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

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**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, etc.

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

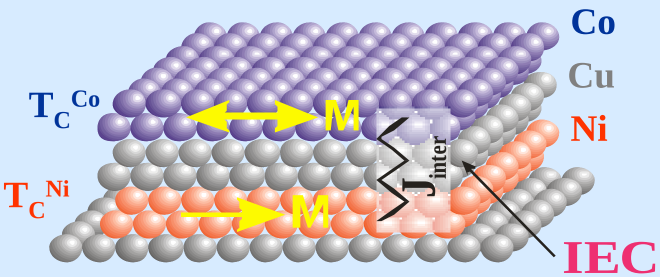
**20 years ago**

## Part I: **Fundamentals**

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

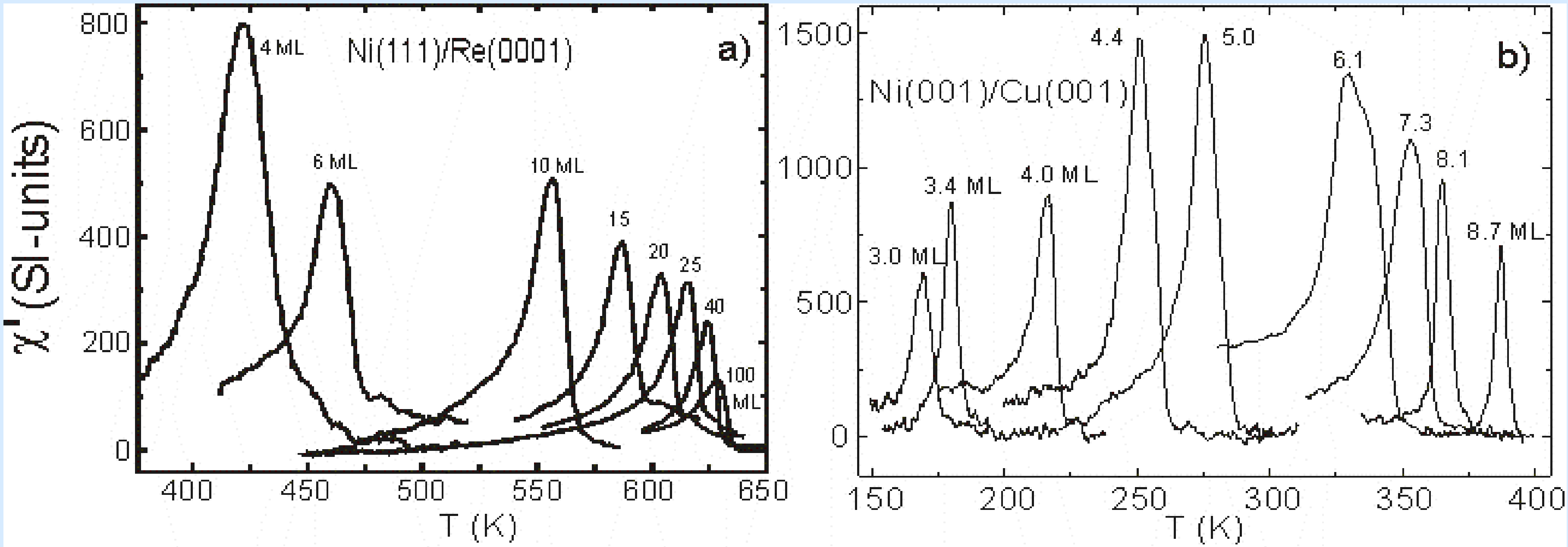
## Part II: **Spin dynamics in nano-magnets:**

- 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

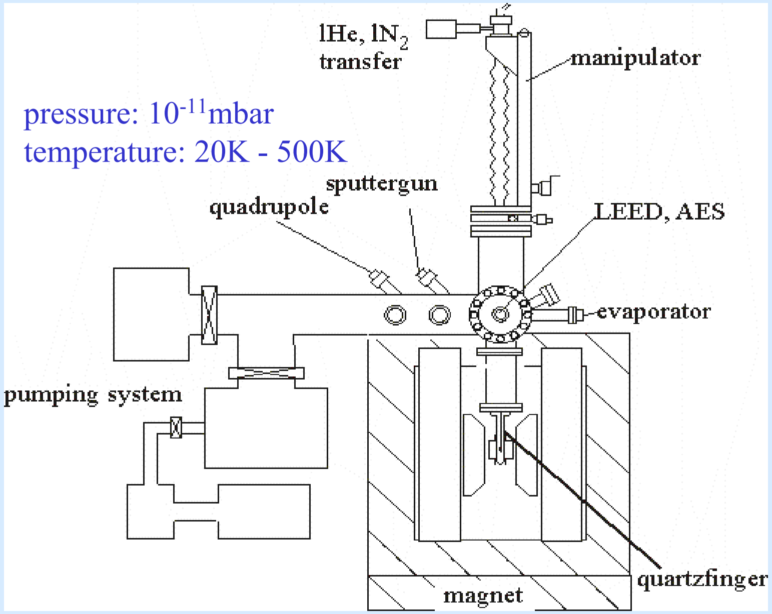
# film prepared and measured *in-situ*

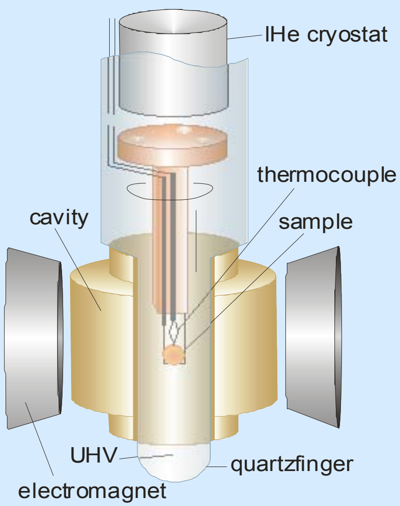



**"Magnetism in thin films"**
P. Poulopoulos, K. B., J. Phys. Condens. Matter. **11**, 9495 (1999)

# EPR / FMR in UHV

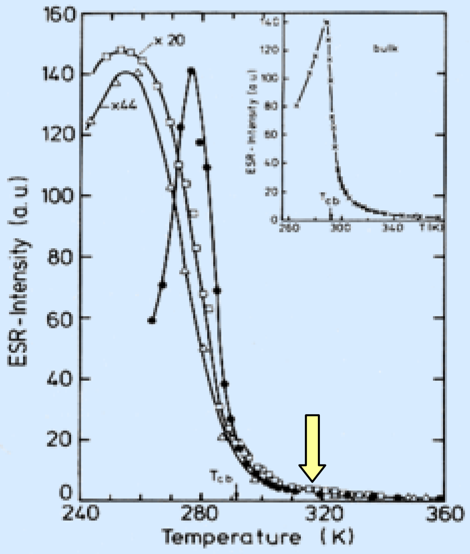
*In situ* UHV-FMR set up 1,4,9 GHz

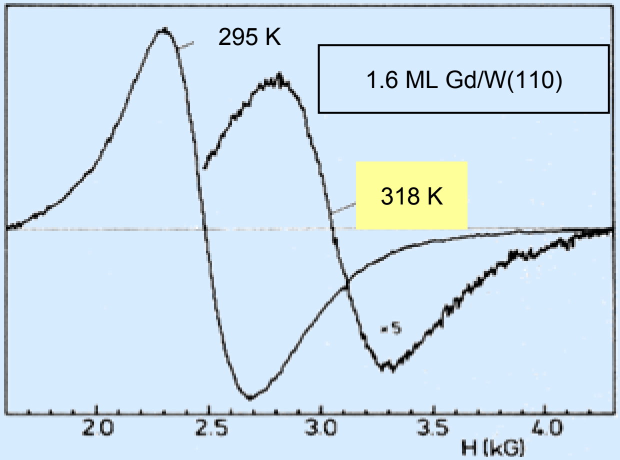



Gd/W(110)

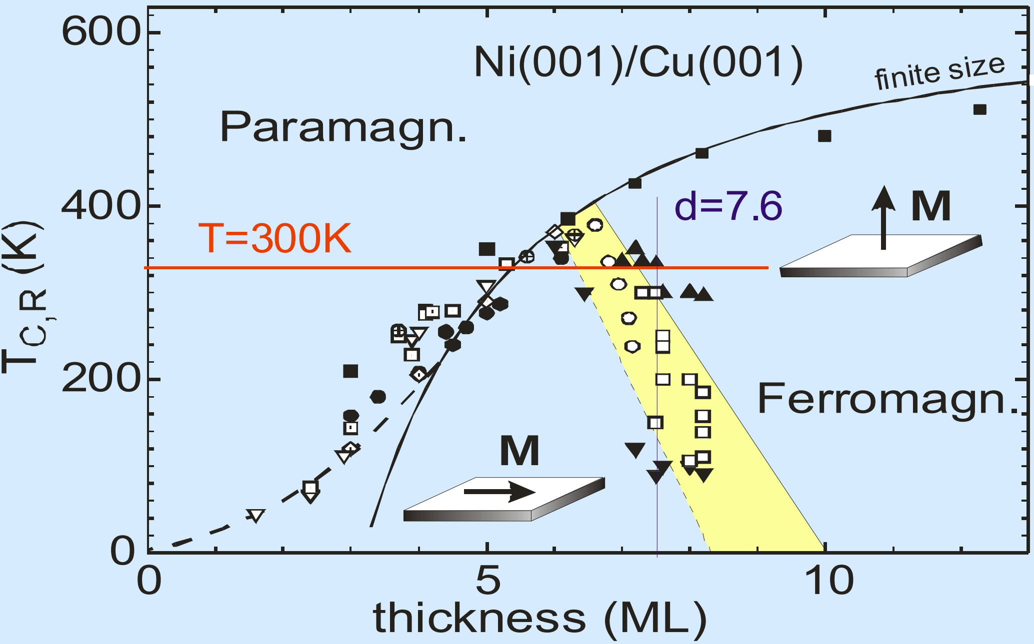
M. Farle, K.B. PRL **58**, 511 (1987)



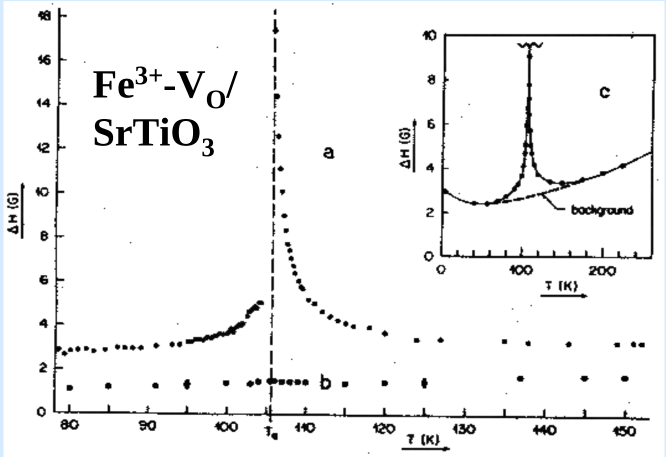




For details see:
K. B. ***Handbook of Magnetism and Advanced Magnetic Materials,*** Vol. 3 Ed. Kronmüller and Parkin, 2007 John Wiley & Sons, Ltd.

# For thin films the Curie temperature can be manipulated

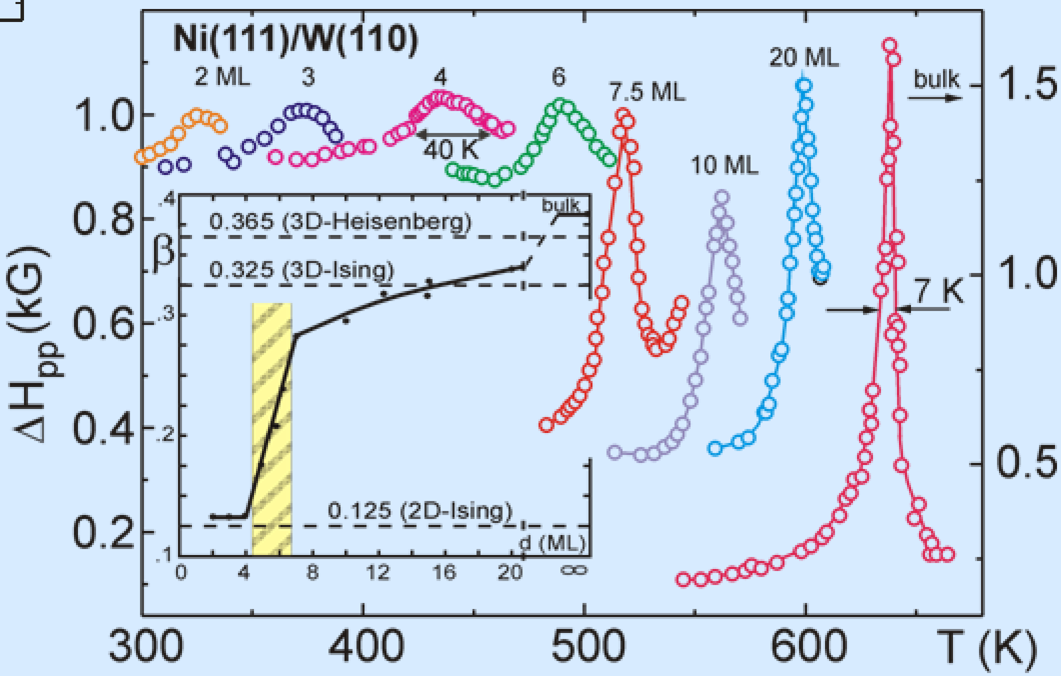



P. Poulopoulos and K. B.
J. Phys.: Condens. Matter **11**, 9495 (1999)



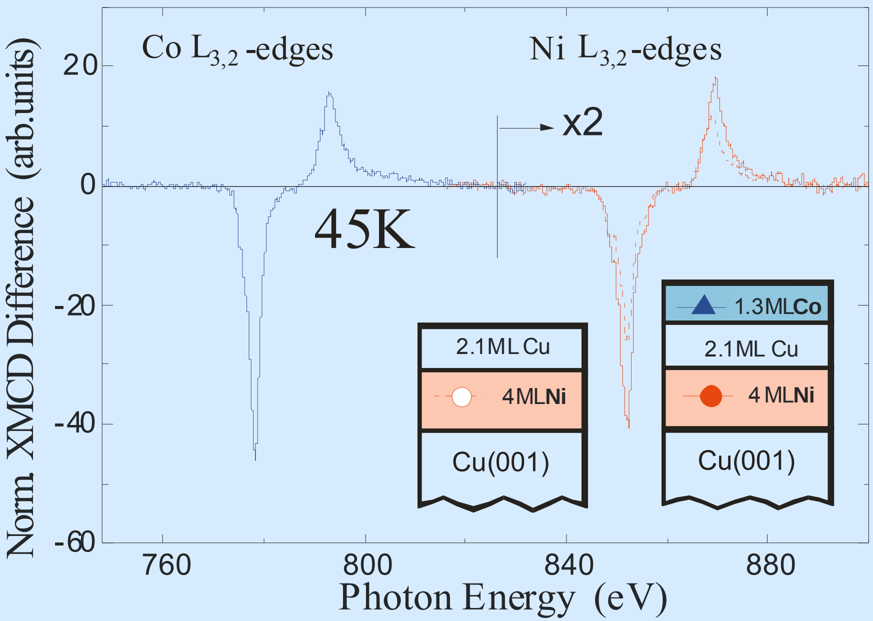

Th.v. Waldkirch, K.A. Müller, W. Berlinger, PRB (1973)

