WHAT IS THE DIFFERENCE IN MAGNETISM OF SIZE CONTROLLED AND OF BULK MATERIAL?

Klaus Baberschke

Institut für Experimentalphysik
Freie Universität Berlin
Arnimallee 14 D-14195 Berlin-Dahlem Germany

Today it is well known fact that the reduction of dimensionality of solid materials imposes extraordinary new features. Discovery and understanding of the properties of nanostructures, quantum dots, nanowires and other low-dimensional interfaces, ….. have lead to numerous technological applications. Prominent examples are applications in information processing and information-storage technologies, new light sources, lasers etc.
Spintronics has emerged as a new field of semiconductor electronics which uses both the charge and spin for unique functionalities.

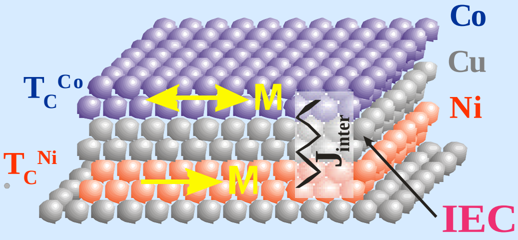
www.physik.fu-berlin.de/~bab

Part I: **Fundamentals**

- Curie temperature T_C ,
- Orbital- and spin- magnetic moments,
- Magnetic Anisotropy Energy (MAE)

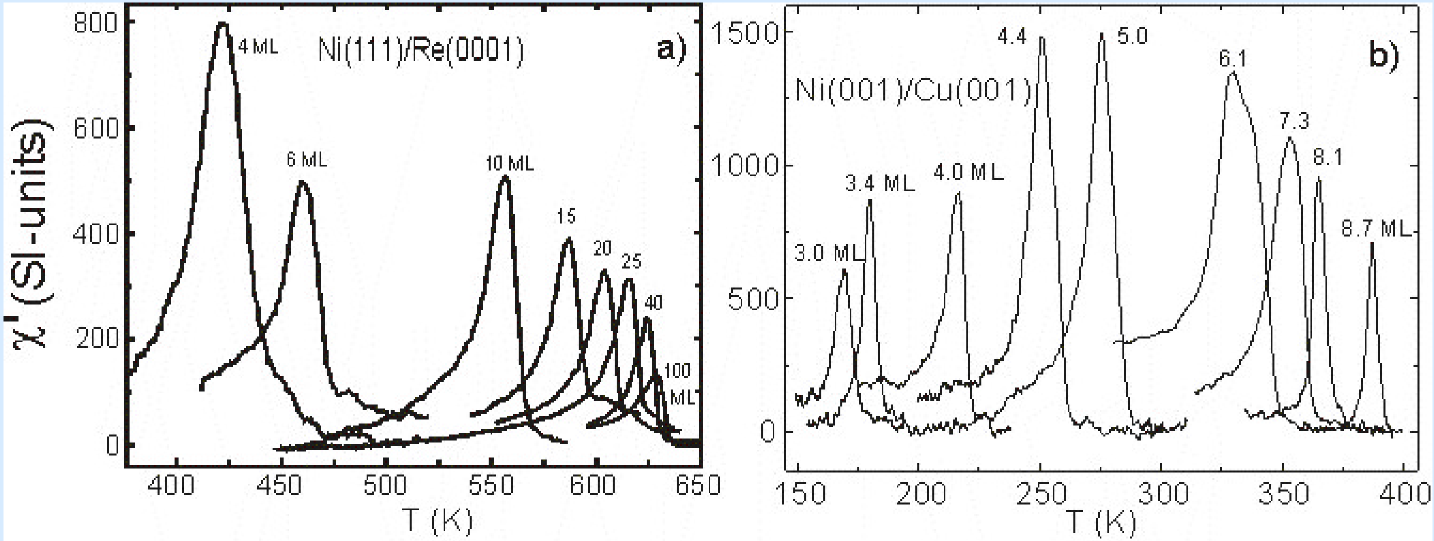
Part II: **Spin dynamics in nano-magnets:**

- Element specific magnetizations and T_C's in trilayers.
- Interlayer exchange coupling and its T-dependence.
- Gilbert damping versus magnon-magnon scattering.



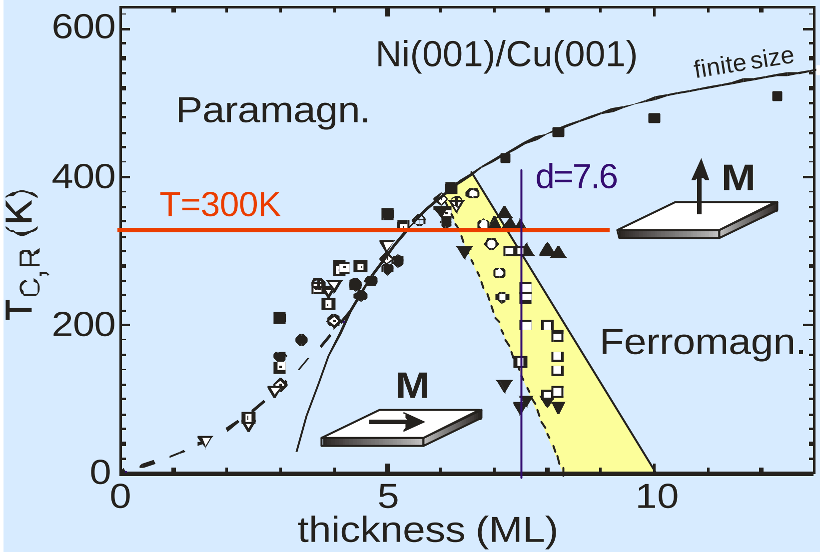
UHV – ac susceptibility

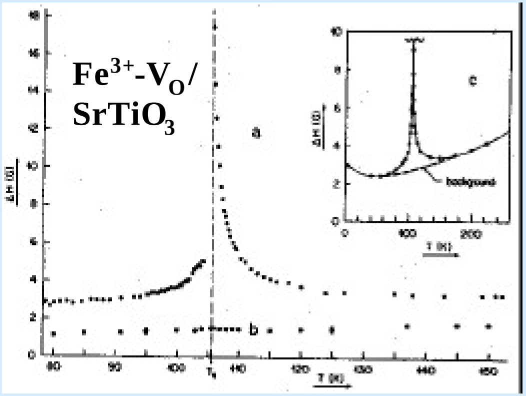
film prepared and measured *in-situ*



"Magnetism in thin films"
P. Poulopoulos, K. B., J. Phys. Condens. Matter. **11**, 9495 (1999)

For thin films the Curie temperature can be manipulated





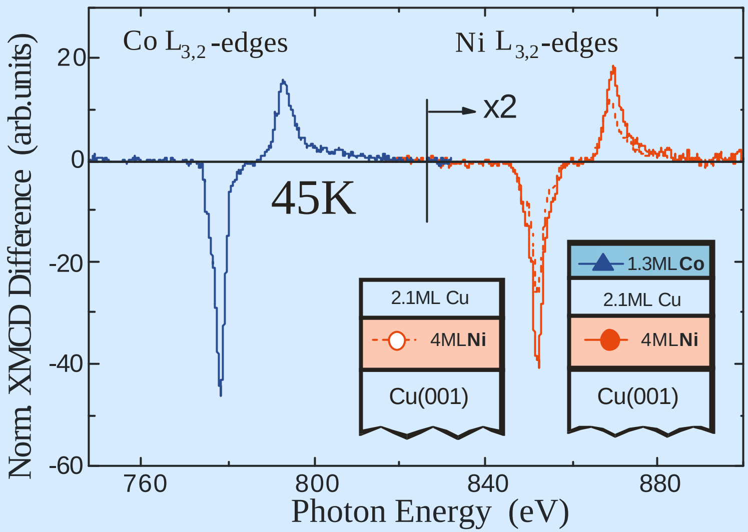
Th.v. Waldkirch, K.A. Müller, W. Berlinger, PRB (1973)

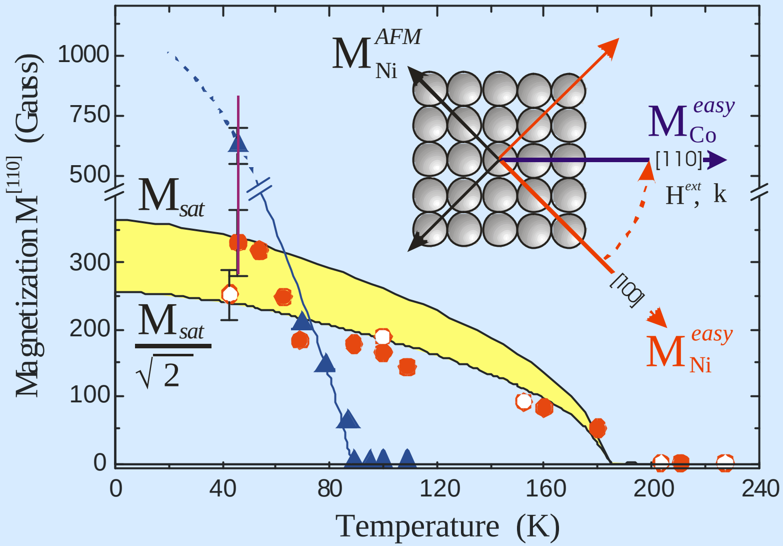
P. Poulopoulos and K. B.
J. Phys.: Condens. Matter **11**, 9495 (1999)

$$\frac{T_C(\infty) - T_C(d)}{T_C(\infty)} = c d^{-1/n}$$

Note that some figures in the web-version are missing due to file-size.

Crossover of $M_{Co}(T)$ and $M_{Ni}(T)$



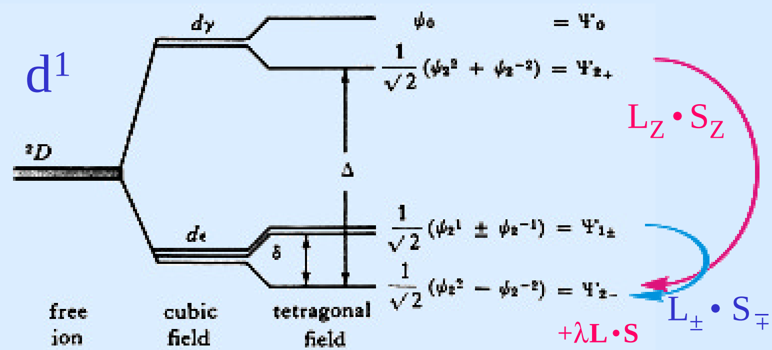


Two order parameter of T_C^{Ni} and T_C^{Co}

A further reduction in symmetry happens at T_C^{low}

Orbital magnetism in second order perturbation theory

$$\mathcal{H}' = \mu_B \mathbf{H}\bullet\mathbf{L} + \lambda\mathbf{L}\bullet\mathbf{S}$$



Splitting of the ²D term by a tetragonally distorted cubic field.

g_{exp} $\quad B_2^0 \rightarrow K_2^0$

$$\mathcal{H} = \sum_{i,j=1}^{3} [\beta g_e(\delta_{ij} - 2\lambda\Lambda_{ij})S_iH_j - \lambda^2\Lambda_{ij}S_iS_j]$$

$$+ \text{ diamagnetic terms in } H_iH_j \qquad (3\text{-}23)$$

where Λ_{ij} is defined in relation to states $(n > 0)$ as

$$\Lambda_{ij} = \sum_{n\neq 0} \frac{(0|L_i|n)(n|L_j|0)}{E_n - E_0} \qquad (3\text{-}24)$$

