Magnetism of ultrathin films:
Theory and Experiment

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Institut für Experimentalphysik
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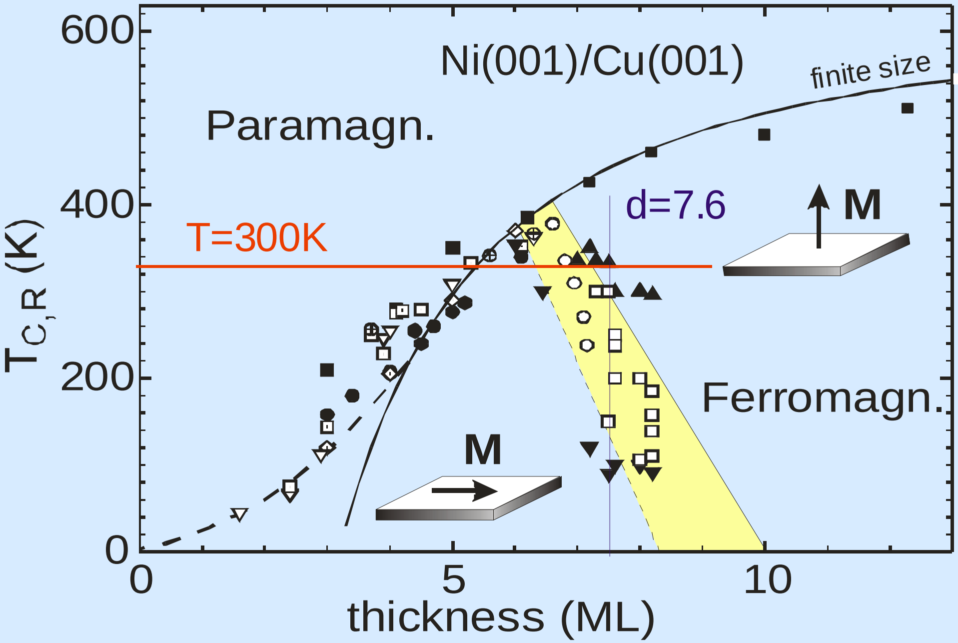
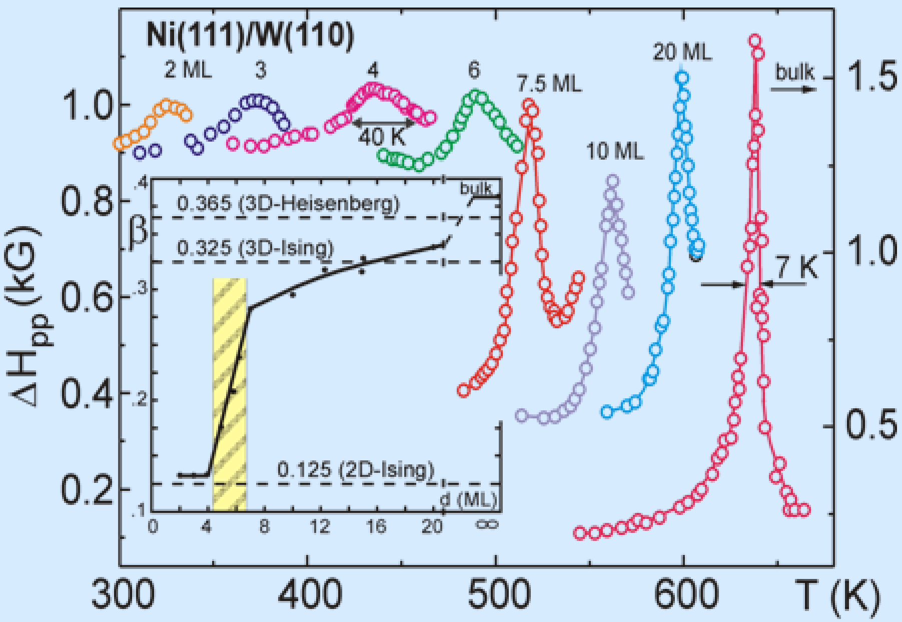
New and fundamental aspects
are found in nanomagnetism with
no counterpart in bulk materials
281. WE-Heraeus-Seminar
“Spin-Orbit Interaction and Local Structure
in Magnetic Systems with Reduced Dimensions“
June 2002 in Wandlitz