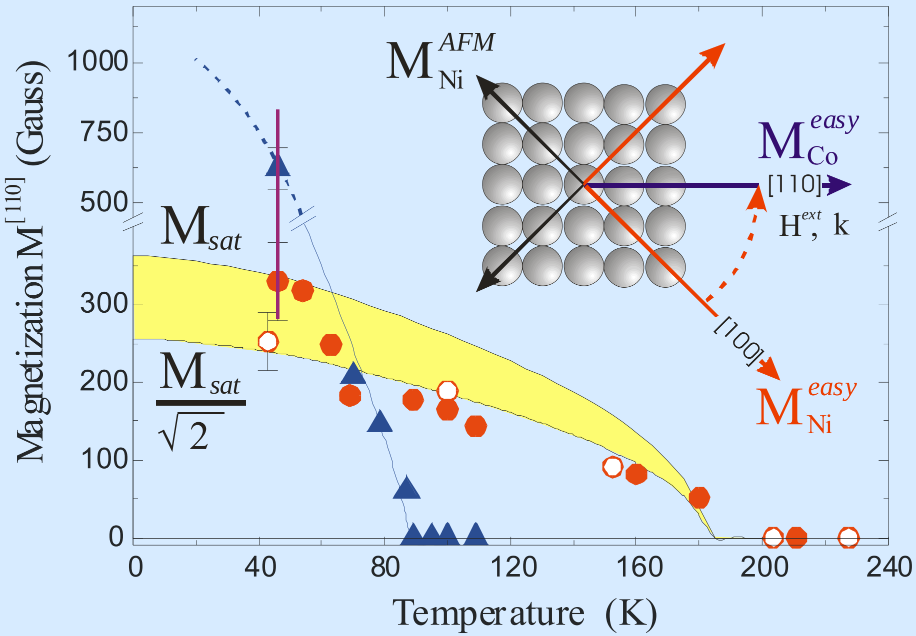
$$\frac{T_C(\infty)-T_C(d)}{T_C(\infty)} = cd^{-1/\nu}$$




Yi Li, K. B., PRL **68**, 1208 (1992)

# Crossover of $M_{Co}(T)$ and $M_{Ni}(T)$ measured with X-ray magnetic circular dichroism



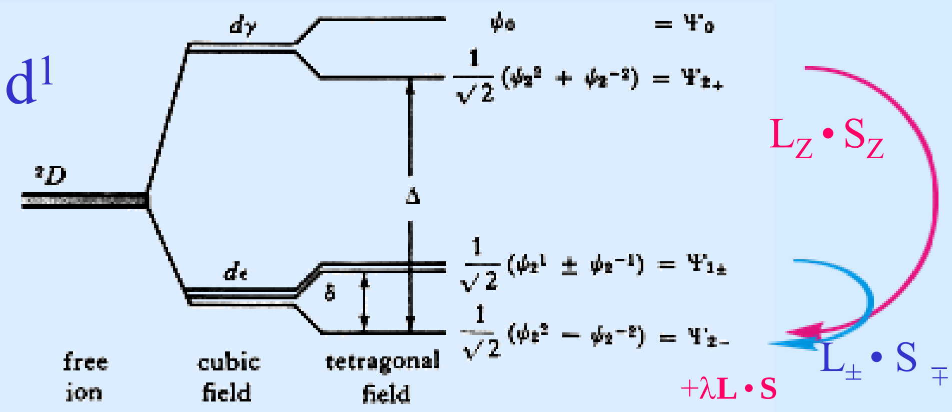




Two order parameter of $T_C^{Ni}$ and $T_C^{Co}$

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.

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

The orbital moment is quenched in cubic symmetry

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

but not for tetragonal symmetry

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

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

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

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

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

$\langle o|\mu_B \mathbf{H}\cdot\mathbf{L}|n\rangle \langle n|\lambda\mathbf{L}\cdot\mathbf{S}|o\rangle$ $\qquad$ $\langle o|\lambda\mathbf{L}\cdot\mathbf{S}|n\rangle \langle n|\lambda\mathbf{L}\cdot\mathbf{S}|o\rangle$

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

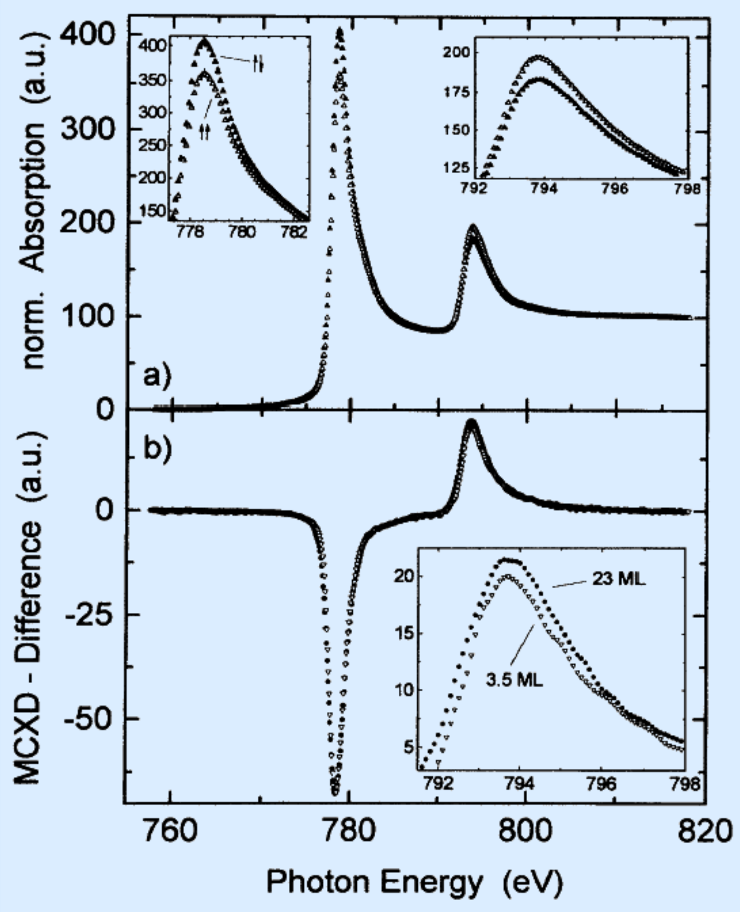
$$\mathcal{H} = g_\parallel \beta H_z S_z + g_\perp \beta (H_x S_x + H_y S_y) + D[S_z^2 - \tfrac{1}{3}S(S+1)] \qquad (3\text{-}25)$$

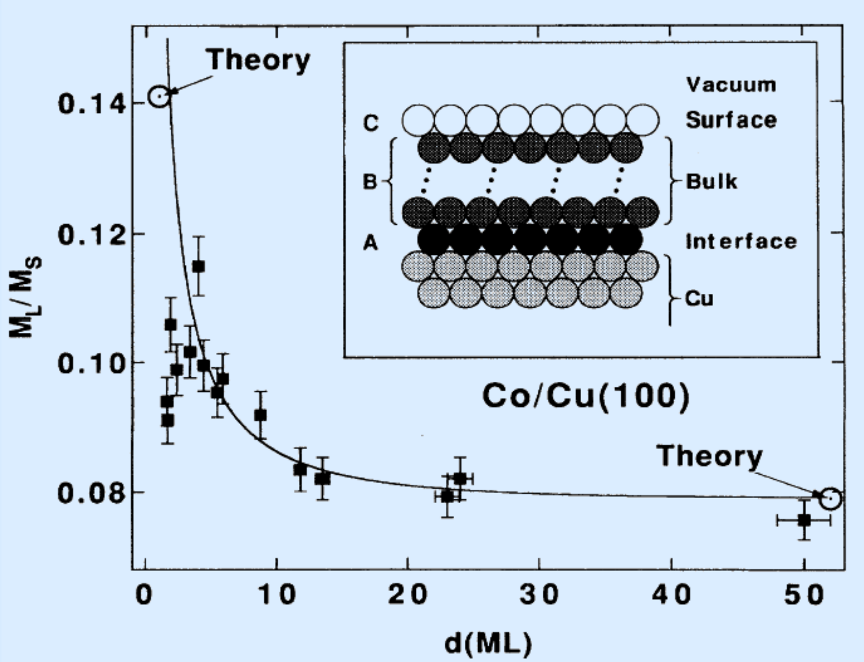
where

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

G.E. Pake, p.66

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



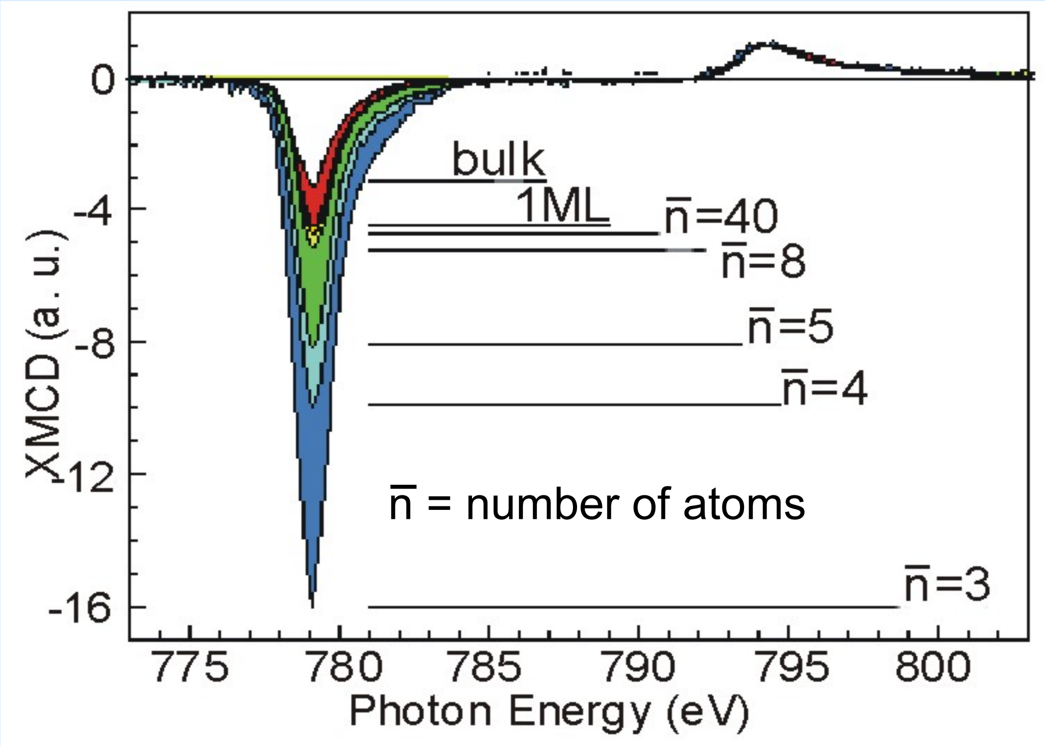




$$\left(\frac{M_L}{M_S}\right)_{\exp} = \frac{Ae^{-D(d-1)/\lambda} + B\Sigma_{n=3}^{d} e^{-D(n-2)/\lambda} + C}{\Sigma_{n=0}^{d-1} e^{-nD/\lambda}}$$

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

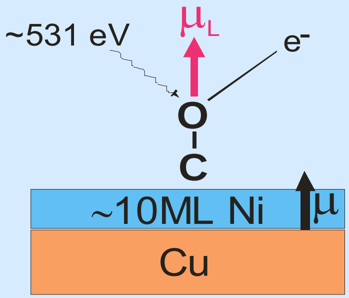
## Giant Magn. Anisotropy of Single Co Atoms and Nanoparticles

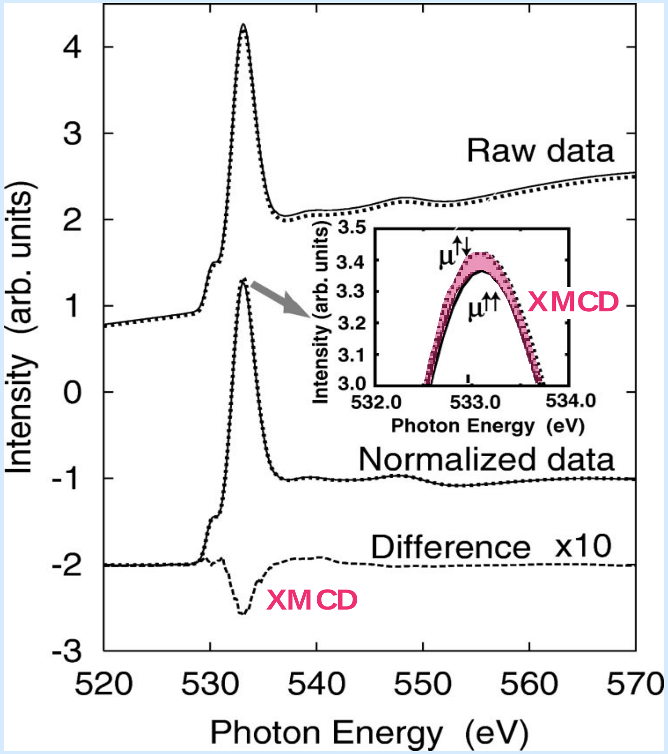
P. Gambardella et al., Science **300**, 1130 (2003)