$< o|\mu_B \mathbf{H}\cdot\mathbf{L}|n > < n|\lambda\mathbf{L}\cdot\mathbf{S}|o >$ $\qquad$ $< o|\lambda\mathbf{L}\cdot\mathbf{S}|n > < n|\lambda\mathbf{L}\cdot\mathbf{S}|o >$

In the principal axis system of a crystal with axial symmetry, the $\underline{\Lambda}$ tensor is diagonal with $\Lambda_{zz} = \Lambda_\parallel$ and $\Lambda_{xx} = \Lambda_{yy} = \Lambda_\perp$. Under these conditions, $\mathcal{H}$ of (3-23) can be simplified, since

$$S_x^2 + S_y^2 = S(S+1) - S_z^2$$

to give

$$\mathcal{H} = g_\parallel \beta H_z S_z + g_\perp \beta (H_x S_x + H_y S_y) + D[S_z^2 - \tfrac{1}{3}S(S+1)] \qquad (3\text{-}25)$$

where

$$g_\parallel = g_e(1 - \lambda\Lambda_\parallel)$$
$$g_\perp = g_e(1 - \lambda\Lambda_\perp) \qquad (3\text{-}26)$$
$$D = \lambda^2(\Lambda_\perp - \Lambda_\parallel)$$

G.E. Pake, p.66

$$\psi_{2-} \equiv (2)^{-1/2}\{|2\rangle - |-2\rangle\} \equiv |2-\rangle$$

The orbital moment is quenched in cubic symmetry

$\langle 2-|L_Z|2-\rangle = 0,$

but not for tetragonal symmetry

W.D. Brewer, A. Scherz, C. Sorg, H. Wende, K. Baberschke, P. Bencok, and S. Frota-Pessoa
Direct observation of orbital magnetism in cubic solids
Phys. Rev. Lett. **93**, 077205 (2004)
and
W.D. Brewer et al. ESRF – Highlights, p. 96 (2004)

Aus der Wissenschaft

Phys. Bl. 53 (1997)

Superstarke Magnete intermetallischer Verbindungen der Seltenerdmetalle

Leistungssteigerung durch nanokristalline Strukturen

H. Kronmüller

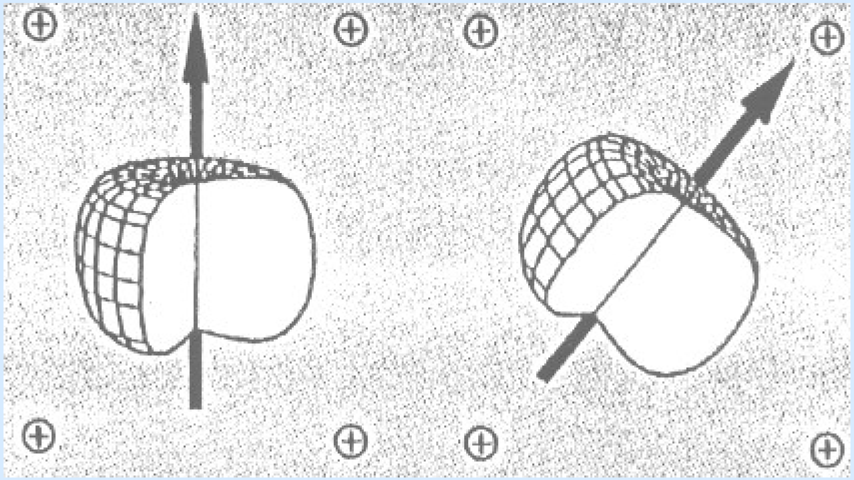
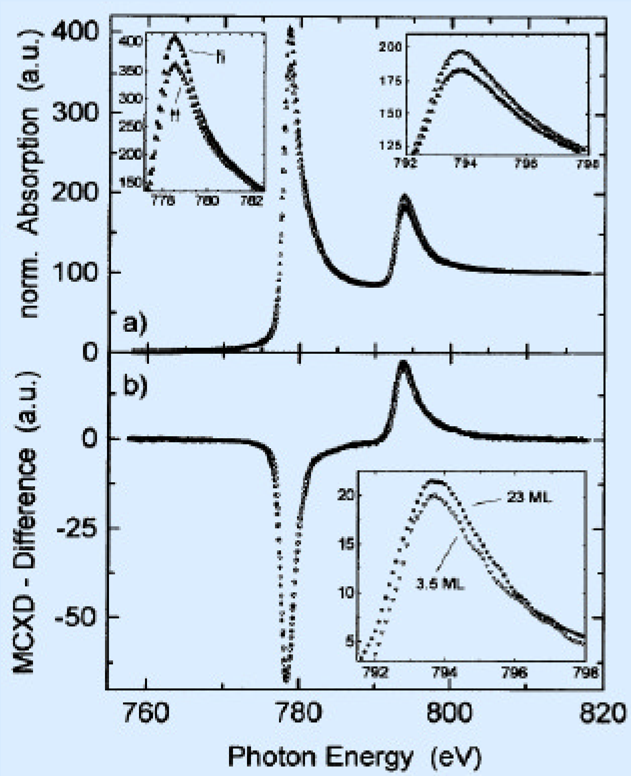
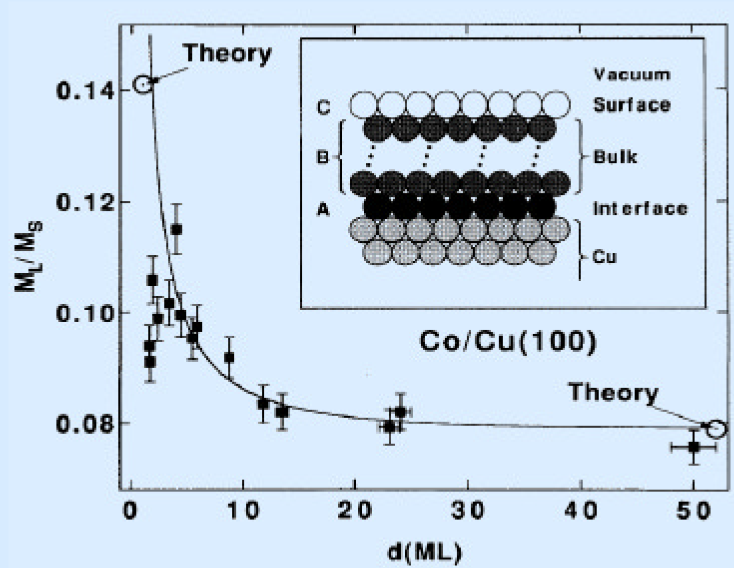


Abb. 3: Die Vorzugsrichtung des magnetischen Moments (*leichte Richtung*) der intermetallischen Seltenerdverbindungen hat ihre Ursache in der starren Kopplung zwischen magnetischem Moment (Pfeil) und Ladungsverteilung der 4f-Eletronen des Neodym. Bei einer Rotation des magnetischen Moments aus der c-Richtung (senkrecht) heraus dreht sich die anisotrope Ladungswolke mit. Da die Wechselwirkungsenergie zwischen 4f-Ladungswolke und Ladungswolken der benachbarten Ionen (⊕) dabei zunimmt, wird die leichte Richtung favorisiert.

Enhancement of Orbital Magnetism at Surfaces: Co on Cu(100)



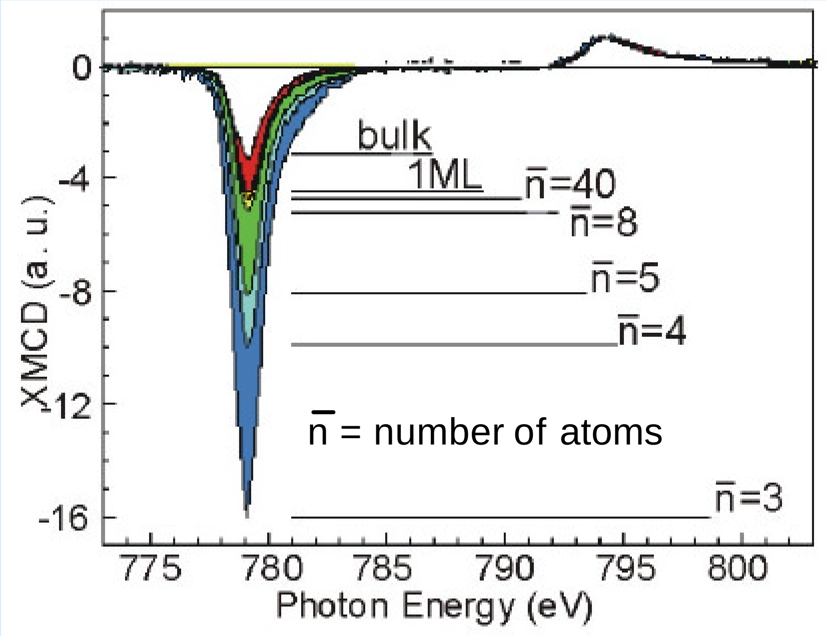


$$\left(\frac{M_L}{M_S}\right)_{\exp} = \frac{A e^{-D(d-1)/l} + B\Sigma_{n=3}^{d} e^{-D(n-2)/l} + C}{\Sigma_{n=0}^{d-1} e^{-nD/l}}$$

M. Tischer et al., Phys. Rev. Lett. **75**, 1602 (1995)

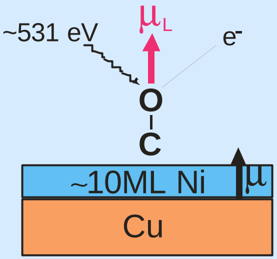
Giant Magn. Anisotropy of Single Co Atoms and Nanoparticles

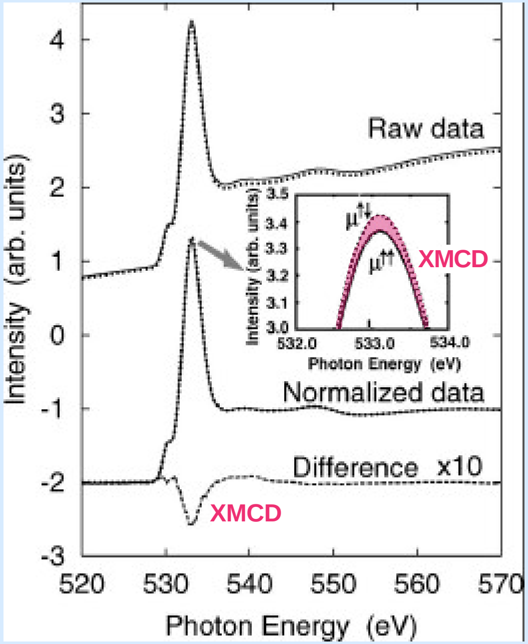
P. Gambardella et al., Science **300**, 1130 (2003)



