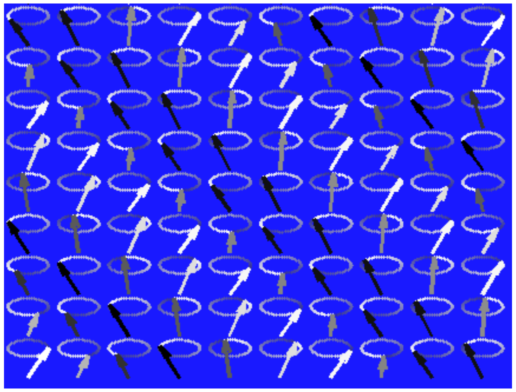
$$\Delta H_{inh.}^{\Delta K_1} = \left|\frac{dH_{res}}{dK_1}\right|\Delta K_1$$

$$\boxed{\Delta H = \Delta H_0 + \frac{4\pi\alpha}{\mu_0\gamma}f}$$

Spin Waves

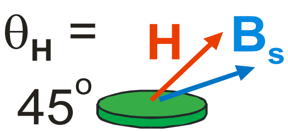


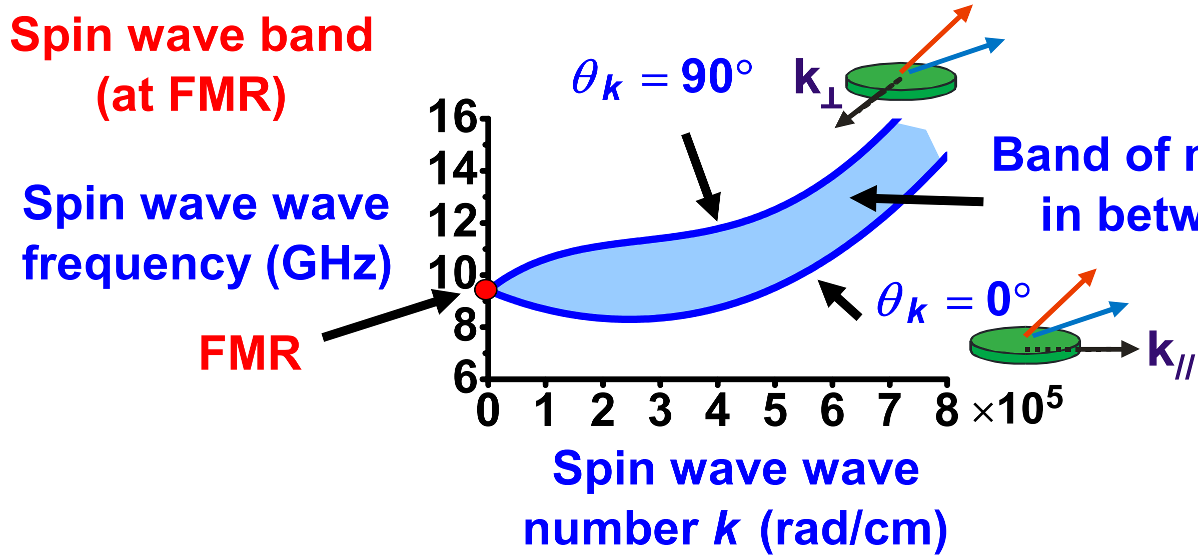
Uniform Precession



Finite k spin waves

Example: $\theta_H = 45°$ **situation**





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Summary of Topics Covered

I. Magnetic Interactions

- *–Exchange, Anisotropy and Dipolar Interactions*
- *–Zeeman Interaction*

II. Micromagnetic Energy

- *–Energy, Field and Length Scales*
- *–Examples of Magnetic Domain Structure*

III. Magnetic Nanostructures

- *–Single Domain Model*
- *–Experiments on Individual (classical) Nanomagnets*
- *–Thermal Activation and Quantum Tunneling of Magnetization*

IV. Classical Magnetization Dynamics

- *–Landau-Lifshitz-Gilbert Equation*

References

Introduction to the Theory of Ferromagnetism, A. Aharoni, Oxford 1996

Lectures on Magnetism, M. Chudnovsky and J. Tejada, Rinton 2006

Magnetic Domains, A. Hubert and R. Schafer, Springer 1998