For thin films the Curie temperature can be manipulated



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



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

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

New artificial structures, like tetragonal (fct) Ni, Fe, Co are grown

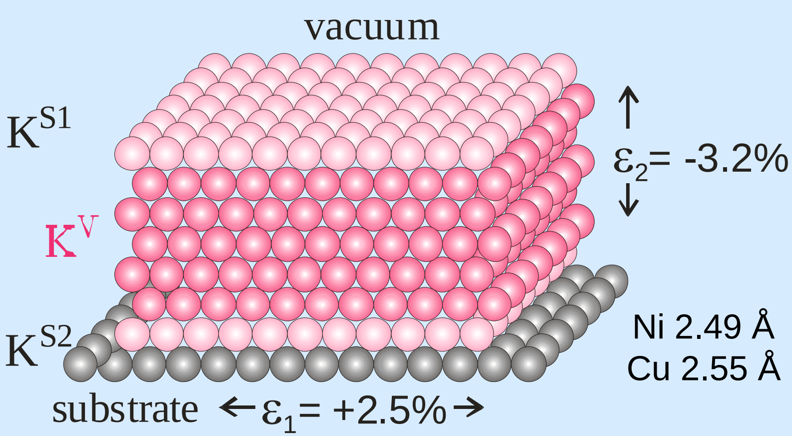


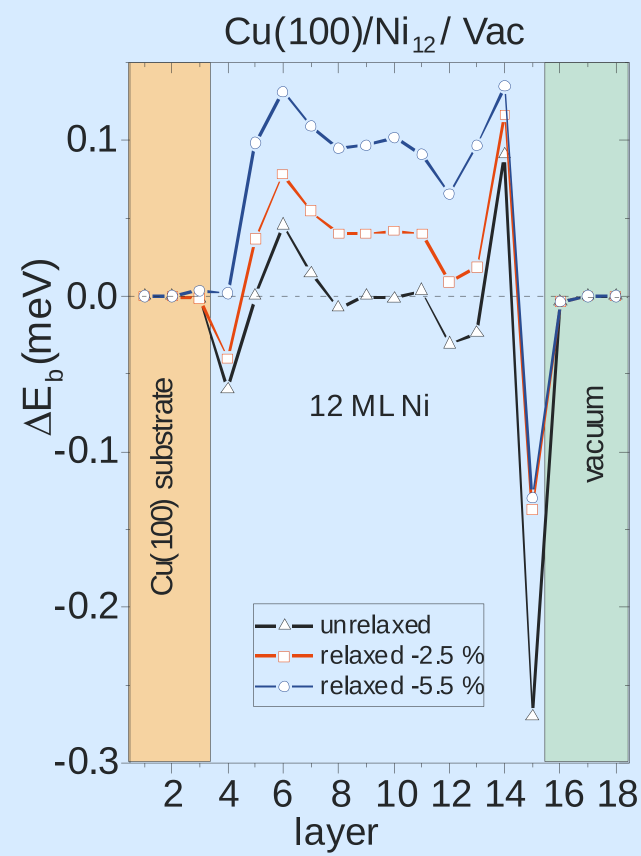
TABLE I. Best-fit structural data for the nickel films of different thickness and the clean c

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
ΔE (eV)	2270	2070	2220	2090	1450	2120
R_p	0.085	0.093	0.170	0.138	0.096	0.111