Induced magnetism in molecules

T. Yokoyama et al., PRB **62**, 14191 (2000)

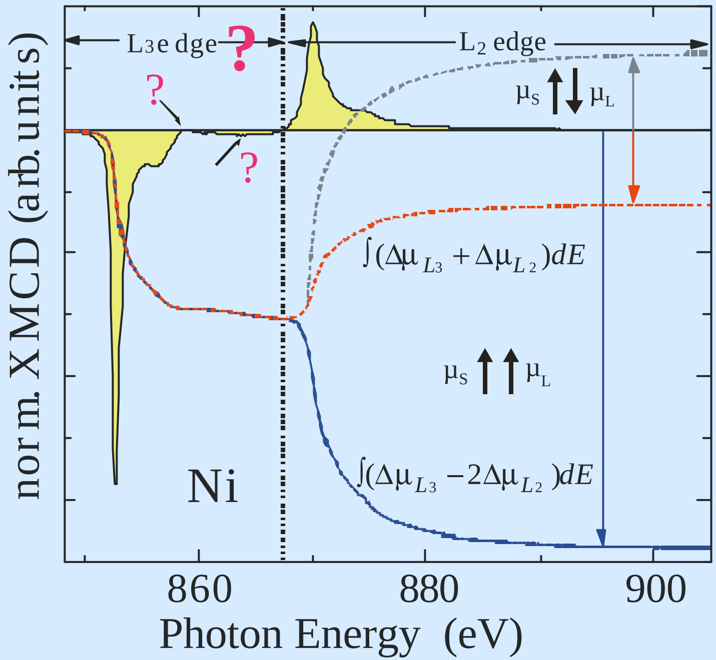




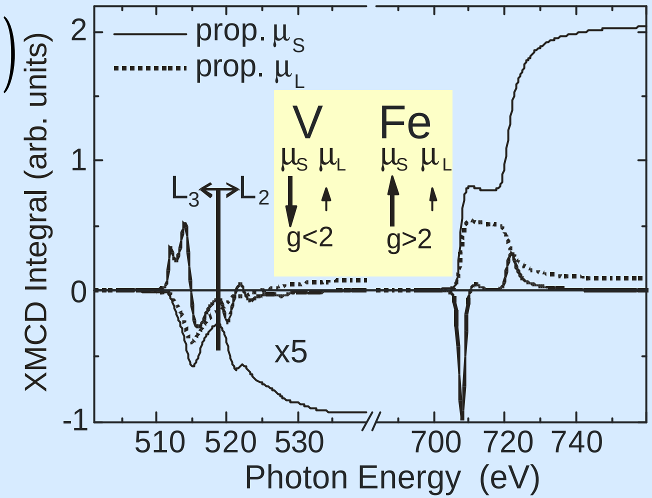
Orbital and spin magnetic moments deduced from XMCD

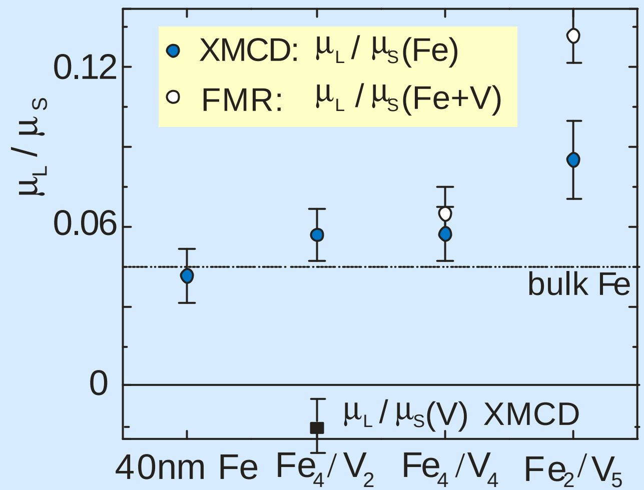
$$\int\left(?\,\mu_{L\,3} - 2\cdot ?\,\mu_{L\,2}\right)dE = \frac{N}{3N_h^d}\left(2\langle S_Z\rangle^d + 7\langle T_Z\rangle^d\right)$$

$$\int\left(?\,\mu_{L\,3} + ?\,\mu_{L\,2}\right)dE = \frac{N}{2N_h^d}\langle L_Z\rangle^d$$



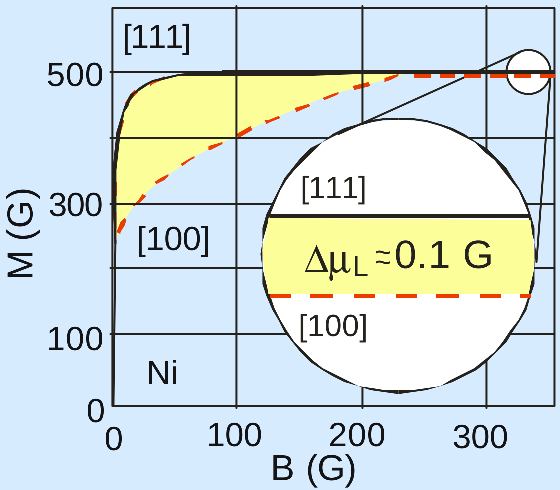
H. Ebert Rep. Prog. Phys. **59**, 1665 (1996)





Magnetic Anisotropy Energy (MAE) and anisotropic μ_L

1. Magnetic anisotropy energy = f(T)
2. Anisotropic magnetic moment ≠ f(T)



MAE = ?M·dB ˜ ½ ?M·?B ˜ ½ 200 · 200 G^2

MAE ˜ $2 \cdot 10^4$ erg / cm^3 ˜ 0.2 µeV / atom

≈ 1µeV/atom is very small compared to
≈ 10 eV/atom total energy but all important

$$g_{||} - g_{\perp} = g_e \lambda (\Lambda_{\perp} - \Lambda_{||})$$

anisotropic μ_L ↔ MAE

$$D = \frac{\lambda}{g_e} \Delta g$$

↕

$$MAE \propto \frac{\xi_{LS}}{4\mu_B} \Delta\mu_L$$ Bruno ('89)

Characteristic energies of metallic ferromagnets

binding energy	1 - 10 eV/atom
exchange energy	10 - 10^3 meV/atom
cubic MAE (Ni)	0.2 µeV/atom
uniaxial MAE (Co)	70 µeV/atom

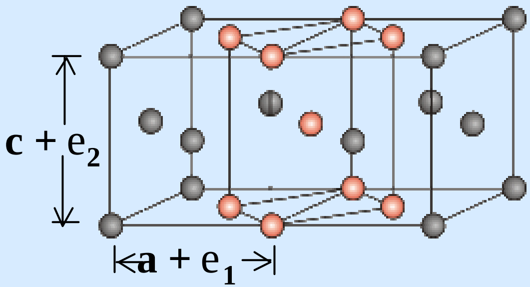
K. Baberschke, Lecture Notes in Physics, Springer **580**, 27 (2001)

There are <u>only 2 origins</u> for MAE: 1) dipol-dipol interaction $\sim (\bar{\mu}_1 \bullet \bar{r})(\bar{\mu}_2 \bullet \bar{r})$ and
2) spin-orbit coupling ? $\mathbf{L}\,\mathbf{S}$ (intrinsic K or ΔE_{band})

Growth of artificial nanostructures
bcc, fcc $\rightarrow$ tetragonal, trigonal

Note that some figures in the web-version are missing due to file-size.

fcc Cu(001) substrate (a_p=2.55Å)



Bain path

$c/a=1$ fcc → fct → bcc $c/a=1/\sqrt{2}$

“volume”, “surface” and “interface” MAE

$$K_i = K_i^V + 2\frac{K_i^S}{d}$$

$t=T/T_C(d)$

full trilayer grows in fct structure

Note that some figures in the web-version are missing due to file-size.

R. Hammerling et al., PRB **68**, 092406 (2003)

PHYSICAL REVIEW B VOLUME 59, NUMBER 19 15 MAY 1999-I

Structure of ultrathin Ni/Cu(001) films as a function of film thickness, temperature, and magnetic order

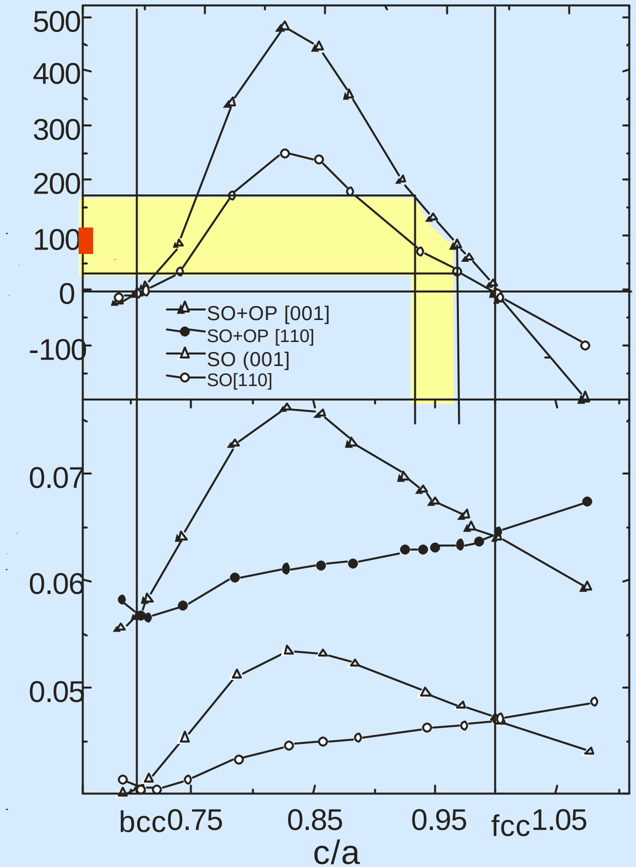
W. Platow, U. Bovensiepen, P. Poulopoulos, M. Farle, and K. Baberschke
Institut für Experimentalphysik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin, Germany

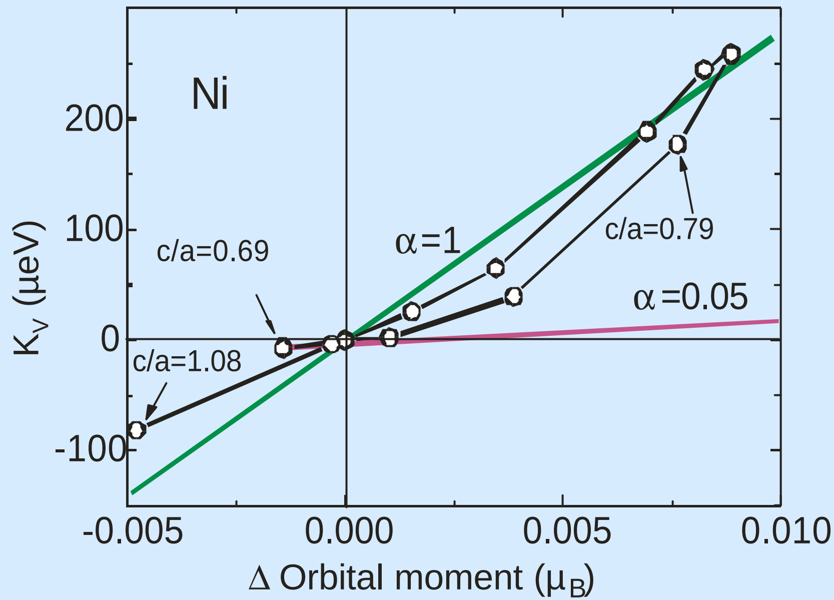
L. Hammer, S. Walter, S. Müller, and K. Heinz
Lehrstuhl für Festkörperphysik, Universität Erlangen-Nürnberg, Staudtstrasse 7, D-91058 Erlangen, Germany

TABLE I. Best-fit structural data for the nickel films of different thickness and the clean copper substrate.