## Induced magnetism in molecules

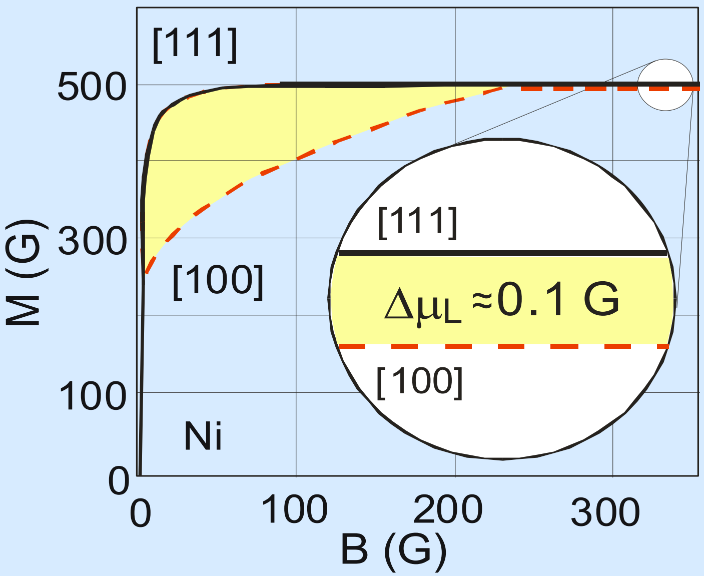
T. Yokoyama et al., PRB **62**, 14191 (2000)



# Magnetic Anisotropy Energy (MAE) and anisotropic $\mu_L$

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




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

anisotropic $\mu_L$ ↔ MAE

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

↕

$$MAE \propto \frac{\xi_{LS}}{4\mu_B} \Delta\mu_L$$

Bruno ('89)

$MAE = \int M \cdot dB \approx \frac{1}{2} \Delta M \cdot \Delta B \approx \frac{1}{2}\, 200 \cdot 200\ G^2$

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

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

*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 |

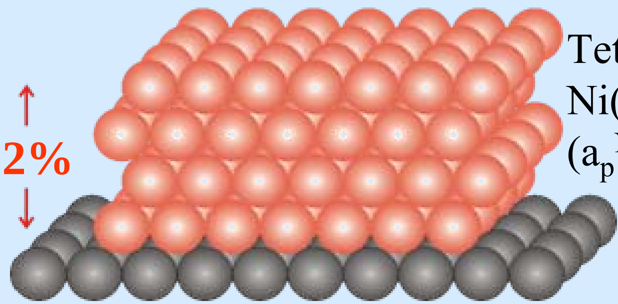
K. Baberschke, Lecture Notes in Physics, Springer **580**, 27 (2001)

There are <u>only 2 origins</u> for MAE: 1) dipol-dipol interaction ~ $(\mu_1 \bullet r)(\mu_2 \bullet r)$ and
2) spin-orbit coupling $\lambda$ **L S** (intrinsic K or $\Delta E_{band}$)

Growth of artificial nanostructures
bcc, fcc → tetragonal, trigonal

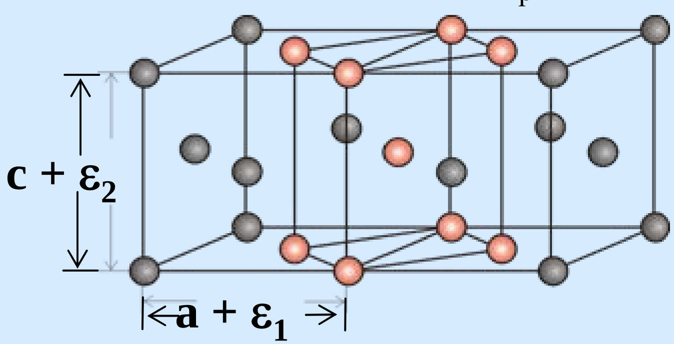
$\varepsilon_1 = +2.5\%$

$\varepsilon_2 = -3.2\%$

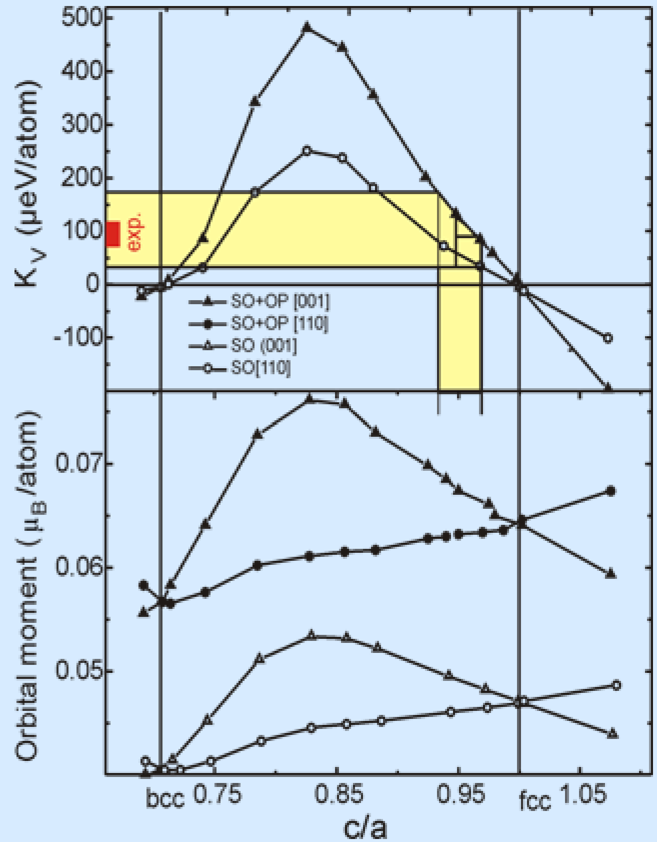


Tetragonal
Ni(001)
($a_p^{Ni\ bulk}$=2.49Å)

fcc Cu(001) substrate ($a_p$=2.55Å)

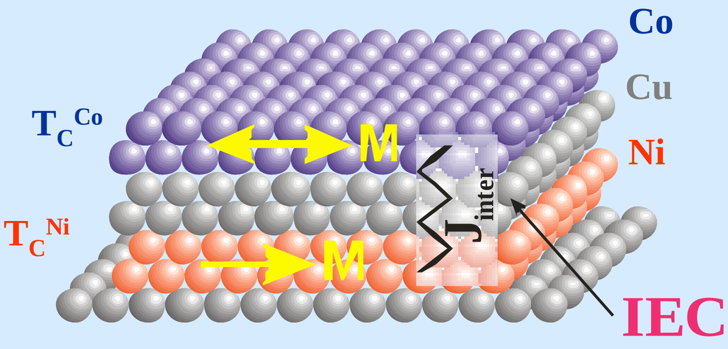



Bain path
c/a=1 fcc → fct → bcc c/a=1/√2



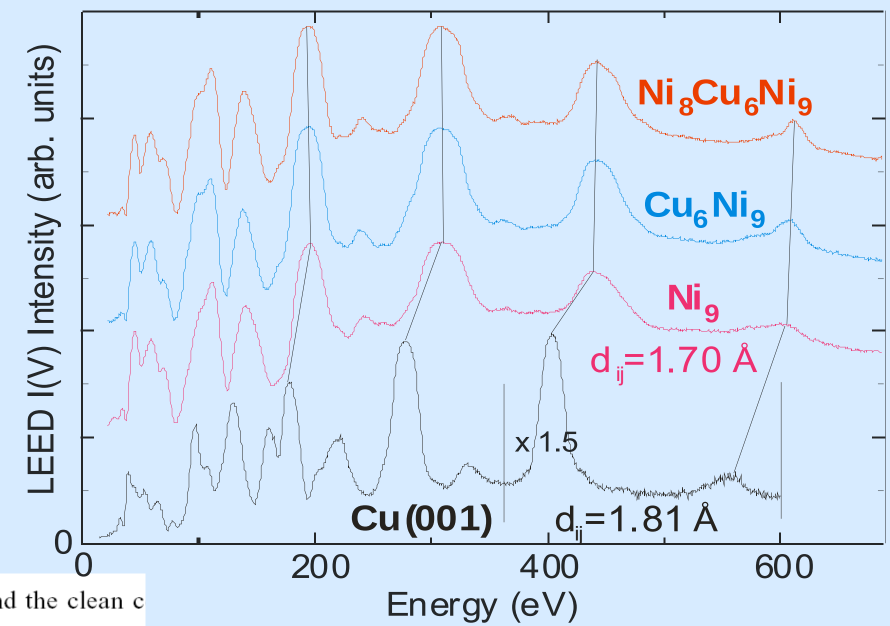

Structural changes by ≈ 0.05 Å increase MAE by 2-3 orders of magnitude (~0.2→100μeV/atom)

O. Hjortstam, K. B. et al. PRB **55**, 15026 ('97)
R. Wu et al. JMMM **170**, 103 ('97)




W. Platow et al. PRB **59,** 12641 (1999)

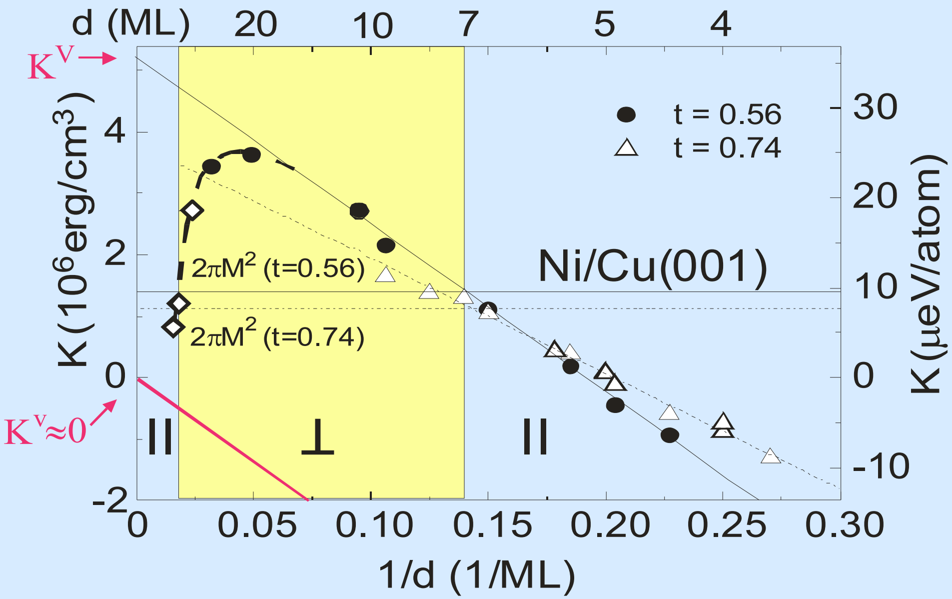
full trilayer grows in fct structure

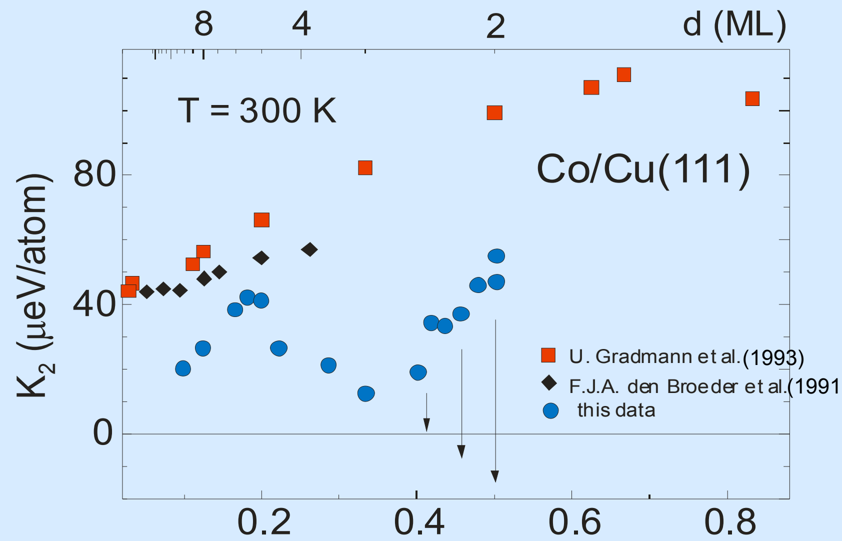


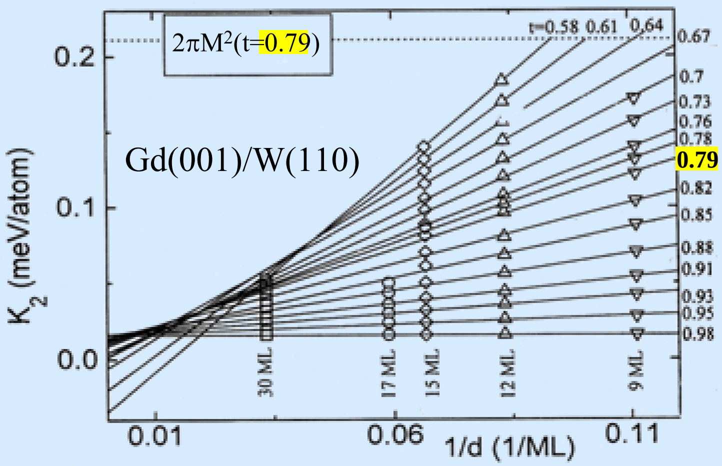

R. Nünthel, PhD Thesis FUB 2003

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

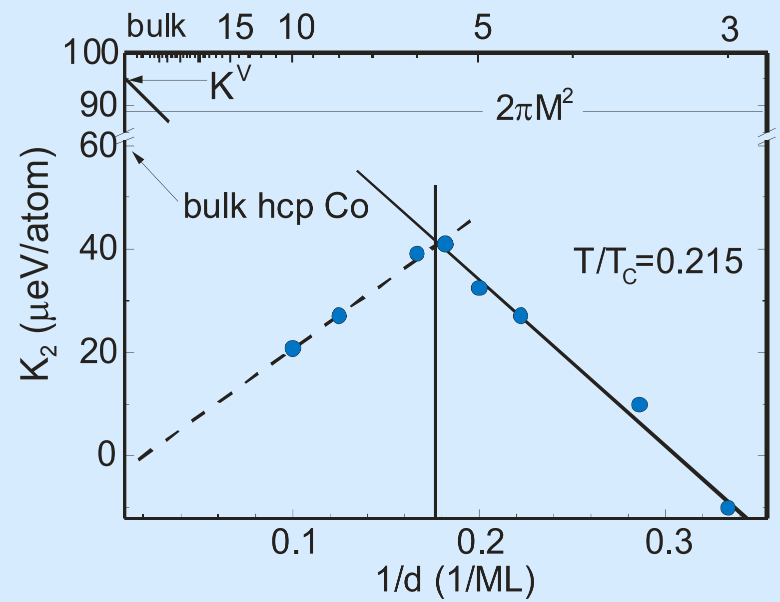
| Parameter | 0 ML | 1 ML | 2 ML | 3 ML | 4 ML | 5 ML |
|---|---|---|---|---|---|---|
| $d_{12}$ (Å) | $1.755^{+0.011}_{-0.007}$ | $1.720^{+0.014}_{-0.018}$ | $1.715^{+0.015}_{-0.015}$ | $1.725^{+0.022}_{-0.016}$ | $1.705^{+0.015}_{-0.011}$ | $1.675^{+0.012}_{-0.014}$ |
| $d_{23}$ (Å) | $1.805^{+0.006}_{-0.011}$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