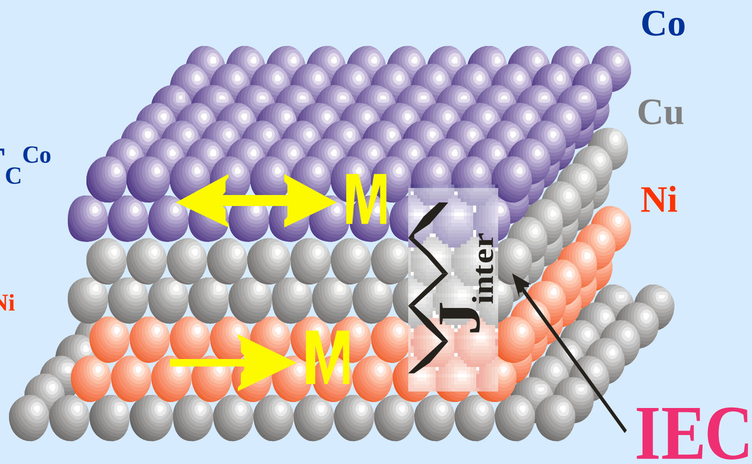
“volume”, and “surface” MAE

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

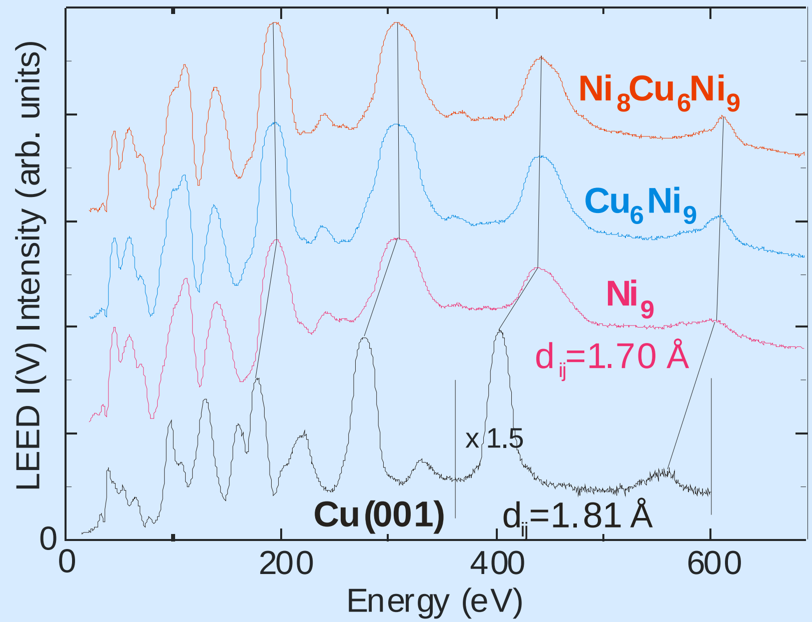
C. Uiberacker et al.
Phys. Rev. Lett. **82**, 1289 (1999)



Interlayer Exchange Coupling and f (T)