Parameter	0 ML	1 ML	2 ML	3 ML	4 ML	5 ML	7 ML	11 ML
d_{12} (Å)	$1.755^{+0.011}_{-0.007}$	$1.720^{+0.014}_{-0.018}$	$1.715^{+0.015}_{-0.015}$	$1.725^{+0.022}_{-0.016}$	$1.705^{+0.015}_{-0.011}$	$1.675^{+0.012}_{-0.014}$	$1.710^{+0.009}_{-0.012}$	$1.690^{+0.008}_{-0.011}$
d_{23} (Å)	$1.805^{+0.006}_{-0.011}$	$1.770^{+0.012}_{-0.014}$	$1.720^{+0.011}_{-0.011}$	$1.710^{+0.012}_{-0.009}$	$1.705^{+0.011}_{-0.013}$	$1.710^{+0.010}_{-0.014}$	$1.695^{+0.009}_{-0.012}$	$1.695^{+0.008}_{-0.013}$
d_{34} (Å)	1.800 ± 0.010	$1.795^{+0.012}_{-0.012}$	$1.775^{+0.014}_{-0.021}$	$1.715^{+0.024}_{-0.017}$	$1.71^{+0.014}_{-0.016}$	$1.700^{+0.014}_{-0.014}$	$1.695^{+0.010}_{-0.010}$	$1.700^{+0.010}_{-0.013}$
d_{45} (Å)	1.790 ± 0.013	$1.800^{+0.017}_{-0.014}$	$1.790^{+0.028}_{-0.015}$	$1.760^{+0.028}_{-0.017}$	$1.72^{+0.024}_{-0.017}$	$1.715^{+0.014}_{-0.014}$	$1.700^{+0.017}_{-0.013}$	$1.690^{+0.016}_{-0.012}$
d_{56} (Å)	$1.800^{+0.010}_{-0.009}$	$1.790^{+0.020}_{-0.017}$	$1.800^{+0.028}_{-0.028}$	$1.790^{+0.021}_{-0.022}$	$1.76^{+0.033}_{-0.022}$	$1.730^{+0.018}_{-0.025}$	$1.710^{+0.024}_{-0.018}$	$1.700^{+0.015}_{-0.015}$
d_b (Å)	1.790	1.79	1.79	1.79	1.77	1.70	1.70	1.70
ΔE (eV)	2270	2070	2220	2090	1450	2120	2100	2200
R_p	0.085	0.093	0.170	0.138	0.096	0.111	0.111	0.112

Magnetic Anisotropy Energy MAE and anisotropic μ_L

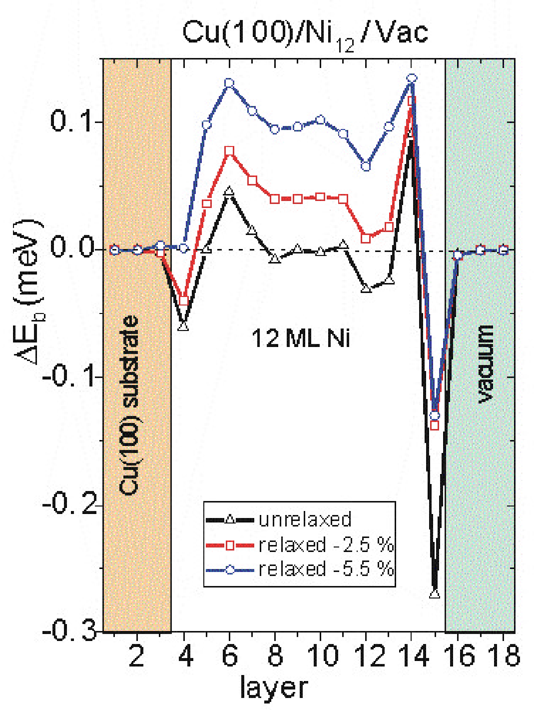




O. Hjortstam, K. B. et al. PRB **55**, 15026 ('97)

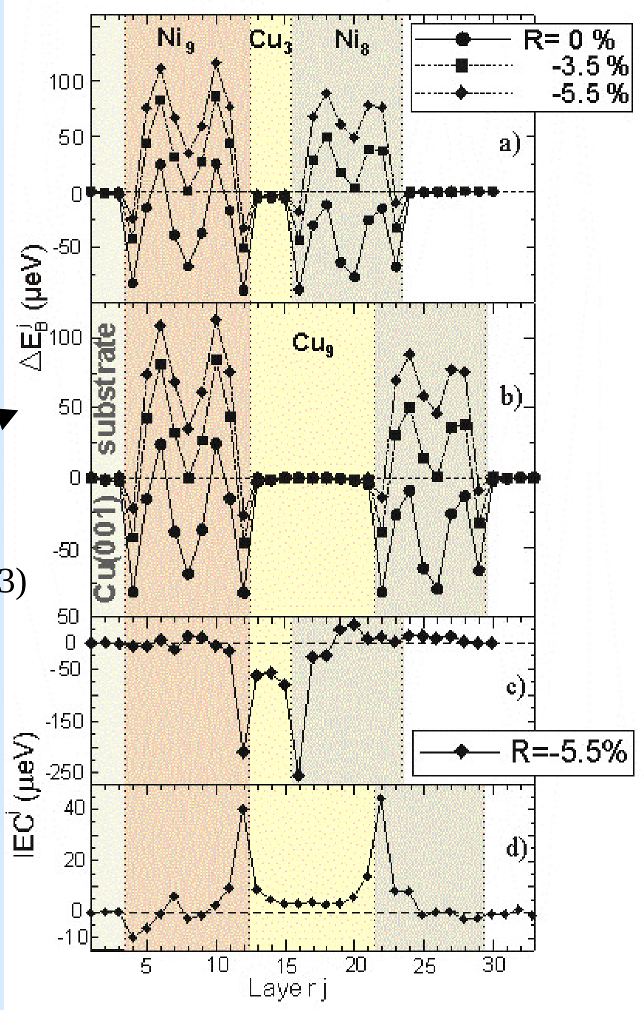
SP-KKR calculation for rigit fcc and relaxed fct structures

layer resolved $\Delta E_b = \Sigma K_i$ at T=0



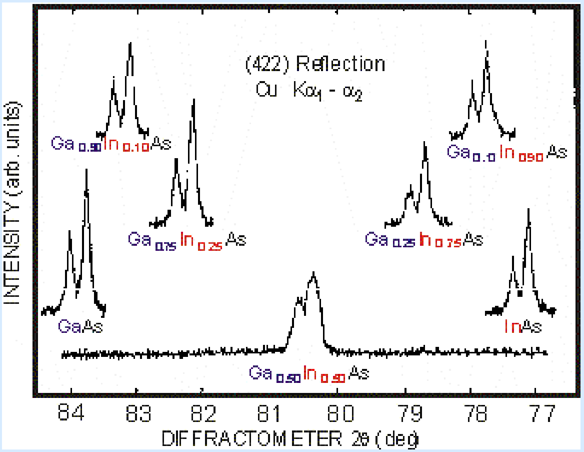
C. Uiberacker et al., PRL **82**, 1289 (1999)

R. Hammerling et al., PRB **68**, 092406 (2003)

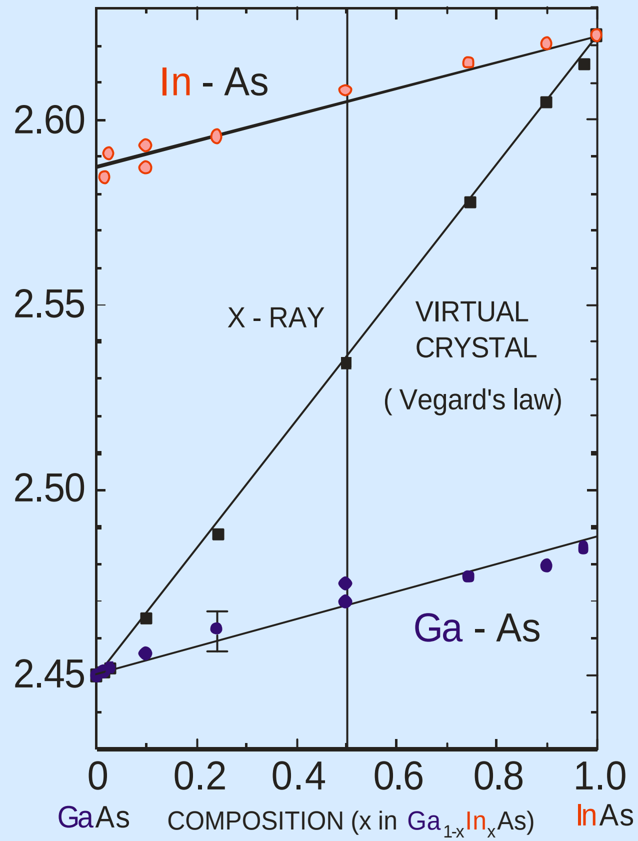


The surface and interface MAE are certainly large (L. Néel, 1954) but count only for one layer each. The inner part (volume) of a nano-structure will overcome this, because they count for n-2 layers.

Virtual Crystal Approximation (VCA)
X-ray diffraction
of pseudobinary $(Ga_{1-x}In_x)As$



EXAFS a local probe



Mikkelsen & Boyce PRL **49**, 1412 (82)

Determination of orbital- and spin- magnetic moments

Which technique measures what?

μ_L , μ_S in UHV-XMCD

μ_L + μ_S in UHV-SQUID

μ_L / μ_S in UHV-FMR

For FMR see: J. Lindner and K. Baberschke
In situ Ferromagnetic Resonance:
An ultimate tool to investigate the coupling in ultrathin magnetic films
J. Phys.: Condens. Matter **15**, R193 (2003)

per definition:

1) spin moments are isotropic

2) also exchange coupling $\mathbf{J\ S_1 \cdot S_2}$ is isotropic

3) so called ***anisotropic exchange*** is a (hidden) projection of the orbital momentum into spin space

Part I: **Fundamentals**

- Curie temperature T_C ,
- Orbital- and spin- magnetic moments,
- Magnetic Anisotropy Energy (MAE)

Part II: **Spin dynamics in nano-magnets:**

- Element specific magnetizations and T_C's in trilayers.
- Interlayer exchange coupling and its T-dependence.
- Gilbert damping versus magnon-magnon scattering.

A whole variety of experiments on nanoscale magnets are available nowadays. Unfortunately many of the data are analyzed using theoretical *static mean field (MF) model*, e. g. by assuming only magnetostatic interactions of multilayers, static exchange interaction, or static interlayer exchange coupling (IEC), etc. We will show that such a mean field ansatz is insufficient for nanoscale magnetism, 3 cases will be discussed to demonstrate the importance of *higher order spin-spin correlations* in low dimensional magnets.

Spin-Spin correlation function $\frac{\partial}{\partial t}\langle\langle S_i^{+} S_j^{-}\rangle\rangle \rightarrow$

$$S_i^z S_j^+ \approx \langle S_i^z\rangle S_j^+ - \langle S_i^- S_i^+\rangle S_j^+ - \langle S_i^- S_j^+\rangle S_i^+ + \bullet\bullet\bullet$$

$\longleftarrow$ RPA $\longrightarrow$

The damping of spin motions in ultrathin films: Is the Landau–Lifschitz–Gilbert phenomenology applicable?☆

D.L. Mills[a,*], Rodrigo Arias[b]

Physica B **384**, 147 (2006)

1. Element specific magnetizations and T_C's in trilayers.

A trilayer is a prototype to study magnetic coupling in multilayers.