G. André et al., Surface Science **326**, 275 (1995)
K. B. and M. Farle, J. Appl. Phys. **81**, 5038 (1997)

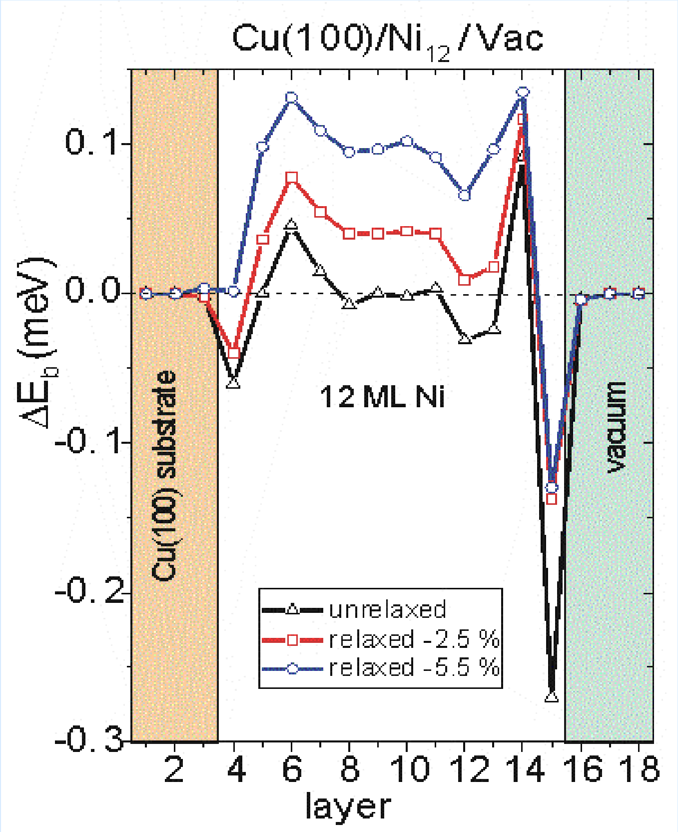



M. Farle et al., Surf. Sci. **439**, 146 (1999)

In a proper analysis, taking $T/T_C(d)$ in consideration, we always find a linear $K=K_V+2K_S/d$ dependence.
A departure from this "Néel argument" indicates changes in the x-tal structure

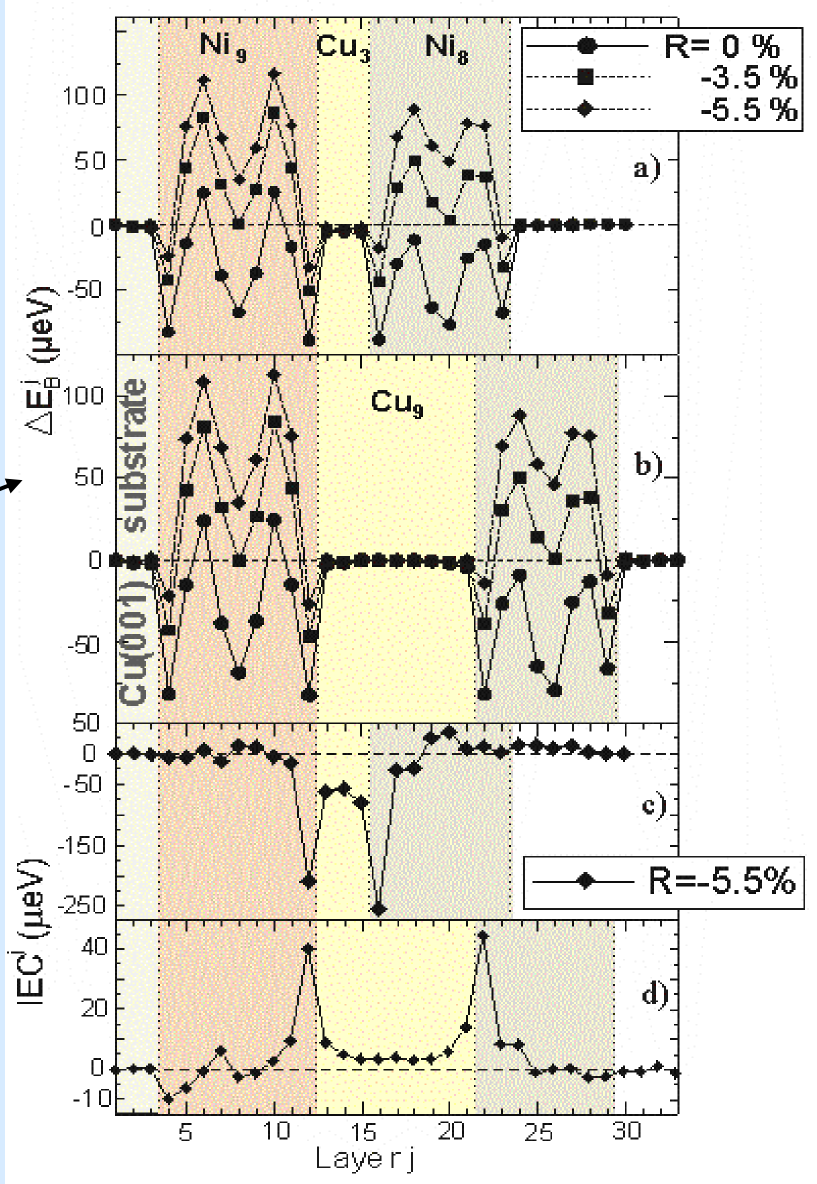
# SP-KKR calculation for rigit fcc and relaxed fct structures

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.

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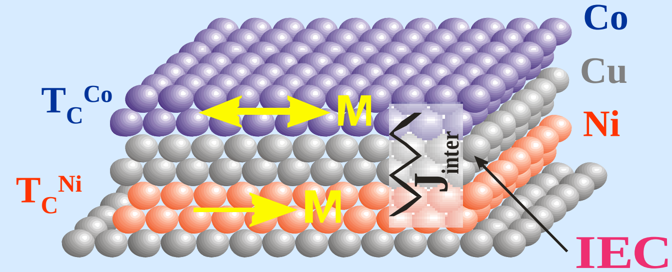


A whole variety of experiments on nanoscale magnets are available nowadays. Unfortunately many of the data are analyzed using theoretical *static mean field (MF) model*, e. g. by assuming only magnetostatic interactions of multilayers, static exchange interaction, or static interlayer exchange coupling (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 $\frac{\partial}{\partial t}\langle\langle S_i^+ S_j^- \rangle\rangle \rightarrow$

$$S_i^z S_j^+ \approx \color{green}{\langle S_i^z \rangle S_j^+} - \langle S_i^- S_i^+ \rangle S_j^+ - \langle S_i^- S_j^+ \rangle S_i^+ + \cdots$$

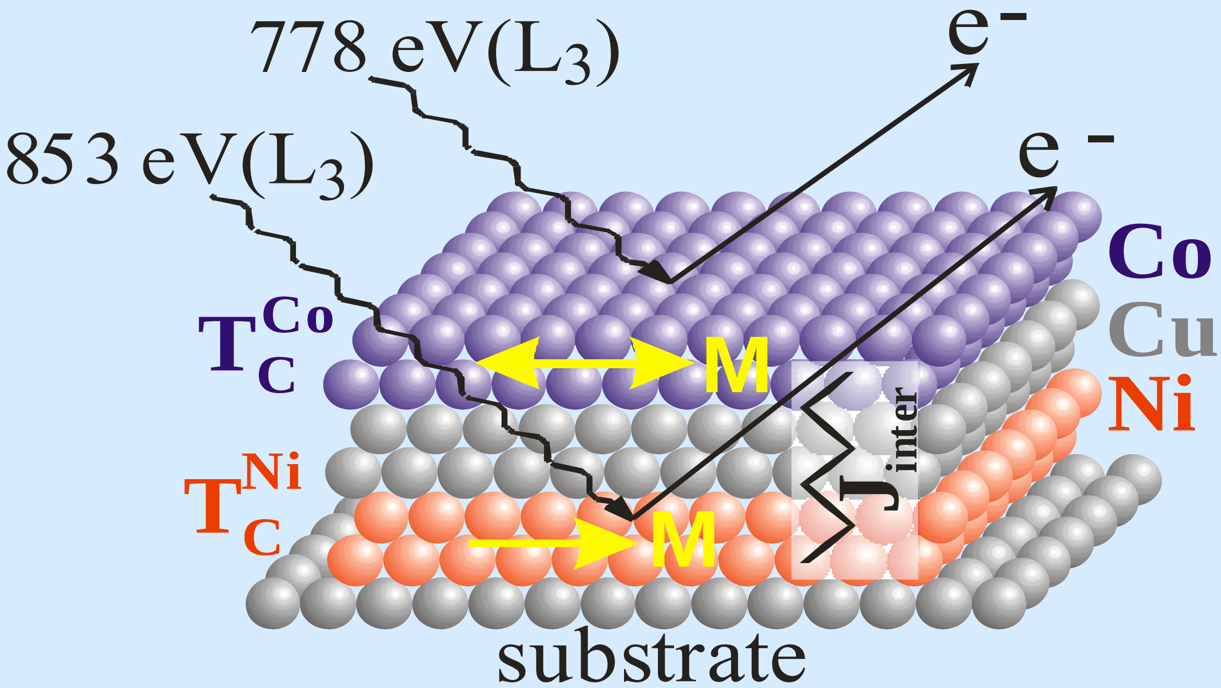
← RPA →

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.

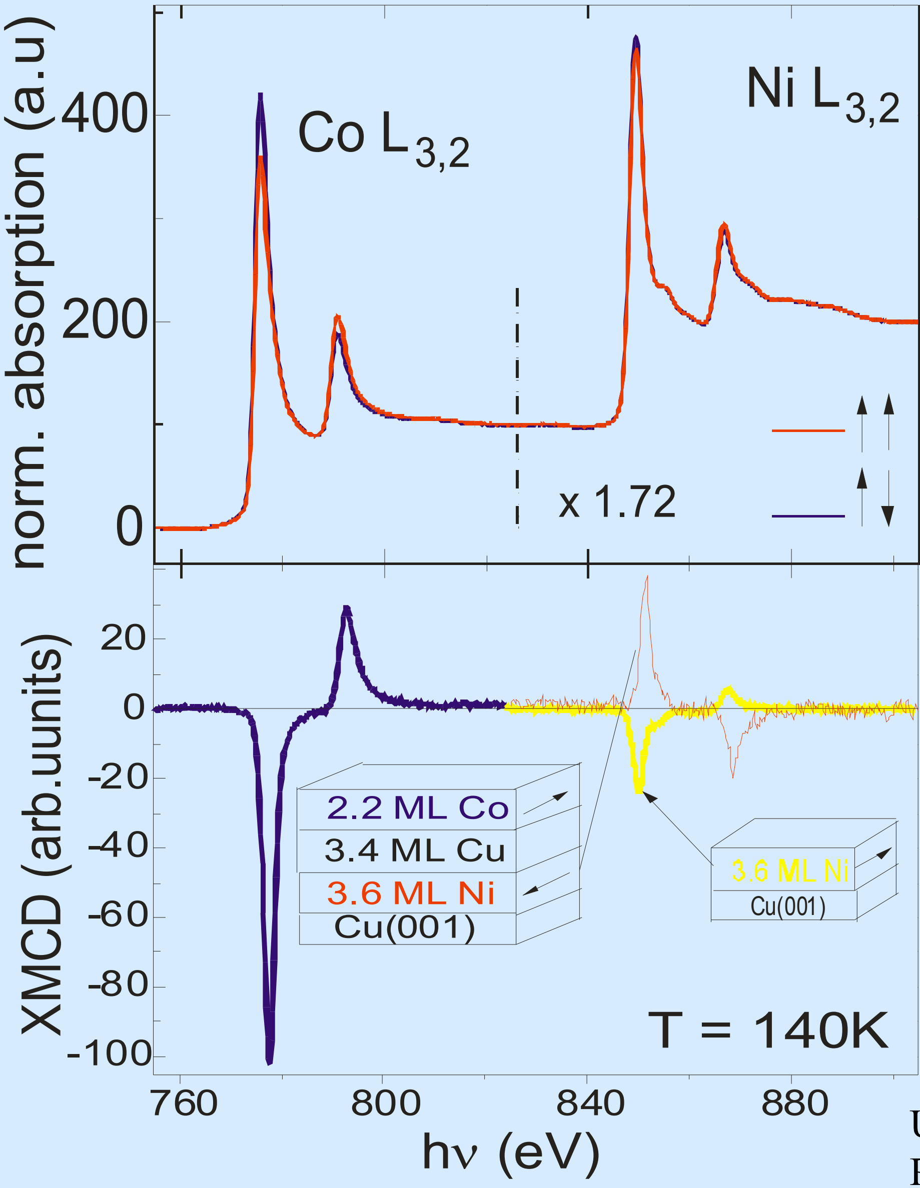
What about element specific Curie-temperatures ?