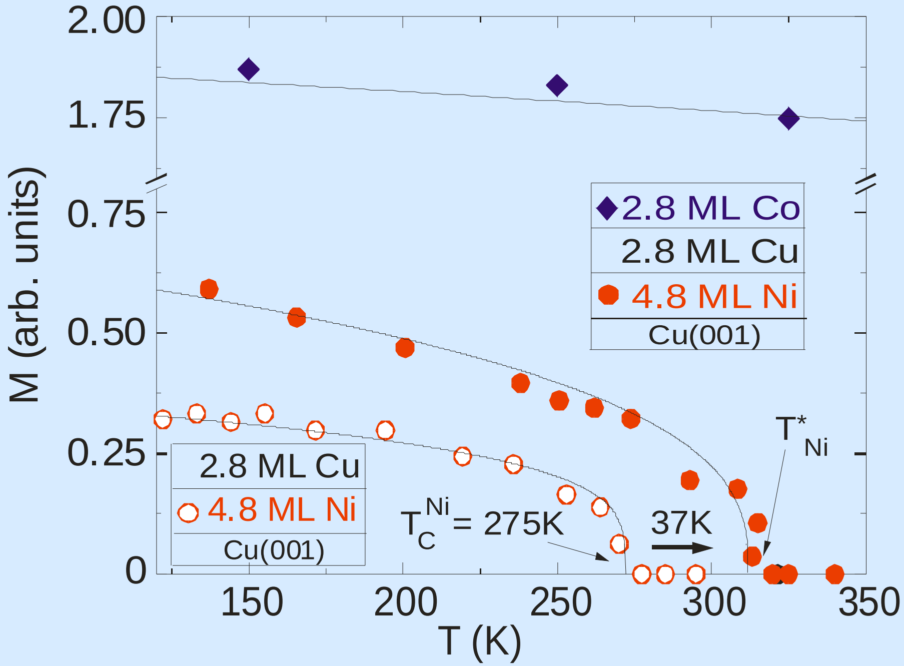
full trilayer grows in fct structure



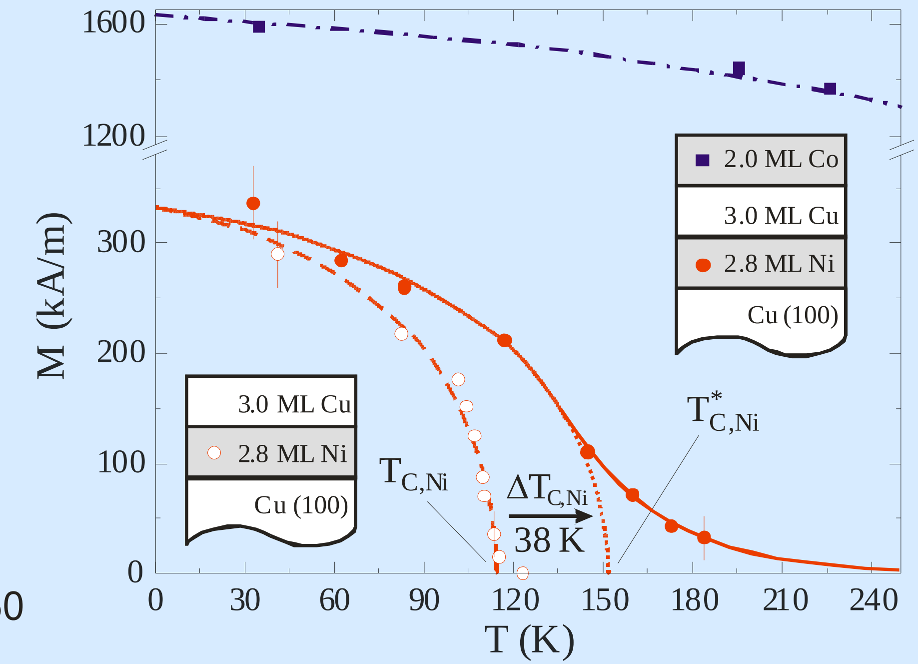
R. Nünthel, PhD Thesis FUB 2003

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 $\Rightarrow$ **?**



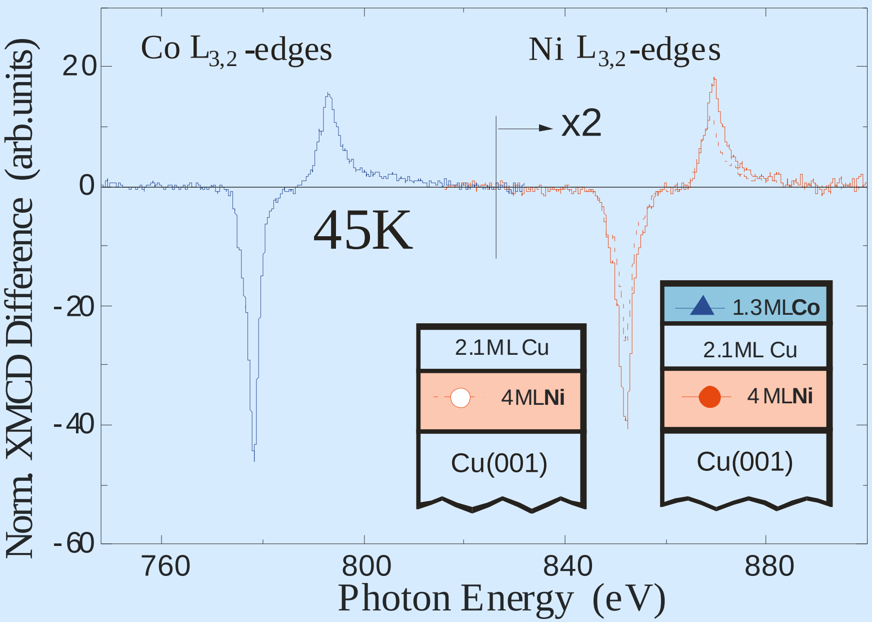
P. Poulopoulos, K. B., Lecture Notes in Physics **580**, 283 (2001)