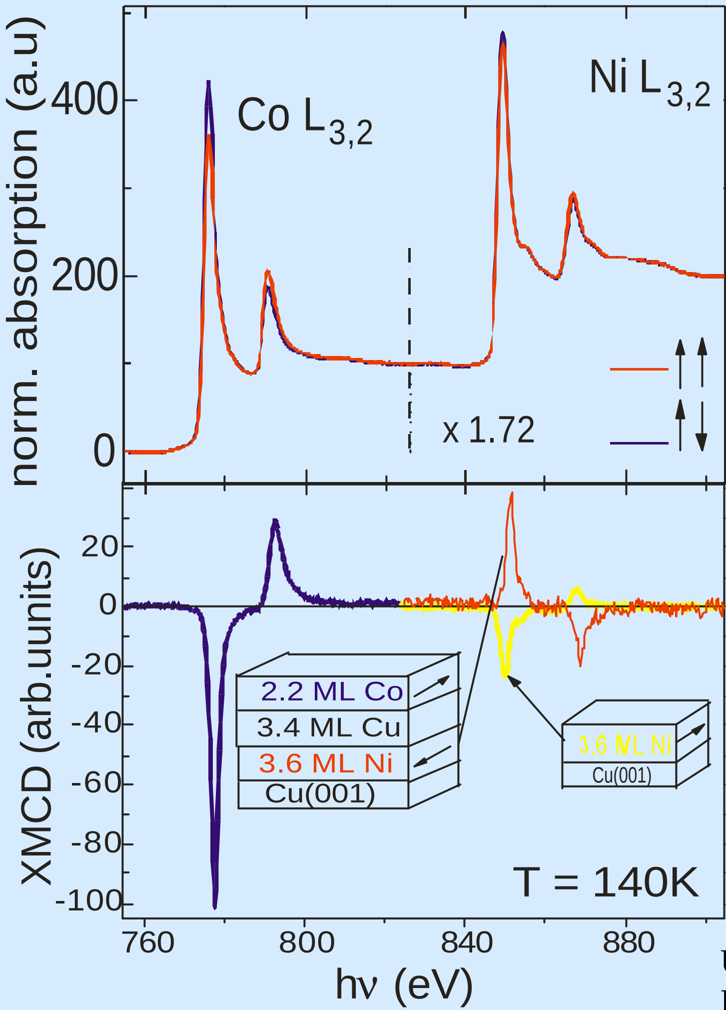
What about element specific Curie-temperatures ?

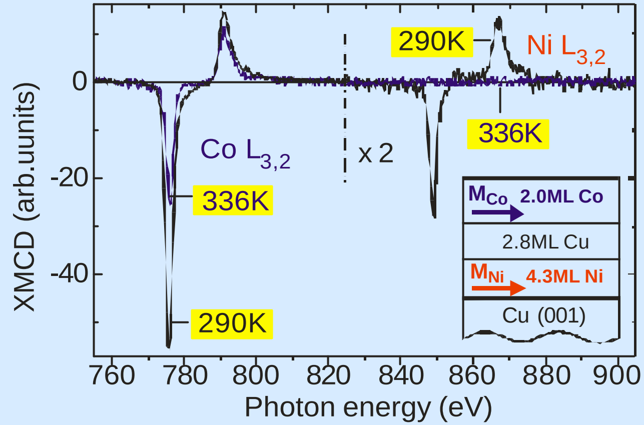
Two trivial limits: (i) $d_{Cu} = 0 \Rightarrow$ direct coupling like a Ni-Co alloy

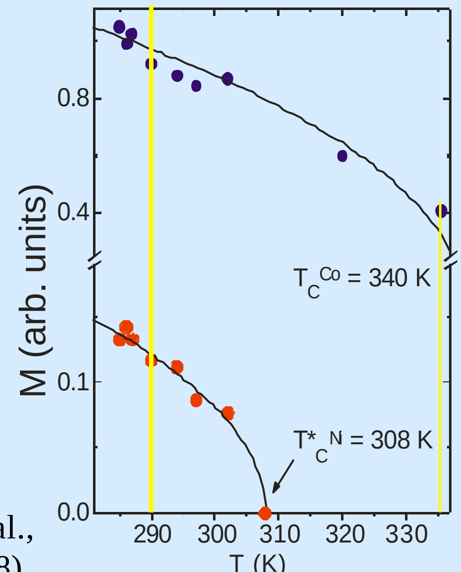
(ii) d_{Cu} = large $\Rightarrow$ no coupling, like a mixed Ni/Co powder

BUT $d_{Cu} \approx 2$ ML $\Rightarrow$ **?**

Ferromagnetic trilayers



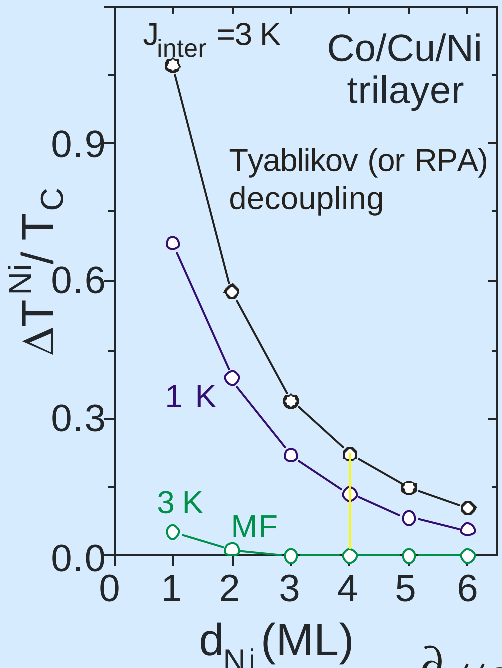




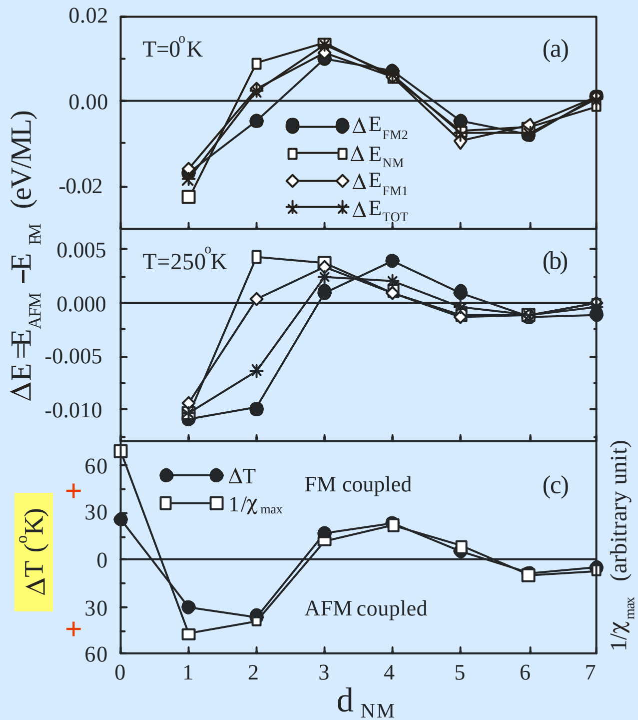
U. Bovensiepen et al., PRL **81**, 2368 (1998)

Enhanced spin fluctuations in 2D (theory)

P. Jensen et al. PRB **60**, R14994 (1999)



J.H. Wu et al. J. Phys.: Condens. Matter **12** (2000) 2847



Spin-Spin correlation function $\frac{\partial}{\partial t}\langle\langle S_i^+ S_j^- \rangle\rangle \rightarrow$

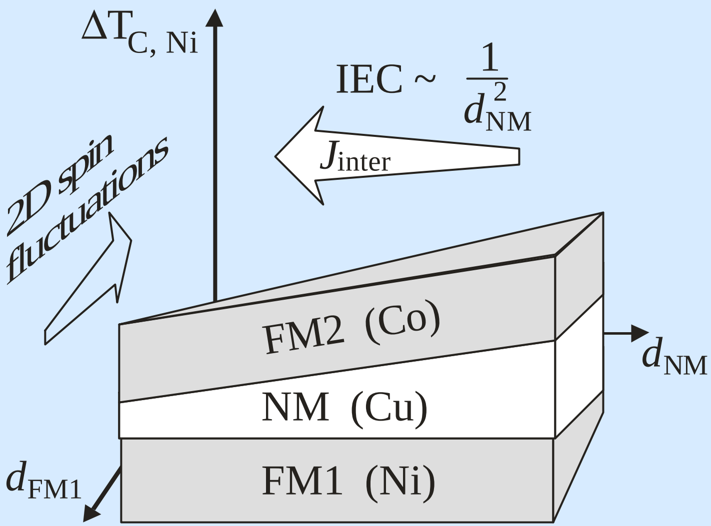
$$S_i^z S_j^+ \approx \langle S_i^z \rangle S_j^+ - \langle S_i^- S_i^+ \rangle S_j^+ - \langle S_i^- S_j^+ \rangle S_i^+ + \cdots$$

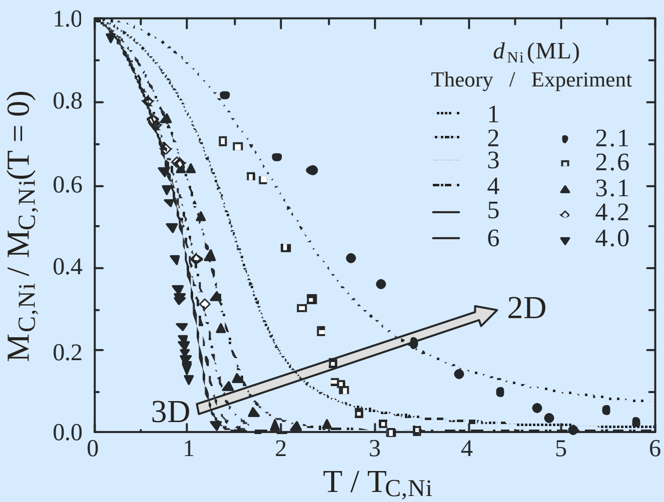
← RPA →

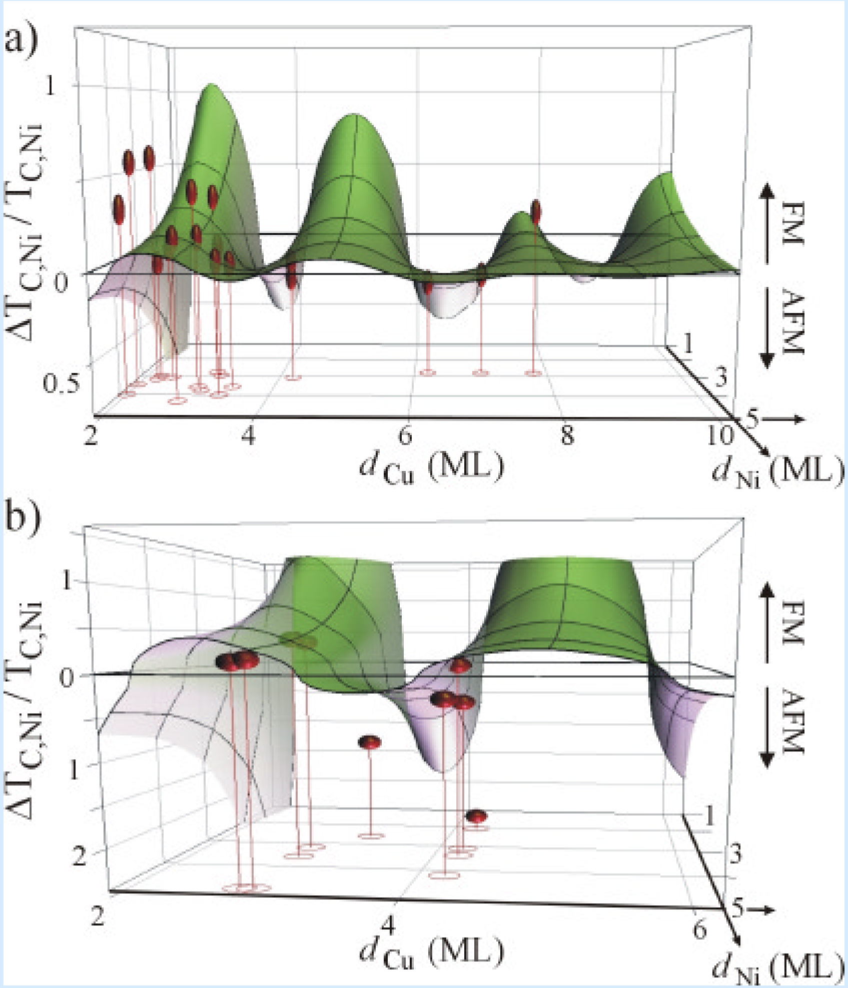
$\langle S_i^z \rangle S_j^+$, mean field ansatz (Stoner model) is insufficient to describe spin dynamics at interfaces of nanostructures