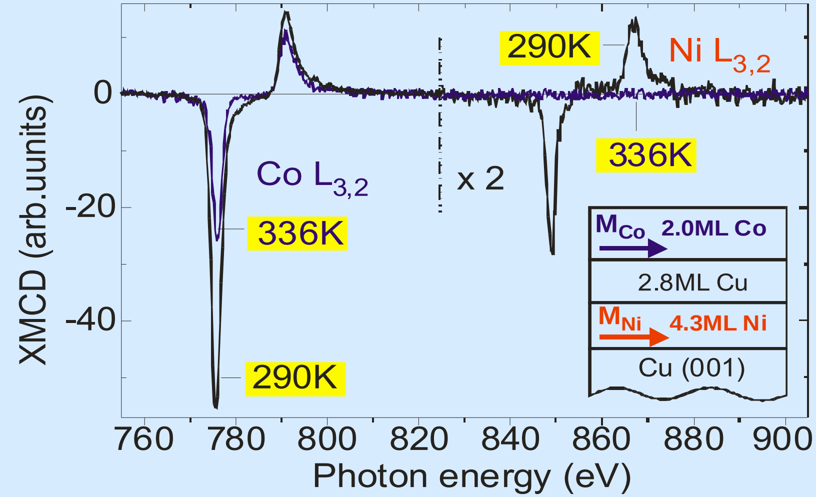
Two trivial limits: (i) $d_{Cu} = 0$ ⇒ direct coupling like a Ni-Co alloy

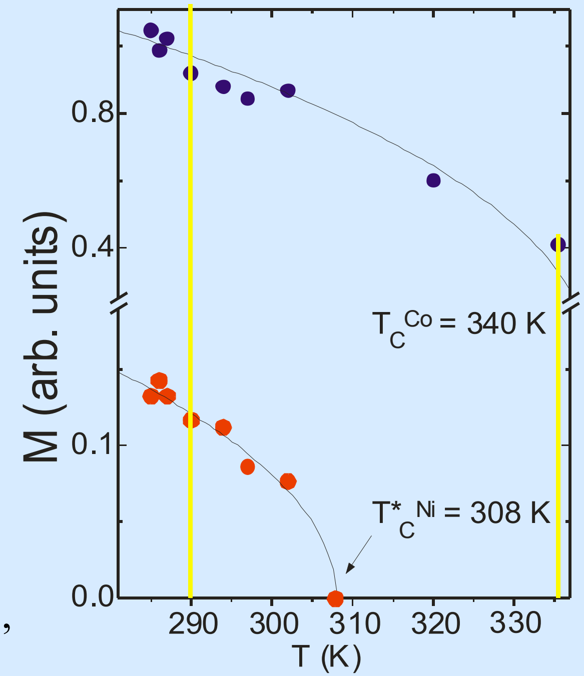
(ii) $d_{Cu}$ = large ⇒ no coupling, like a mixed Ni/Co powder

**BUT** $d_{Cu} \approx 2$ ML ⇒ **?**

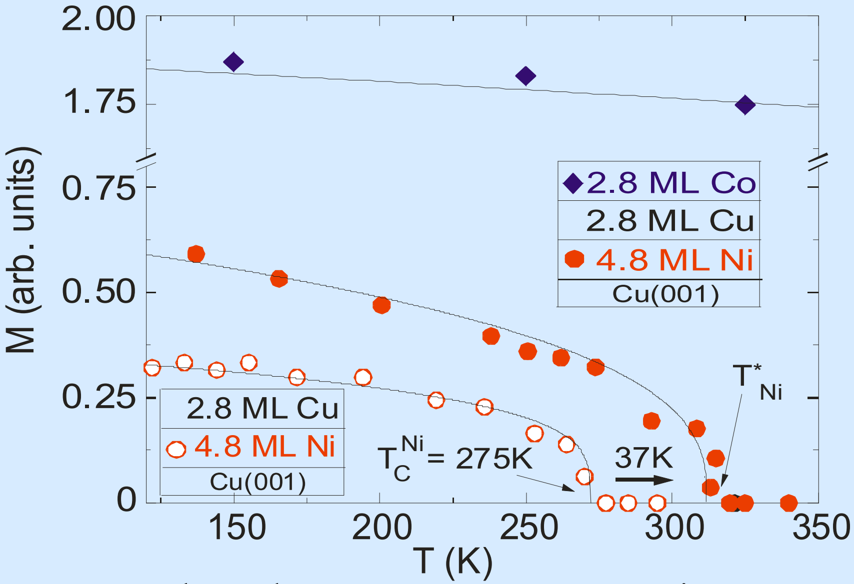
# Ferromagnetic trilayers



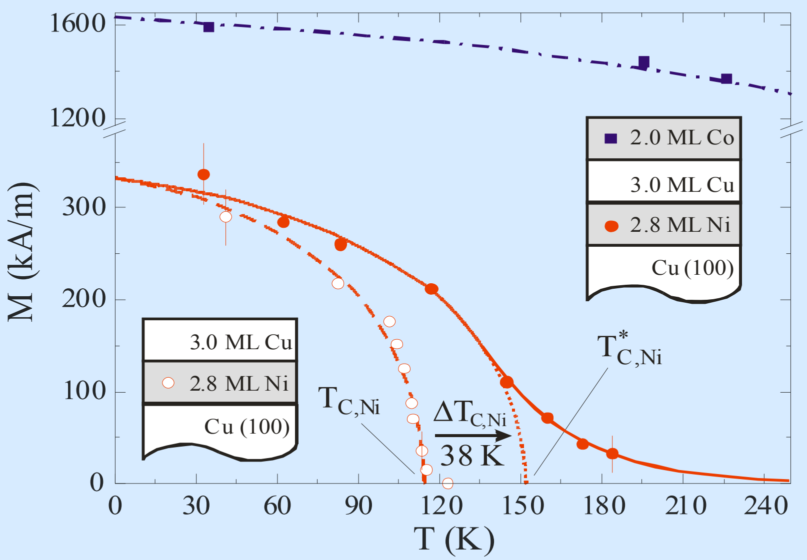



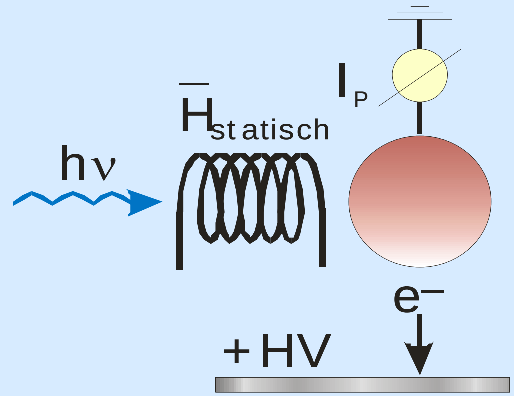




U. Bovensiepen et al., PRL **81**, 2368 (1998)

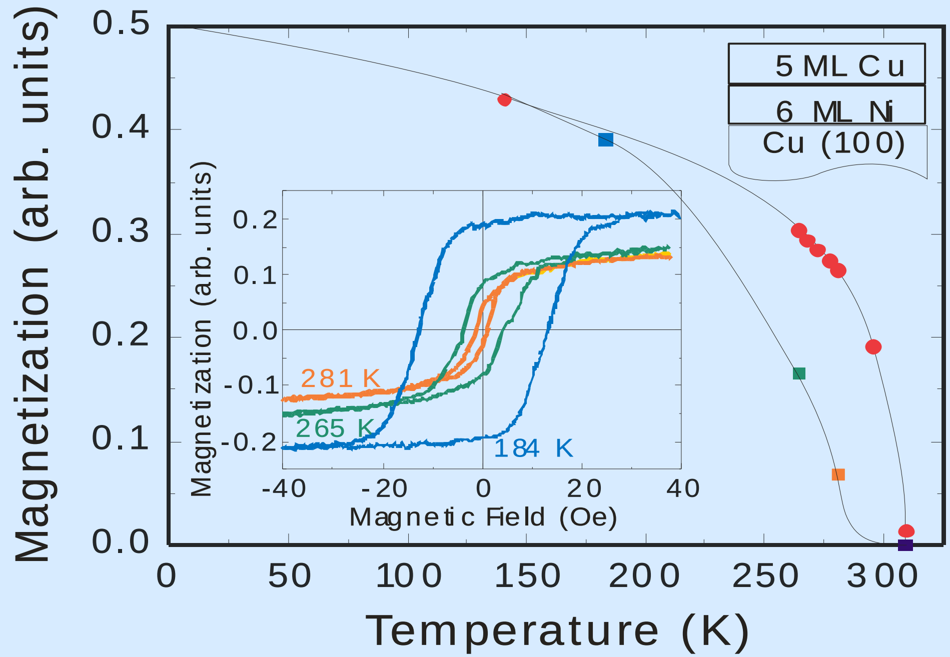



P. Poulopoulos, K. B., Lecture Notes in Physics **580**, 283 (2001)



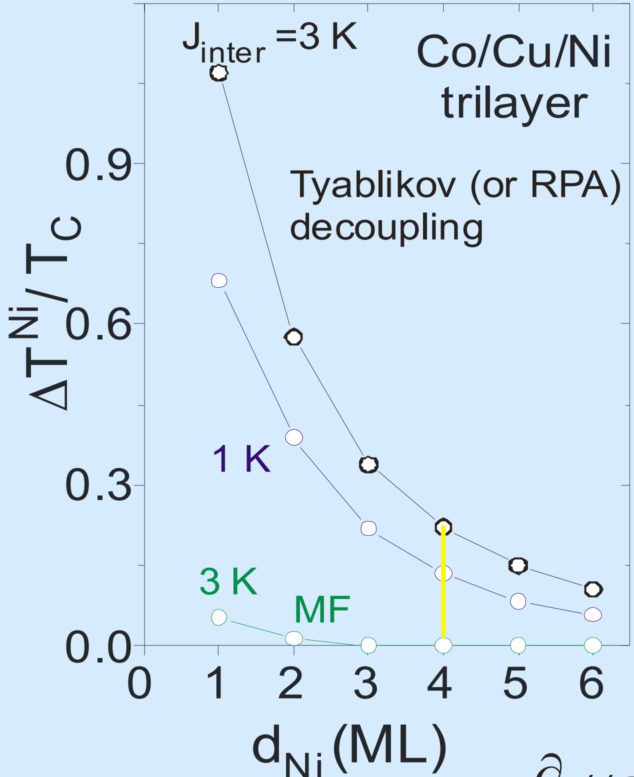




C. Sorg et al.,
XAFS XII, June 2003
Physica Scripta
**T115**, 49 (2005)

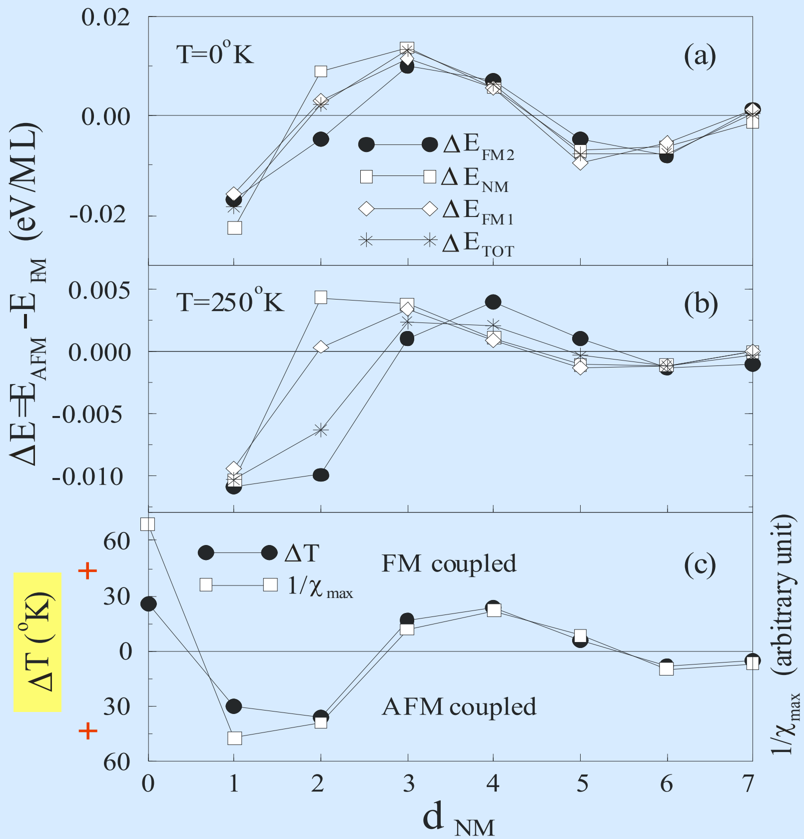


# Enhanced spin fluctuations in 2D (theory)

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




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




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

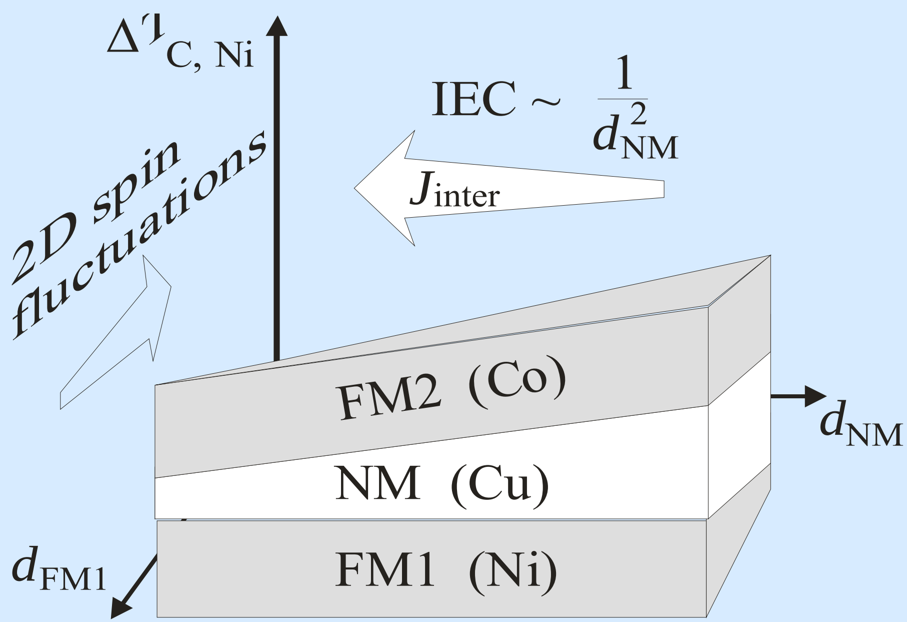
$$S_i^z S_j^+ \approx \langle S_i^z \rangle S_j^+ - \langle S_i^- S_i^+ \rangle S_j^+ - \langle S_i^- S_j^+ \rangle S_i^+ + \cdots$$