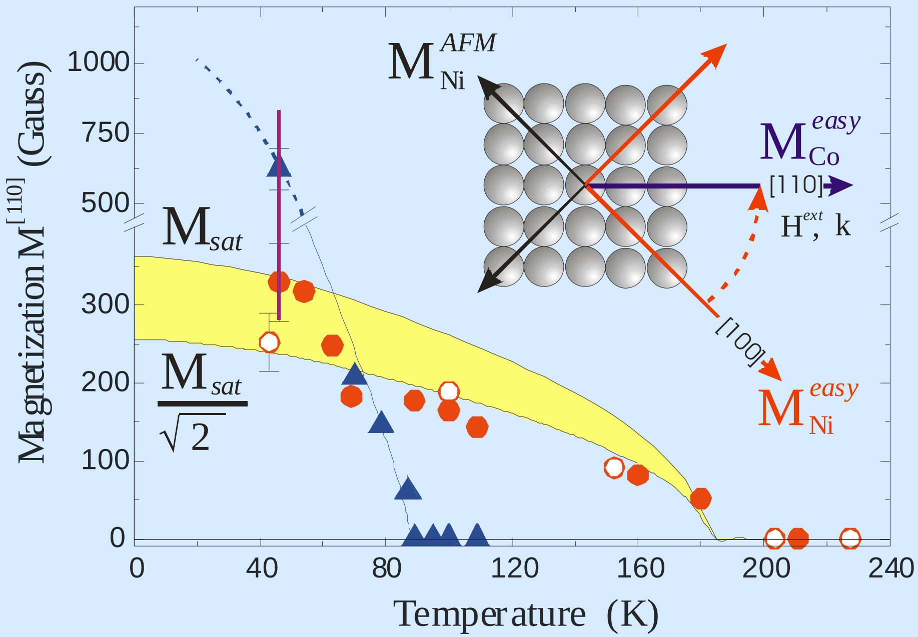


A. Scherz et al. PRB **65**, 24411 (2005)

The large shift of T_C^{Ni} can **NOT** be explained by the static exchange field of Co.

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}

A. Scherz et al. J. Synchrotron Rad. **8**, 472 (2001)

L. Bergqvist, O. Eriksson J. Phys. Conds. Matter **18** ,4853 (2006)

Interlayer exchange coupling and its T-dependence.

P. Bruno, PRB **52**, 411 (1995); V. Drchal et al. PRB **60** , 9588 (1999)

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

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

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

VOLUME 75, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JULY 1995

Temperature Variation of the Interfilm Exchange in Magnetic Multilayers: The Influence of Spin Wave Interactions

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(Received 12 December 1994)

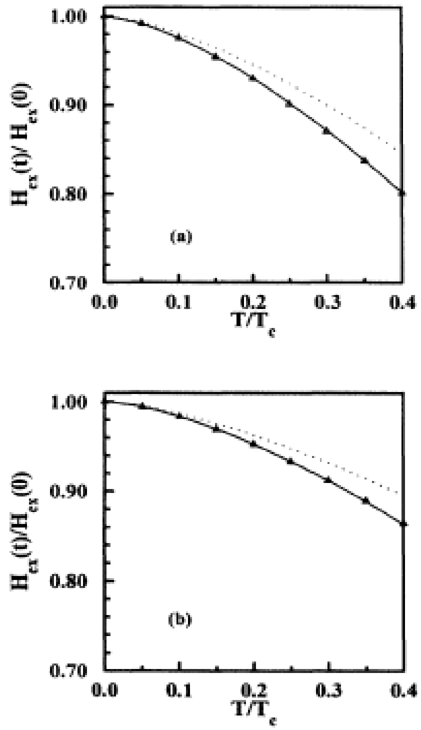
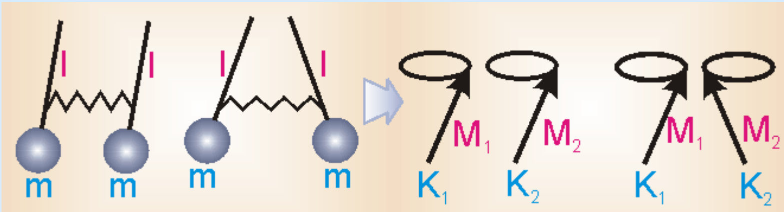
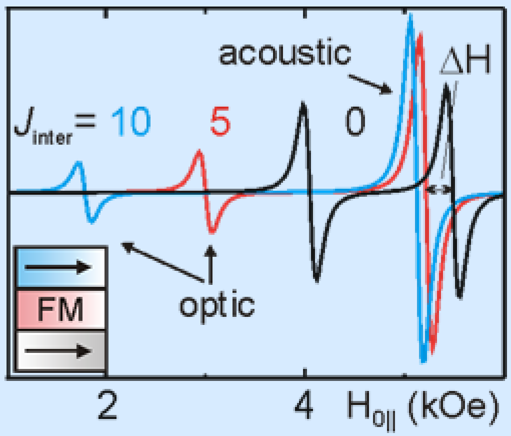