Single band Hubbard model:
Simple Hartree-Fock (Stoner) ansatz is insufficient
Higher order correlations are needed to explain T_C-shift

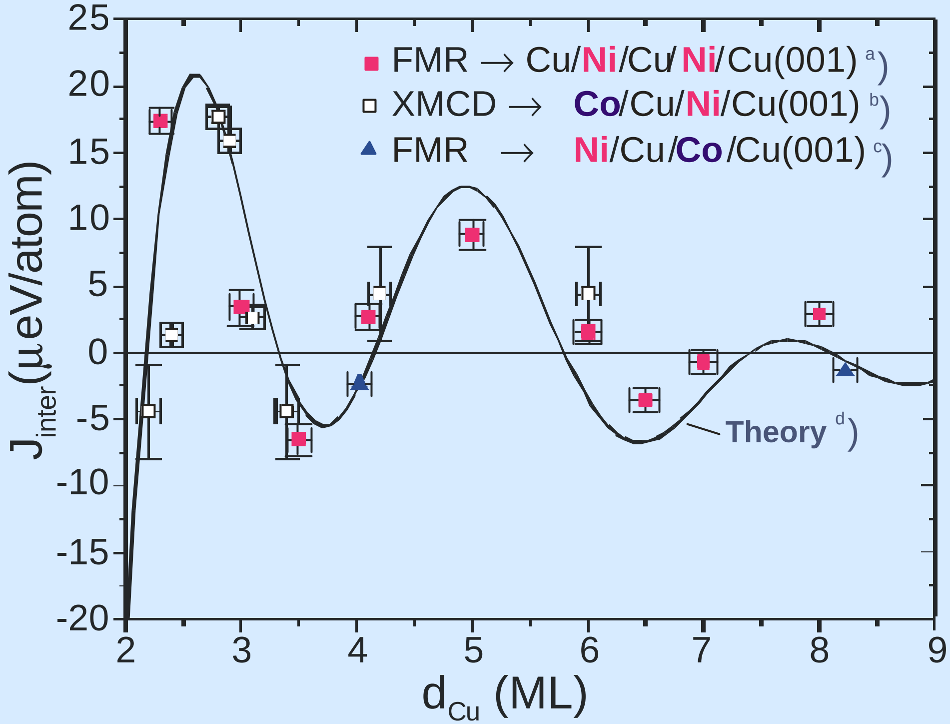
Evidence for giant spin fluctuations [A. Scherz et al.PRB, **73** 54447 (2005)]





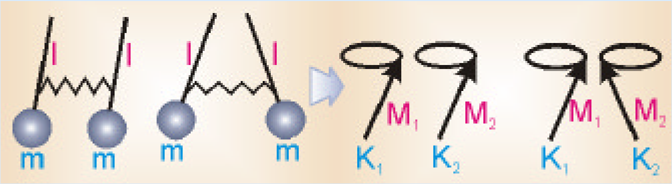


2. Interlayer exchange coupling and its T-dependence.



a) J. Lindner, K. B., J. Phys. Condens. Matter **15**, S465 (2003)
b) A. Ney et al., Phys. Rev. B **59**, R3938 (1999)
c) J. Lindner et al., Phys. Rev. B **63**, 094413 (2001)
d) P. Bruno, Phys. Rev. B **52**, 441 (1995)

in-situ FMR in coupled films



theory

FMR

in-situ
UHV-experiment

Note that some figures in the web-version are missing due to file-size.

J. Lindner, K. B. Topical Rev., J. Phys. Condens. Matter **15**, R193-R232 (2003)

Temperature dependence of J_{inter} Û D free energy

P. Bruno, PRB **52**, 411 (1995)

N.S. Almeida et al. PRL **75**, 733 (1995)

$$J_{inter} = J_{inter,0} \left[\frac{T/T_0}{\sinh(T/T_0)} \right] \qquad T_0 = \hbar v_F / 2\pi k_B d$$

$$J_{inter} = J_{inter,0} \left[1 - (T/T_C)^{3/2} \right]$$

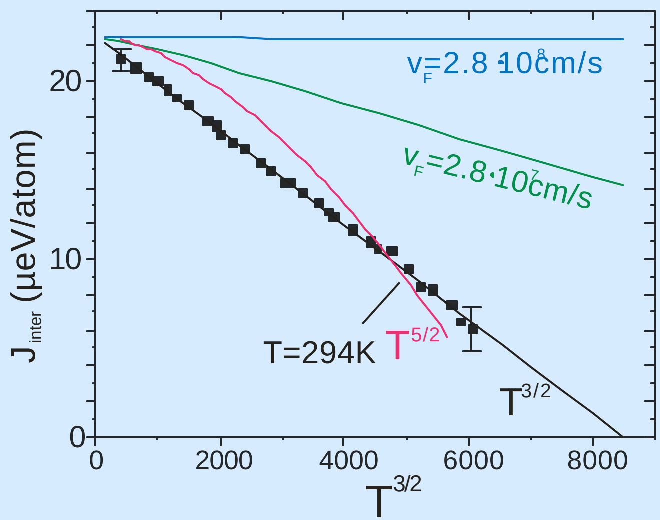
$Ni_7Cu_9Co_2/Cu(001)$

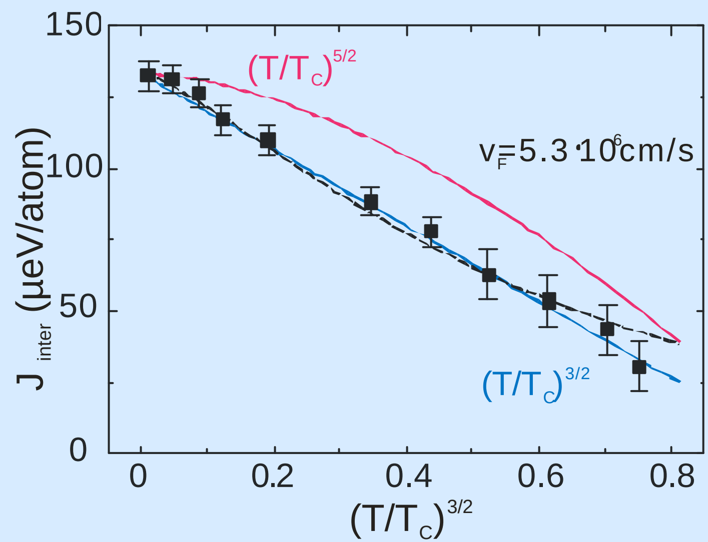
T=55K - 332K

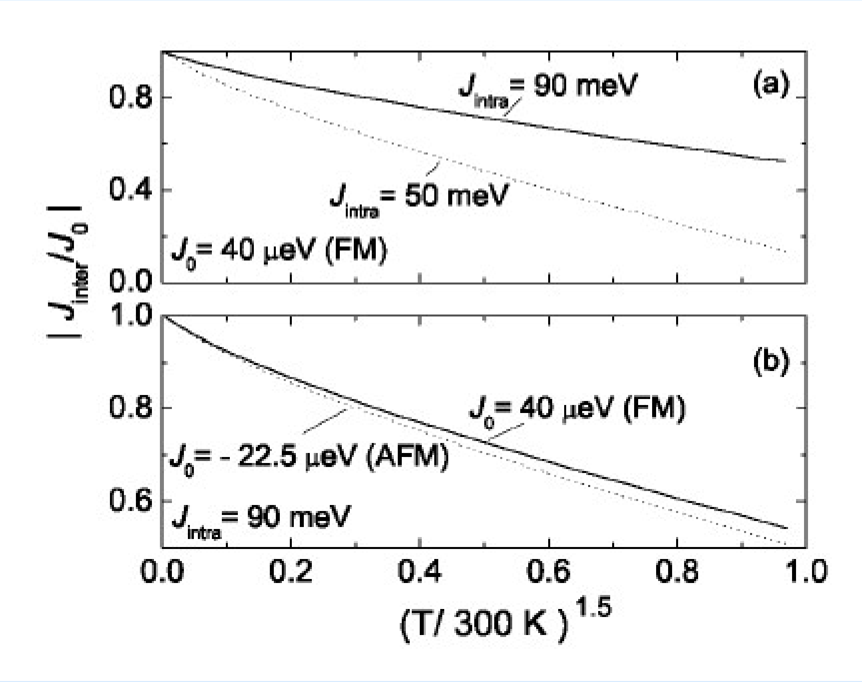
J. Lindner et al.
PRL **88**, 167206 (2002)

$(Fe_2V_5)_{50}$

T=15K - 252K, T_C=305K







All contributions due to the spacer, interface and magnetic layers, nevertheless give an effective power law dependence on the temperature:

$$J(T) \approx 1 - AT^n, \quad n \approx 1.5 \qquad (1)$$

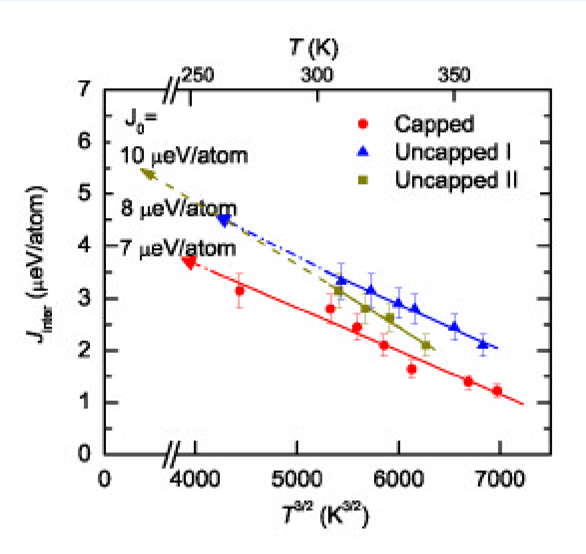
S. Schwieger, W. Nolting,
PRB **69**, 224413 (2004)

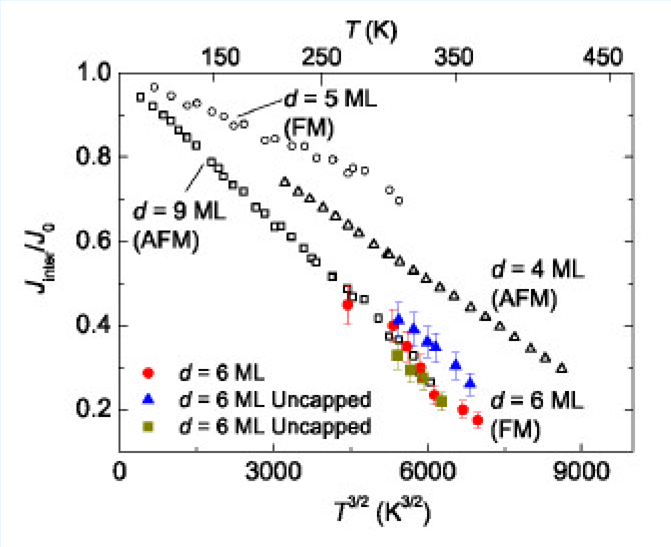
$$J(T) \approx 1 - AT^n$$
$$n \approx 1.5$$

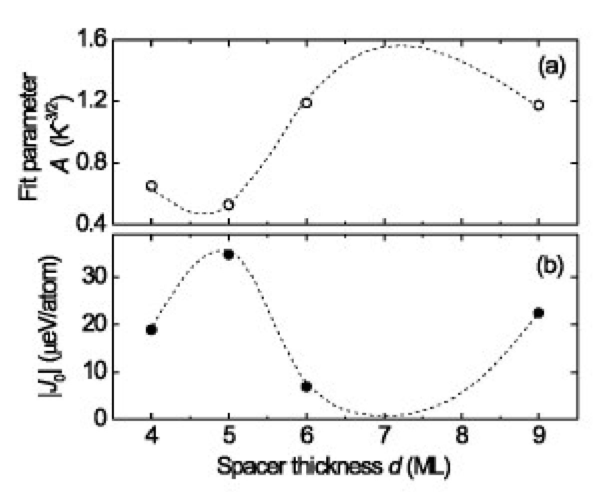
The dominant role of thermal magnon excitation in the temperature dependence of the interlayer exchange coupling: experimental verification

S. S. Kalarickal,* X. Y. Xu,† K. Lenz, W. Kuch, and K. Baberschke‡
Institut für Experimentalphysik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin, Germany
(Dated: March 20, 2007)

PRB (2007) submitted.