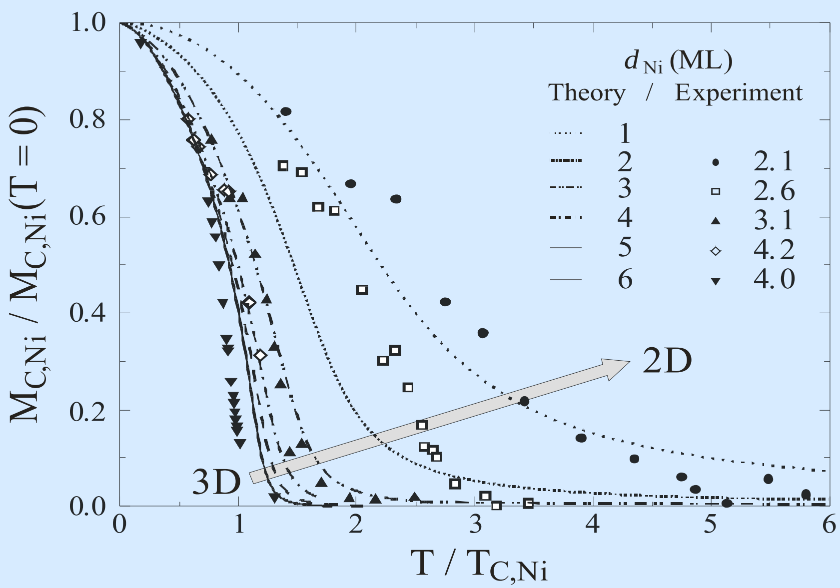
$\longleftarrow$ RPA $\longrightarrow$

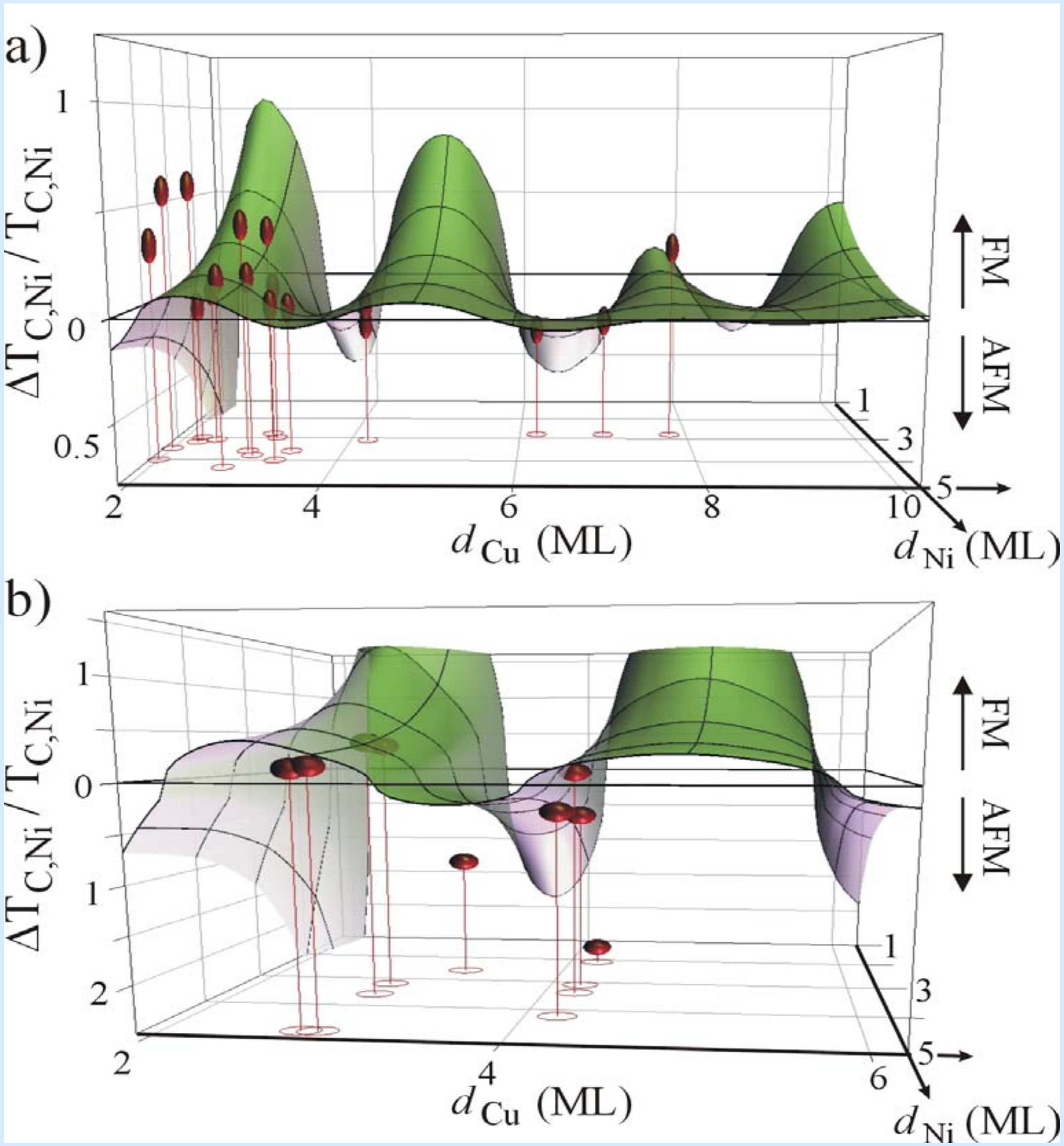
$\langle S_i^z \rangle S_j^+$, mean field ansatz (Stoner model) is insufficient to describe spin dynamics at interfaces of nanostructures

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

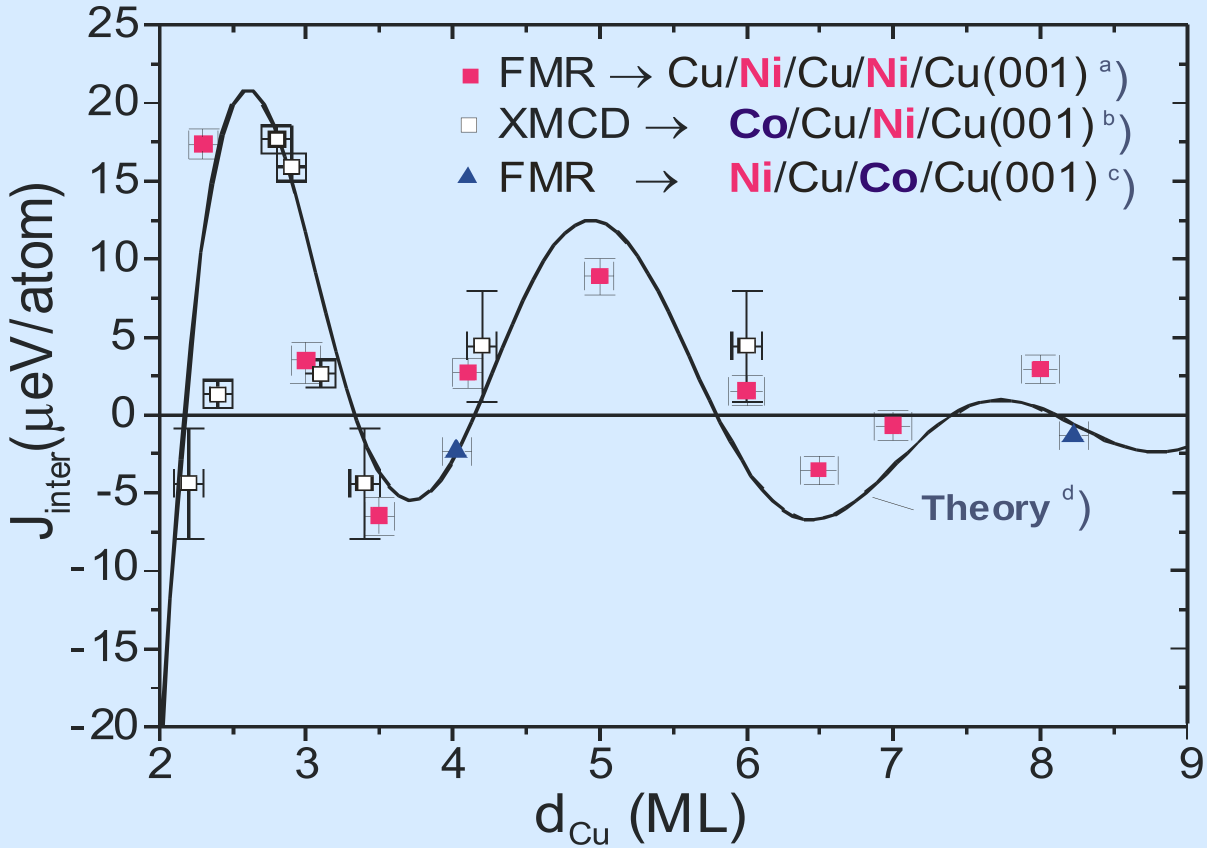
# Evidence for giant spin fluctuations [A. Scherz et al.PRB, **73** 54447 (2005)]



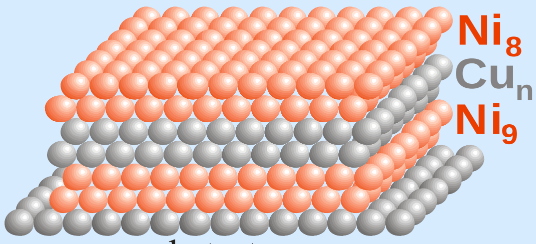



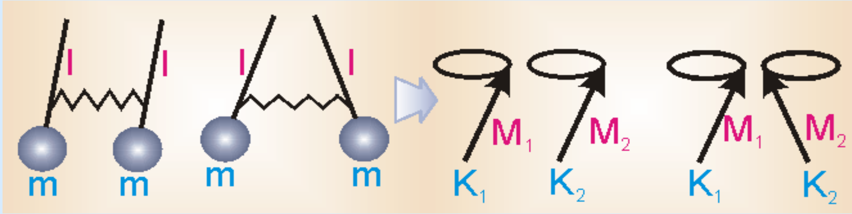
# 2. Interlayer exchange coupling and its T-dependence.

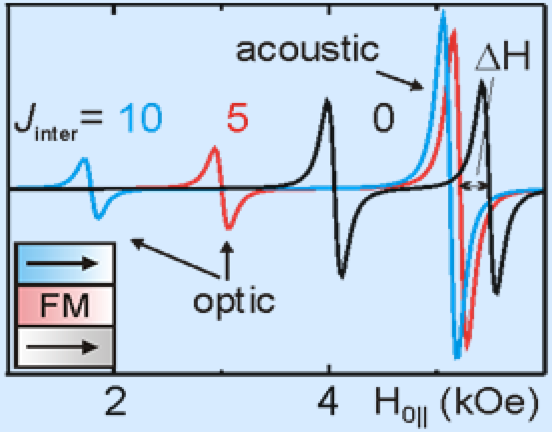


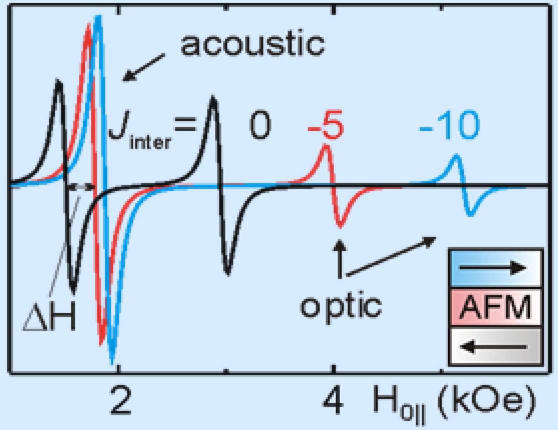

a) J. Lindner, K. B., J. Phys. Condens. Matter **15**, S465 (2003)
b) A. Ney et al., Phys. Rev. B **59**, R3938 (1999)
c) J. Lindner et al., Phys. Rev. B **63**, 094413 (2001)
d) P. Bruno, Phys. Rev. B **52**, 441 (1995)