FIG. 2. (a) The temperature variation of the effective exchange field $H_{ex}(t)$, defined as in Ref. [3], for a trilayer with two identical films, and (b) the same for a trilayer with two different films, one with Curie temperature T_C and one with $2T_C$. Here again $t = T/T_C$.

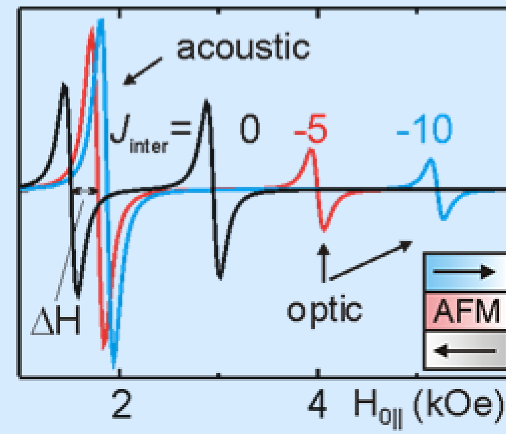
in-situ FMR in coupled films ⇒IEC => f(T) in μeV/ particle



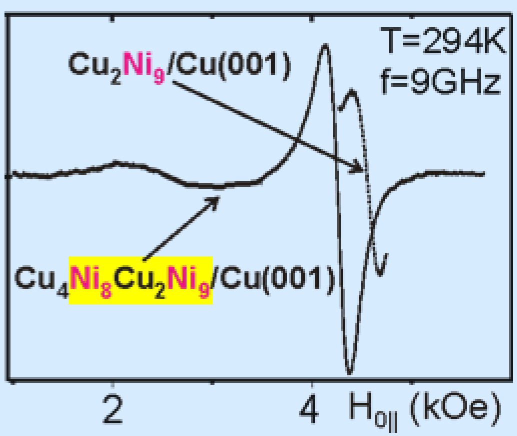
Advantage: FM and AFM



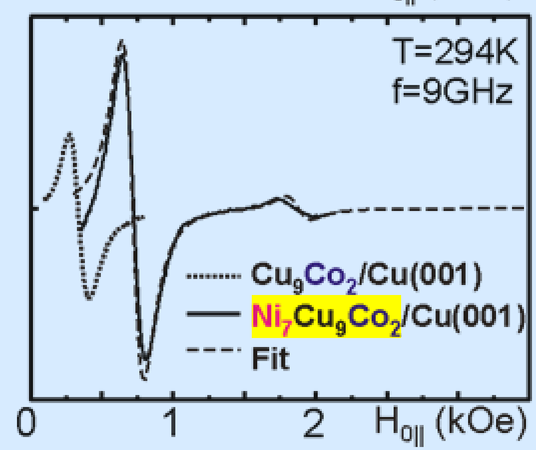
theory



FMR



in-situ
UHV-experiment



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

VOLUME 88, NUMBER 16 PHYSICAL REVIEW LETTERS 22 APRIL 2002

$T^{3/2}$ Dependence of the Interlayer Exchange Coupling in Ferromagnetic Multilayers