T (K)
J0=
10 µeV/atom
8 µeV/atom
7 µeV/atom
Capped
Uncapped I
Uncapped II
J_inter (µeV/atom)
T^3/2 (K^3/2)


T (K)
d = 5 ML
(FM)
d = 9 ML
(AFM)
d = 4 ML
(AFM)
d = 6 ML
d = 6 ML Uncapped
d = 6 ML Uncapped
d = 6 ML
(FM)
J_inter/J_0
T^3/2 (K^3/2)


(a)
(b)
Fit parameter
A (K^-3/2)
|J0| (µeV/atom)
Spacer thickness d (ML)

T-dependence of interlayer exchange coupling

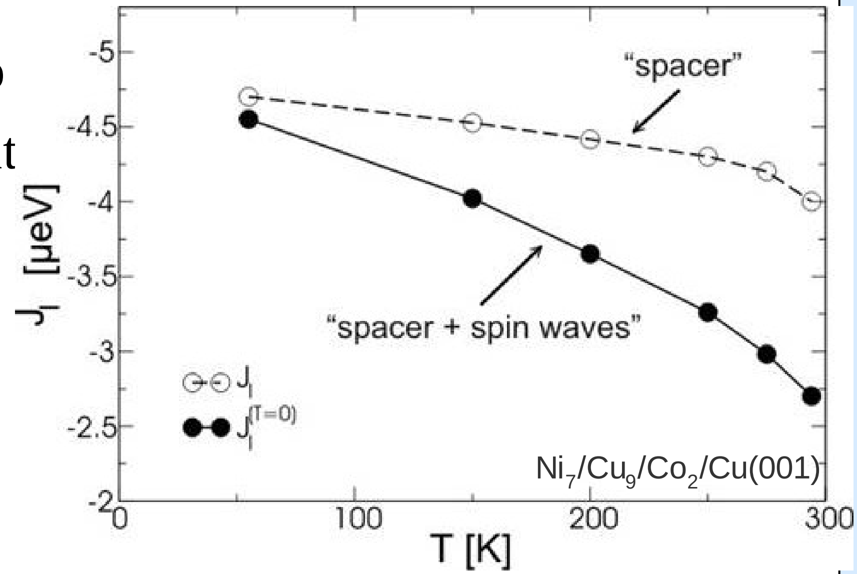
- What causes the temperature dependence of IEC?
- *band structure effects (smearing out of Fermi edge)?*
- *spin wave excitations?*
- Experiment measures only one observable (IEC)

- Theory has the opportunity to

→ Spin wave excitations account 75% of *T*-dependence

→ band structure effect (25%) is not negligible!

- S. Schwieger et al., unpublished RICHTIG



3. Gilbert damping versus magnon-magnon scattering.

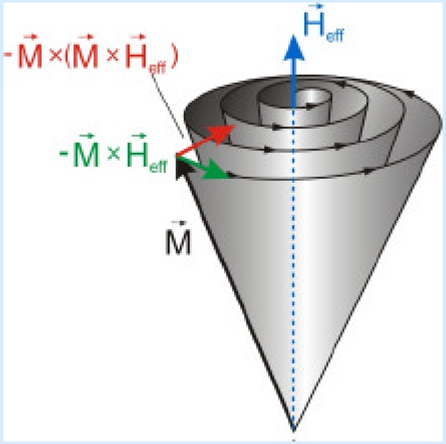
Landau-Lifshitz-Gilbert equation (1935)

$$\frac{d\mathbf{m}}{dt} = -g\,\mathbf{m}\times\mathbf{H}_{\mathrm{eff}} + a\,\mathbf{m}\times\frac{d\mathbf{m}}{dt}$$

$$T \sim \frac{1}{aw}$$

Gilbert damping

|M|=const.



Bloch-Bloembergen Equation (1956)

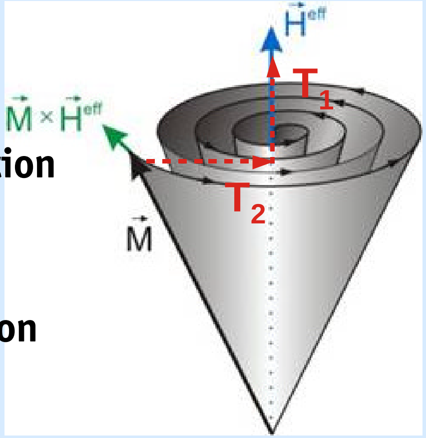
$$\frac{dm_z}{dt} = -g\,(\mathbf{m}\times\mathbf{H}_{\mathrm{eff}})_z - \frac{m_z - M_S}{T_1}$$

spin-lattice relaxation
(longitudinal)

$$\frac{dm_{x,y}}{dt} = -g\,(\mathbf{m}\times\mathbf{H}_{\mathrm{eff}})_{x,y} - \frac{m_{x,y}}{T_2}$$

spin-spin relaxation
(transverse)

M_z=const.



THEORY OF THE MAGNETIC DAMPING CONSTANT

Harry Suhl
Department of Physics, and Center for Magnetic Recording Research, Mail Code 0319,
University of California-San Diego, La Jolla, CA 92093-0319.

Abstract—The aim of this paper is to express the effects of basic dissipative mechanisms involved in the dynamics of the magnetization field in terms of the one most commonly observed quantity: the spatial average of that field. The mechanisms may be roughly divided into direct relaxation to the lattice, and indirect relaxation via excitation of many magnetic modes. Two illustrative examples of these categories are treated; direct relaxation via magnetostriction into a lattice of known elastic constant, and relaxation into synchronous spin waves brought about by imperfections. Finally, a somewhat speculative account is presented of time constants to be expected in magnetization reversal.

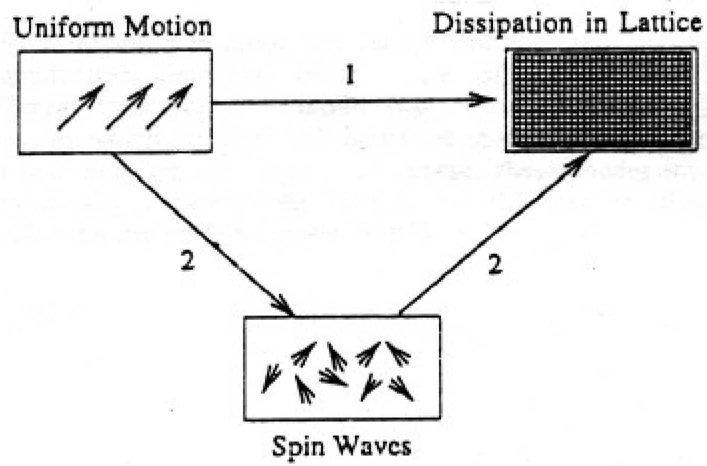


Figure 1. Two paths for degradation of uniform motion: 1) Direct relaxation to the lattice; 2) Decay into non-uniform motions, which in turn decay to the lattice.

FMR Linewidth - Damping

Landau-Lifshitz-Gilbert-Equation

$$\frac{1}{\gamma}\frac{\partial M}{\partial t} = -(M \times H_{eff}) + \frac{G}{\gamma M_S^2}\left(M \times \frac{\partial M}{\partial t}\right)$$

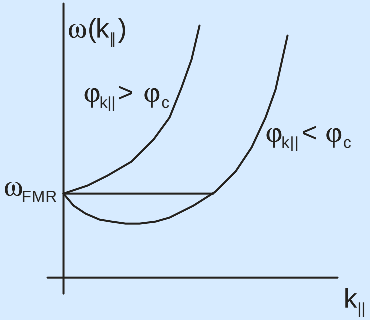
viscous damping,
energy dissipation

Gilbert-damping ~ω

$$\Delta H^{Gil}(\omega) = \frac{G}{\gamma^2 M_S}\,\omega$$

2-magnon-scattering

R. Arias, and D.L. Mills, *Phys. Rev. B* ***60***, *7395 (1999);*
D.L. Mills and S.M. Rezende in
'*Spin Dynamics in Confined Magnetic Structures* ',
edt. by B. Hillebrands and K. Ounadjela, Springer Verlag



$$\Delta H^{2Mag}(\omega) = \Gamma \arcsin\sqrt{\frac{[\omega^2+(\omega_0/2)^2]^{1/2} - \omega_0/2}{[\omega^2+(\omega_0/2)^2]^{1/2} + \omega_0/2}}$$

$\omega_0 = \gamma(2K_{2\perp} - 4\pi M_S)$, $\gamma = (\mu_B/h)g$
$K_{2\perp}$ - uniaxial anisotropy constant
M_S - saturation magnetization

- Gilbert damping contribution:
- linear in frequency
- two-magnon excitations (thin films): non-linear frequency dependence

$$\Delta H_{2-\text{magnon}}(w) = \Gamma \arcsin \sqrt{\frac{\sqrt{w^2 + (w_0/2)^2} - w_0/2}{\sqrt{w^2 + (w_0/2)^2} + w_0/2}}$$