# *in-situ* FMR in coupled films



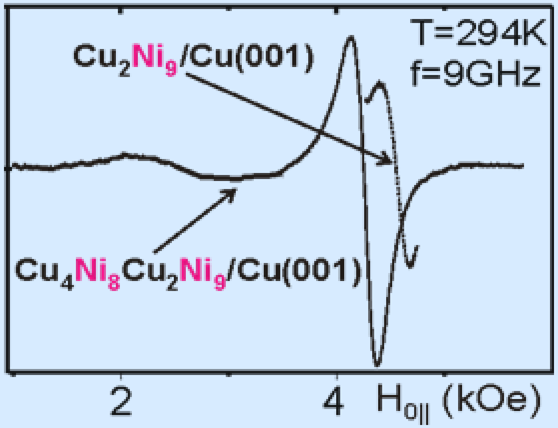



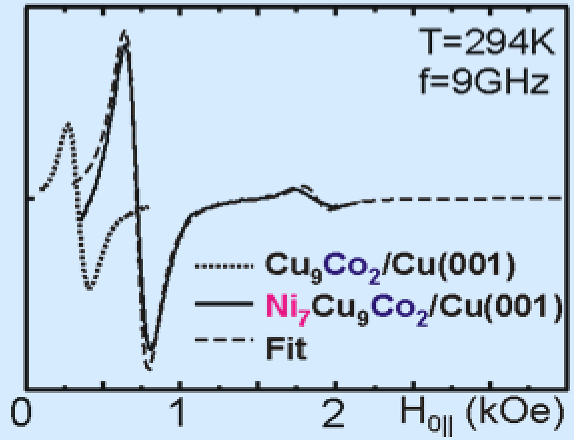




theory

**FMR**




*in-situ*
UHV-experiment




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

# Temperature dependence of $J_{inter}$ ⇔ Δ free energy

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

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

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

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

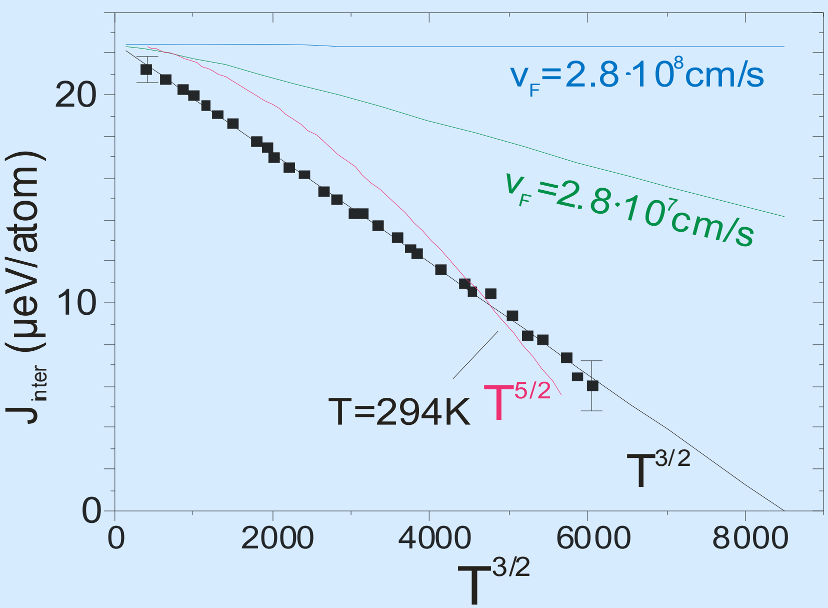
**$Ni_7Cu_9Co_2/Cu(001)$**

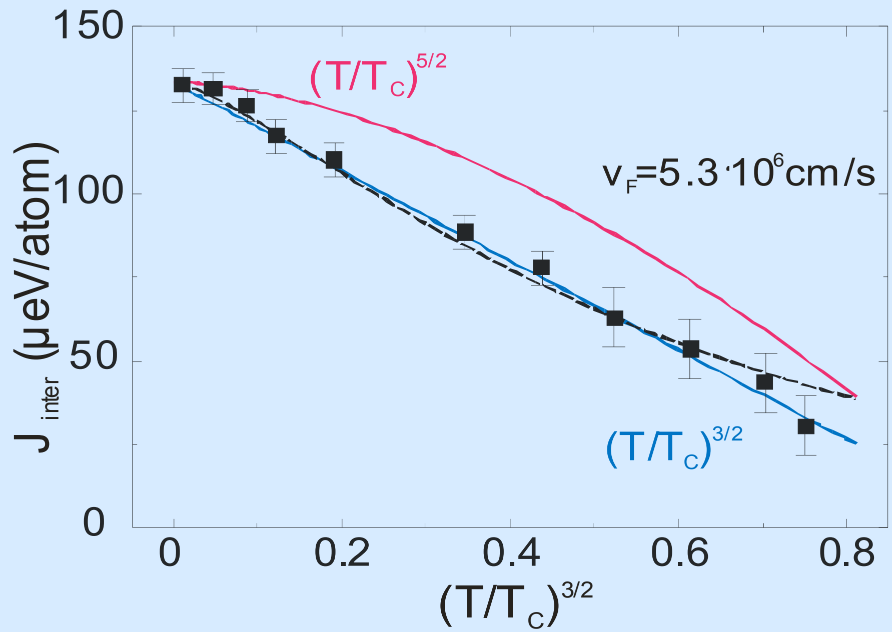
T=55K - 332K

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

**$(Fe_2V_5)_{50}$**

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



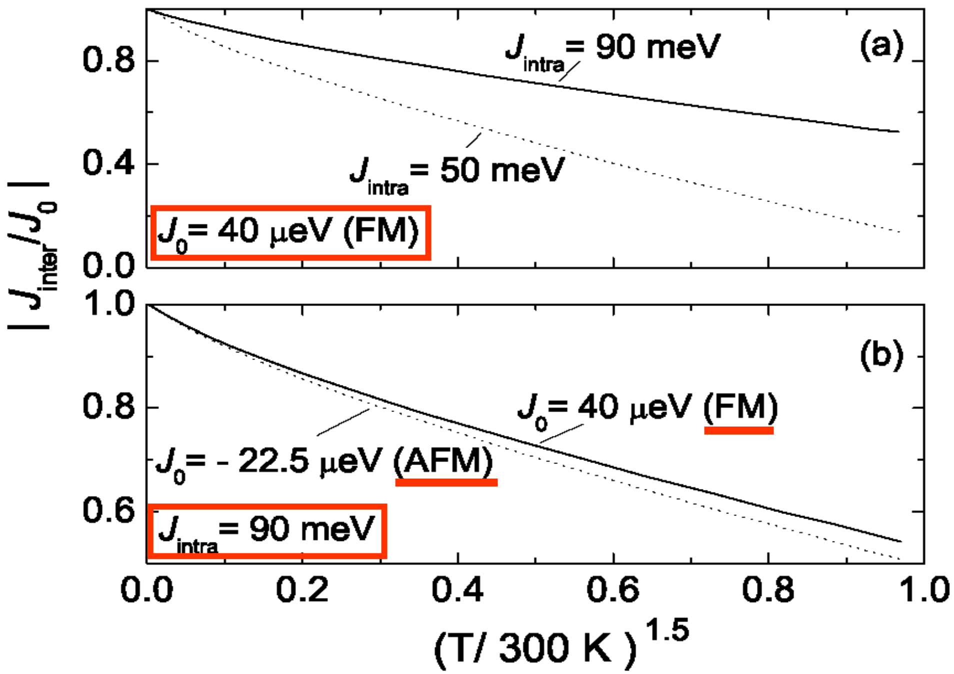
S. Schwieger, W. Nolting, PRB **69**, 224413 (2004)

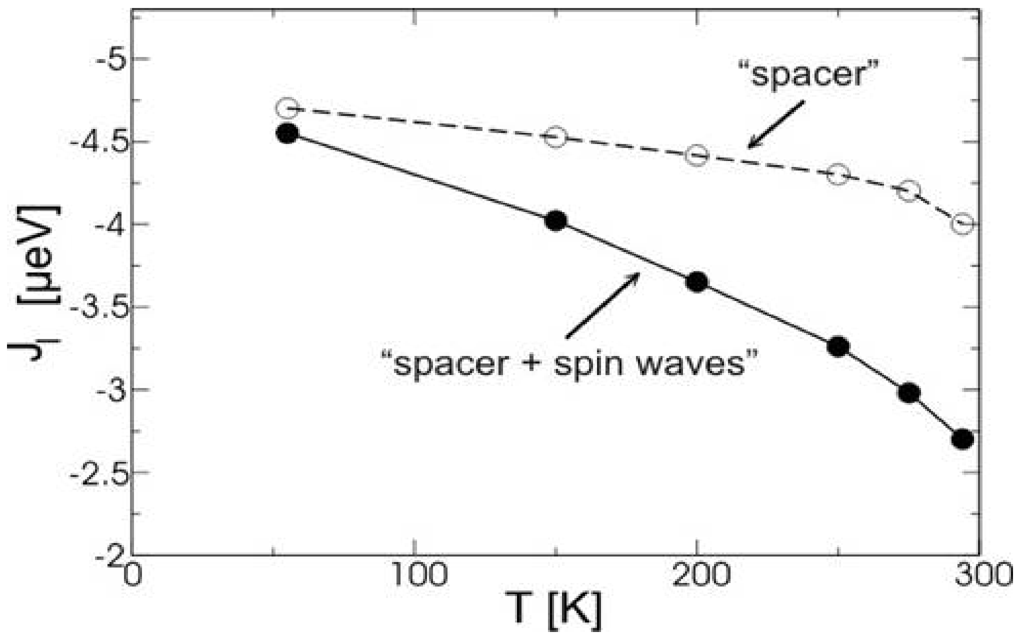
## T dependence of IEC

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 et al., PRL **98**, 57205 (2007)

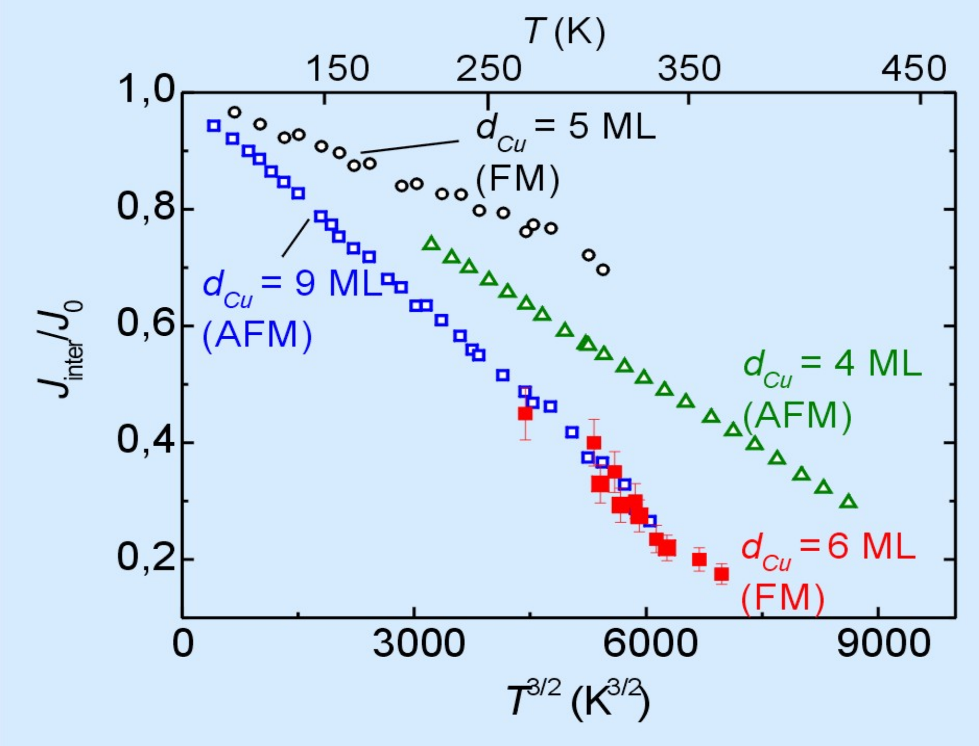


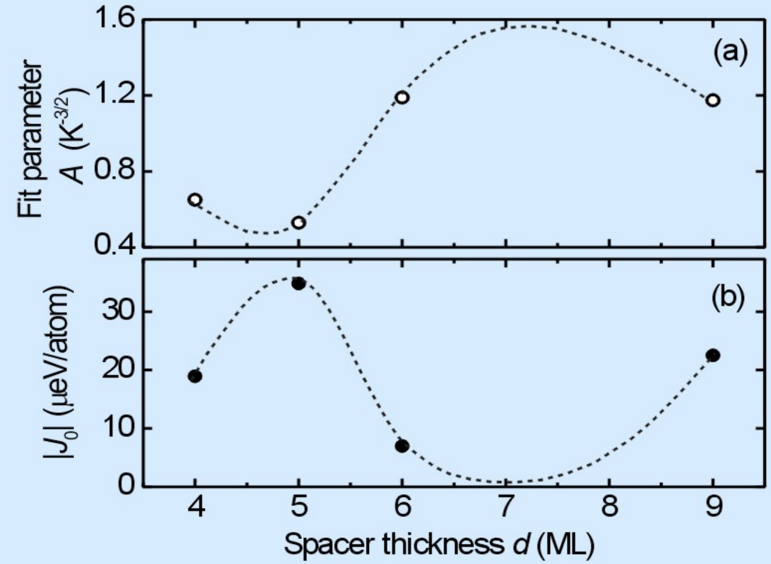
The dominant role of thermal magnon excitation in the temperature dependence of the interlayer exchange coupling: experimental verification

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*

PRB **75**, 224429 (2007)




## $J(T) \approx 1 - A(d)T^n$, with $n \approx 1.5$




$A(d) \neq$ const. (interface)

$A(d) \neq$ linear function (electronic bandstructure)

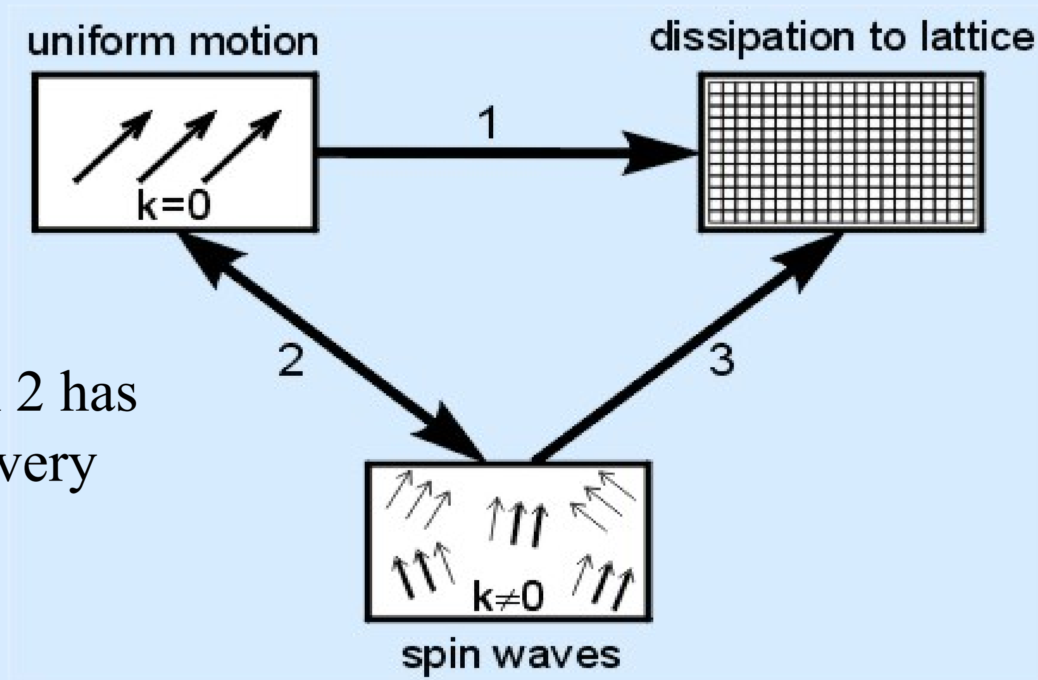
$A(d) \approx$ osc. function (spin wave excitation)

# 3. Gilbert damping versus magnon-magnon scattering.

1834 IEEE TRANSACTIONS ON MAGNETICS, VOL. 34, NO. 4, JULY 1998

## 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.




Mostly an effective damping (path 1) was modeled/fitted.

In nanoscale magnetism path 2 has been discussed very very little.