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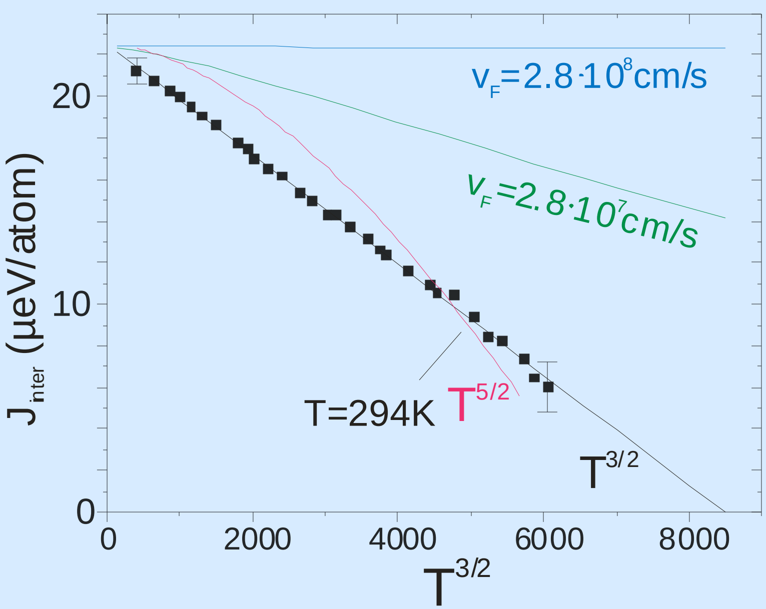
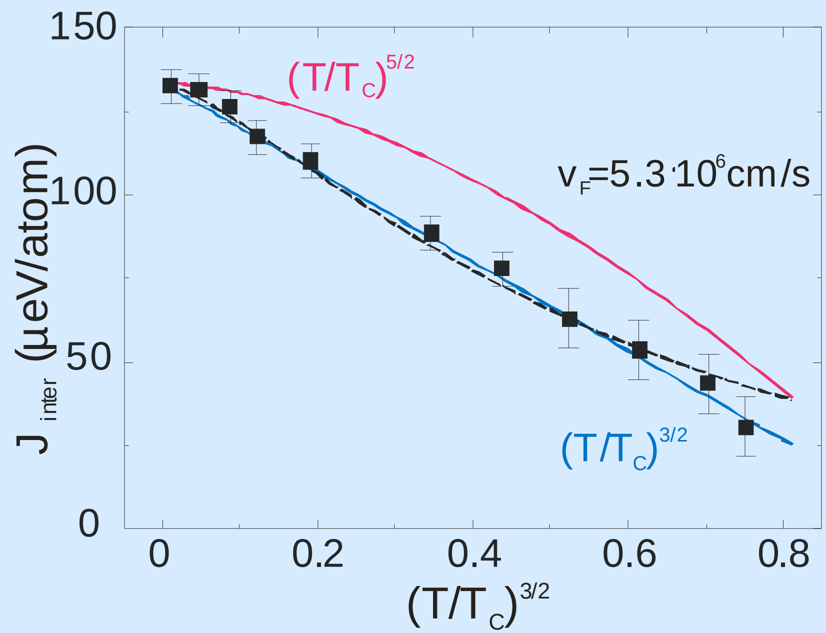
(Received 23 August 2001; published 8 April 2002)

The temperature dependence of the interlayer exchange coupling in ferromagnetic films coupled across nonmagnetic spacers is determined via *in situ* ferromagnetic resonance experiments for various systems. Clear evidence for a $T^{3/2}$ law is found over a wide temperature regime.