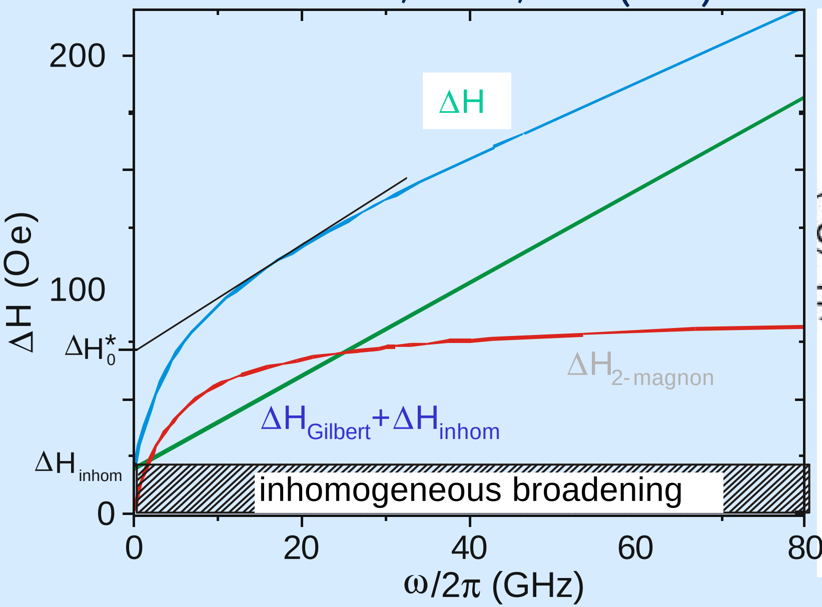
with $w_0 = gM_{\text{eff}}$

real relaxation – no inhomogeneous broadening

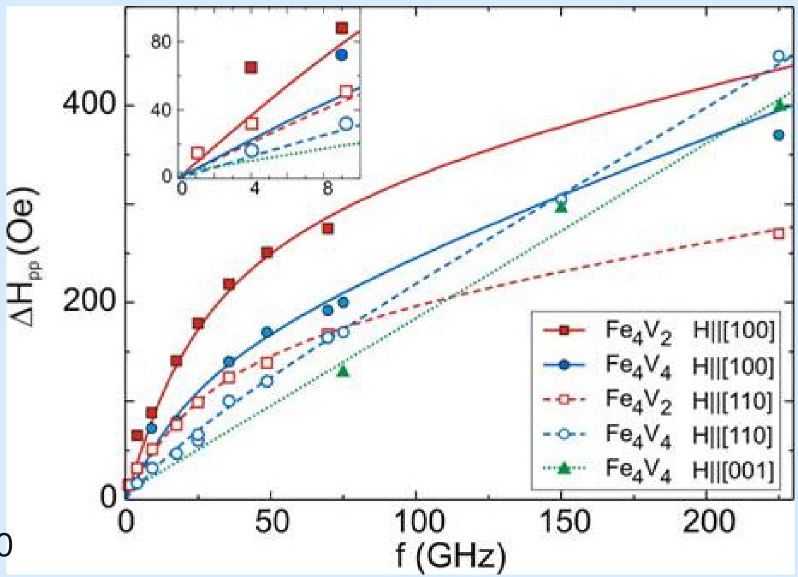
two-magnon damping dominates Gilbert damping by two orders of magnitude:

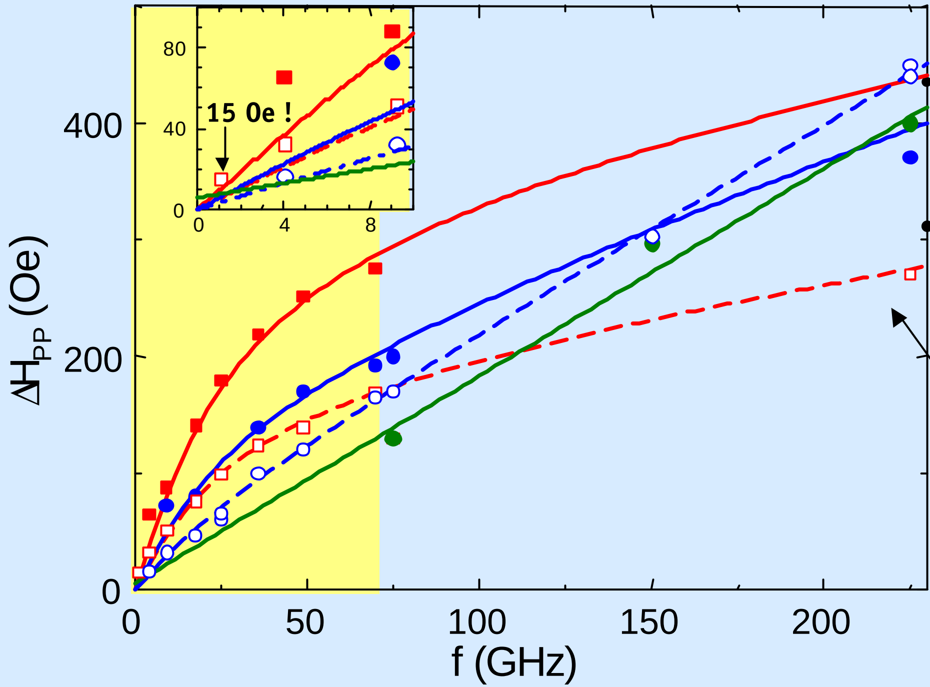
$1/T_2 \sim 10^9\ s^{-1}$ vs. $1/T_1 \sim 10^7\ s^{-1}$

R. Arias et al., PRB 60, 7395 (1999)



K. Lenz et al., PRB 73, 144424 (2006)





two-magnon scattering observed in Fe/V superlattices –

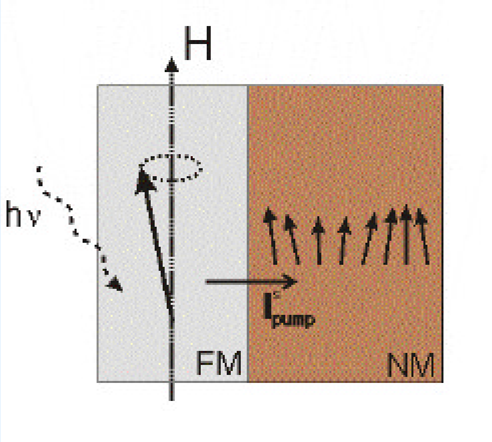
J. Lindner et al., PRB ***68****, 060102(R) (2003)*

HF FMR *K. Lenz et al. PRB* ***73****, 144424 (2006)*

	Γ (kOe)	γ·Γ (10^8 s^{-1})	G (10^8 s^{-1})	α (10^{-3})	ΔH_0 (Oe)
■ Fe_4V_2 ; H‖[100]	0.270	50.0	0.26	1.26	0
● Fe_4V_4 ; H‖[100]	0.139	26.1	0.45	2.59	0
□ Fe_4V_2 ; H‖[110]	0.150	27.9	0.22	1.06	0
○ Fe_4V_4 ; H‖[110]	0.045	8.4	0.77	4.44	0
● Fe_4V_4 ; H‖[001]	0	0	0.76	4.38	5.8

- **recent publications with similar results:**
  - Pd/Fe on GaAs(001) – network of misfit dislocations *G. Woltersdorf et al. PRB* ***69****, 184417 (2004)*
  - NiMnSb films on InGaAs/InP *B. Heinrich et al. JAP* ***95****, 7462 (2004)*

“Spin pump” effects,



s-d-exchange between spin wave and s-electron

R.H. Silsbee, A. Janossy, P. Monod, PRB **19**, 4382 (1979)

Y. Tserkovnyak, A. Brataas, G.E.W. Bauer, PRB **66**, 224403 (2002)

Landau-Lifshitz equation + extension

precession Gilbert-damping spin-pump current

$$\frac{d\mathbf{M}}{dt} = -\gamma\,\mathbf{M}\times\mathbf{H}_{\mathrm{eff}} + \frac{G}{\gamma M_S^2}\,\mathbf{M}\times\frac{d\mathbf{M}}{dt} + \frac{\gamma}{M_S V}\,\mathbf{I}^{\mathrm{S}}_{\mathbf{pump}}$$

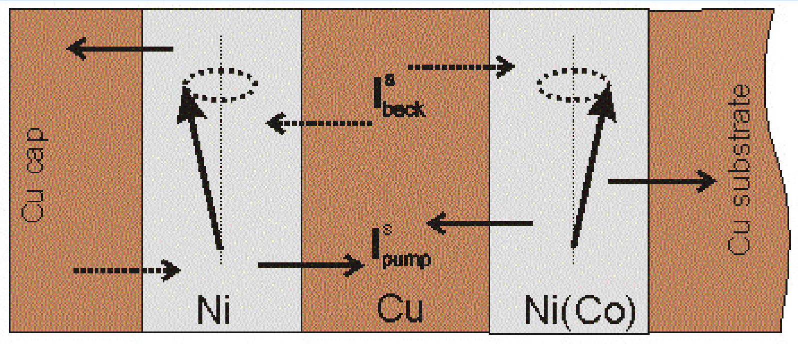
Precession drives spin current into NM

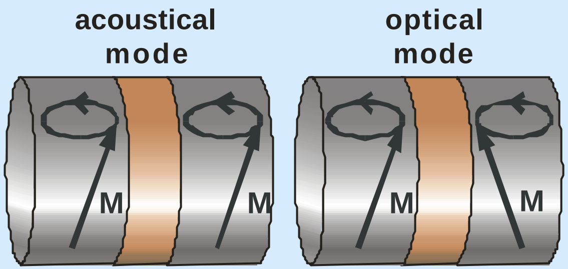
$$\mathbf{I}^{\mathrm{S}}_{\mathbf{pump}} = \frac{\hbar}{4\pi}\left(A_r\,\mathbf{M}\times\frac{d\mathbf{M}}{dt} - A_i\,\frac{d\mathbf{M}}{dt}\right)$$

NM-substrate acts as spin-sink $\Rightarrow I^S_{back} = 0$

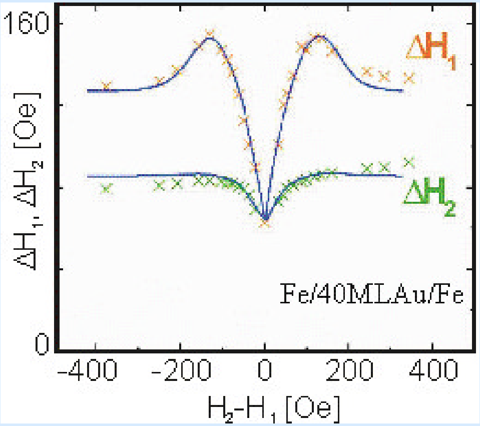
$\Rightarrow$ torque is carried away

$\Rightarrow$ Gilbert damping enhanced by spin-pump effect!





at „point of contact“ compensation of pumped currents decrease the linewidth



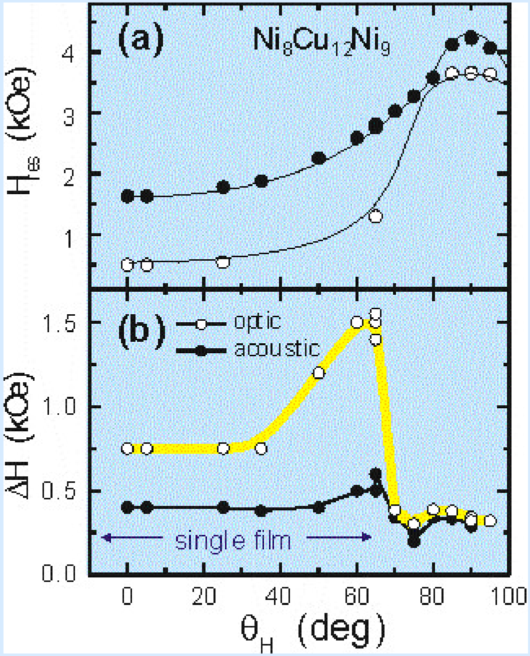
B. Heinrich et al., PRL **90**, 187601 (2003)

$d_{NM} \geq \lambda_{SF}$ $\Rightarrow$ no spin-accumulation $\Rightarrow$ $I^s_{back} = 0$

$\Rightarrow$ Gilbert-damping enhanced by spin-pump effect

compensation, if both films precess simultaneously (H_{res1}=H_{res2})

$\Rightarrow$ only Gilbert contribution remains!



K. Lenz et al.,
Phys. Rev. B **69**, 144422 (2004)

Conclusion

For nanoscale ferromagnets :

• use the reduced temperature $t = T/T_C$

• the orbital magnetic moment is NOT quenched

• the MAE may be larger by orders of magnitude

Higher order spin-spin correlations are important to explain the magnetism of nanostructures.

In most cases a *mean field model* is insufficient.

A phenomenological effective *Gilbert damping parameter* gives very little insight into the microscopic relaxation mechanism. It seems to be more instructive to separate scattering mechanisms within the magnetic subsystem from the dissipative scattering into the thermal bath

www.physik.fu-berlin.de/~bab