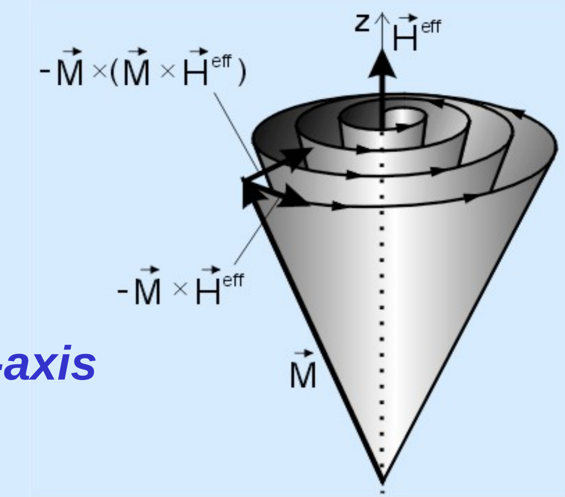
## Landau-Lifshitz-Gilbert equation(1935)

$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = -\gamma\,\mathbf{m}\times\mathbf{H}_{\mathrm{eff}} \quad + \alpha\,\mathbf{m}\times\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t}$$

**Gilbert damping**

***|M|=const.***

***M spirals on a sphere into z-axis***




## Bloch-Bloembergen Equation (1956)

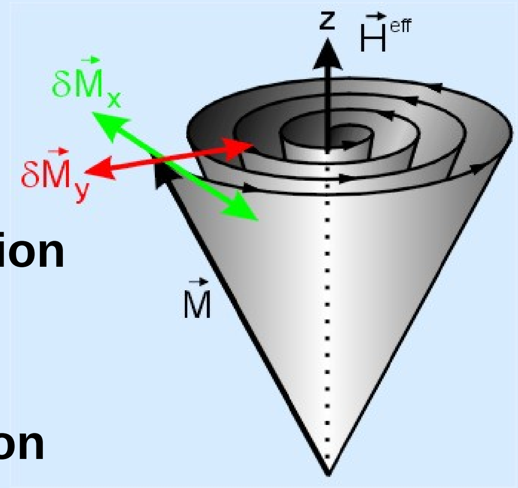
$$\frac{\mathrm{d}m_z}{\mathrm{d}t} = -\gamma(\,\mathbf{m}\times\mathbf{H}_{\mathrm{eff}}\,)_z - \frac{m_z - M_S}{T_1}$$

**spin-lattice relaxation *(longitudinal)***

$$\frac{\mathrm{d}m_{x,y}}{\mathrm{d}t} = -\gamma(\,\mathbf{m}\times\mathbf{H}_{\mathrm{eff}}\,)_{x,y} - \frac{m_{x,y}}{T_2}$$

**spin-spin relaxation *(transverse)***

***$M_z$=const.***



# FMR Linewidth - Damping

## Landau-Lifshitz-Gilbert-Equation

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

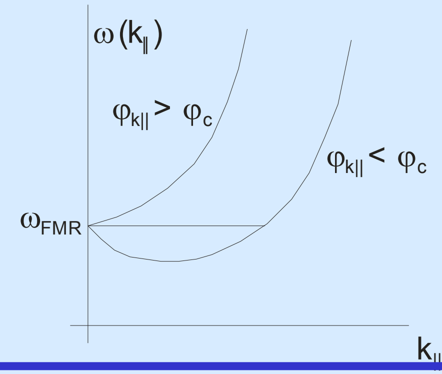
viscous damping,
energy dissipation

## 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

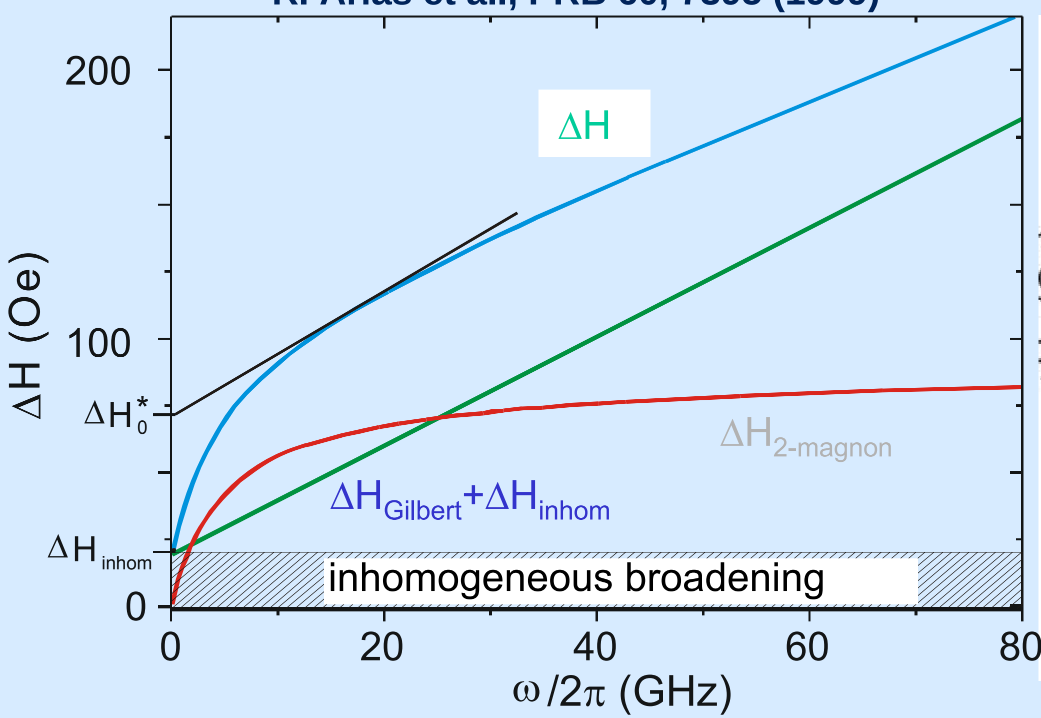
**Which FMR-publication has checked (disproved) quantitatively this analytical function?**

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

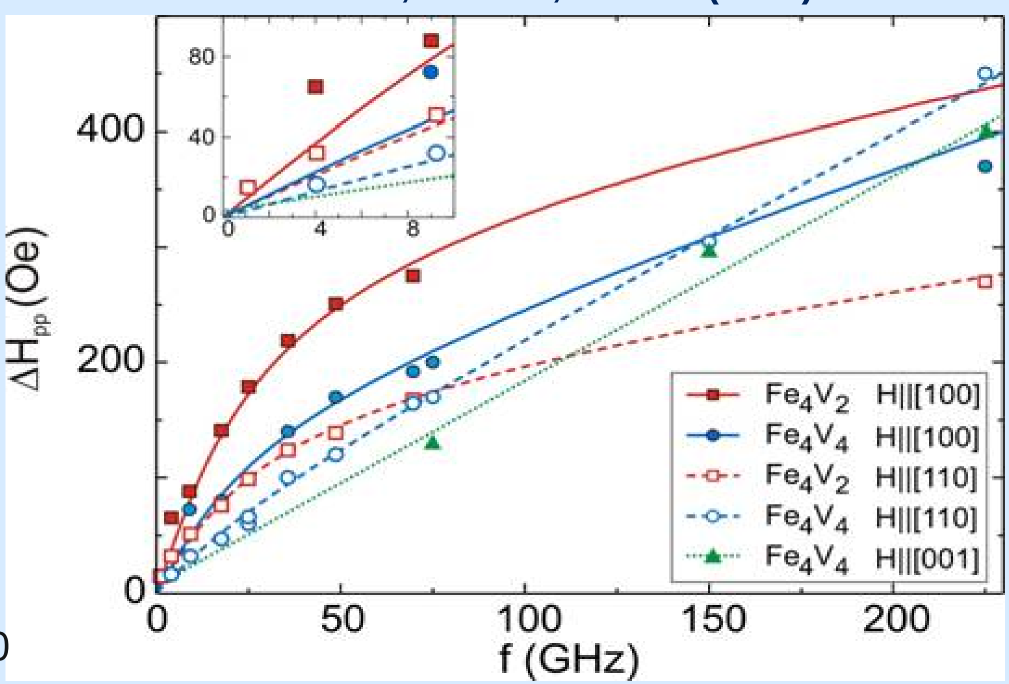
$$\Delta H_{2-\text{magnon}}(\omega) = \Gamma \arcsin \sqrt{\frac{\sqrt{\omega^2 + (\omega_0/2)^2} - \omega_0/2}{\sqrt{\omega^2 + (\omega_0/2)^2} + \omega_0/2}}$$

with $\omega_0 = \gamma M_{eff}$

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



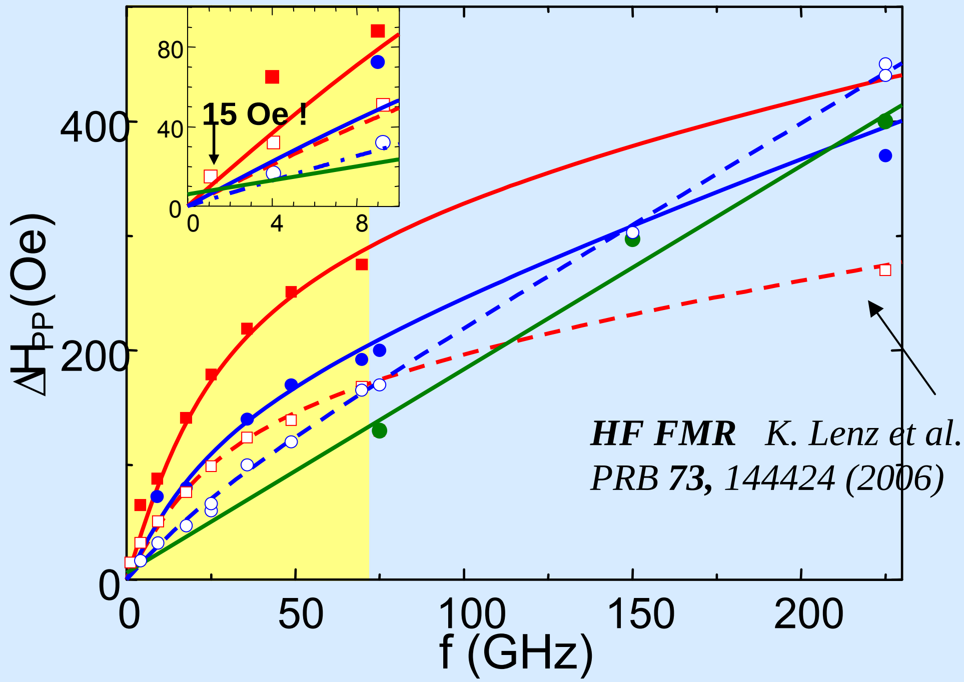

**K. Lenz et al., PRB 73, 144424 (2006)**



K. B. Physica Status Solidi b **245**, 174 (2008)

- **two-magnon scattering observed in Fe/V superlattices –**

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




**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. $1/T_1 \sim 10^7\ s^{-1}$**

| | Γ (kOe) | γ·Γ ($10^8\ s^{-1}$) | G ($10^8\ s^{-1}$) | α ($10^{-3}$) | $\Delta H_0$ (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 |

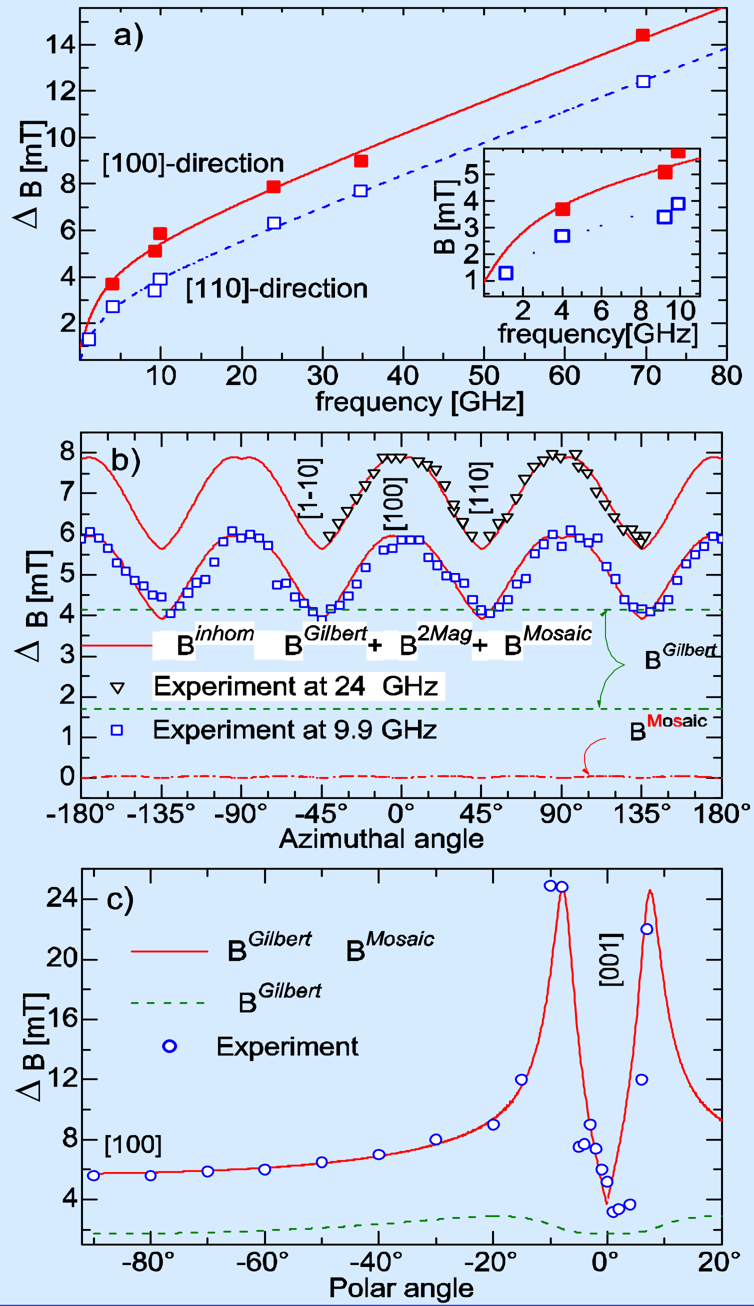
- **recent publications with similar results:**
  - Pd/Fe on GaAs(001) – network of misfit dislocations  
    *G. Woltersdorf et al. PRB **69**, 184417 (2004)*
  - NiMnSb films on InGaAs/InP  
    *B. Heinrich et al. JAP **95**, 7462 (2004)*

# Angular- and frequency-dependent FMR on $Fe_3Si$ binary Heusler structures epitaxially grown on MgO(001)

**d = 40nm**

**Kh. Zakeri et al.**

**PRB <u>76</u>,104416 (2007)**




Angular dependence at 9 and 24 GHZ

$\gamma\Gamma \approx (26 – 53) \cdot 10^7\ sec^{-1}$, anisotropic

$G \approx 5 \cdot 10^7\ sec^{-1}$, isotropic

# 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

K. B. ***Handbook of Magnetism and Advanced Magnetic Materials,*** Vol. 3
Ed. Kronmüller and Parkin, 2007 John Wiley & Sons, Ltd.

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

# Acknowledgement

**BESSY-crew:** H. Wende, C. Sorg, A. Scherz, F. Wilhelm

**Lab. experiments:** J. Lindner, K. Lenz, T.Toliński, E. Kosubek

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R. Wu, D.L. Mills, UCI; P. Jensen + K.H. Bennemann, FUB; W. Nolting, HUB


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