$Ni_7Cu_9Co_2/Cu(001)$
T=55K - 332K



$(Fe_2V_5)_{50}$
T=15K - 252K, T_C=305K



PRL 98, 057205 (2007) PHYSICAL REVIEW LETTERS week ending 2 FEBRUARY 2007

Spin-Wave Excitations: The Main Source of the Temperature Dependence of Interlayer Exchange Coupling in Nanostructures

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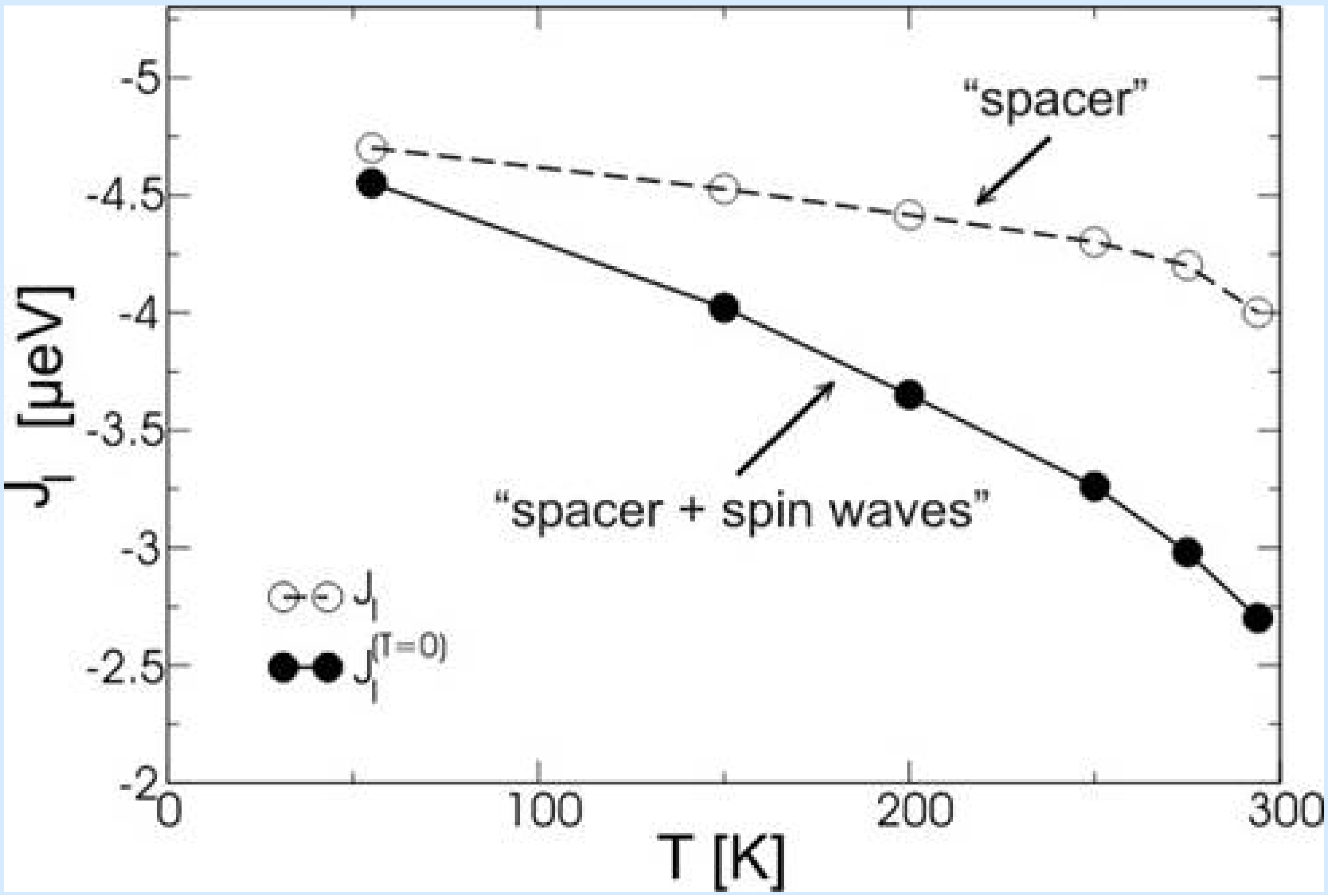
(Received 6 July 2006; published 30 January 2007)



PHYSICAL REVIEW B 75, 224429 (2007)

Dominant role of thermal magnon excitation in temperature dependence of interlayer exchange coupling: Experimental verification

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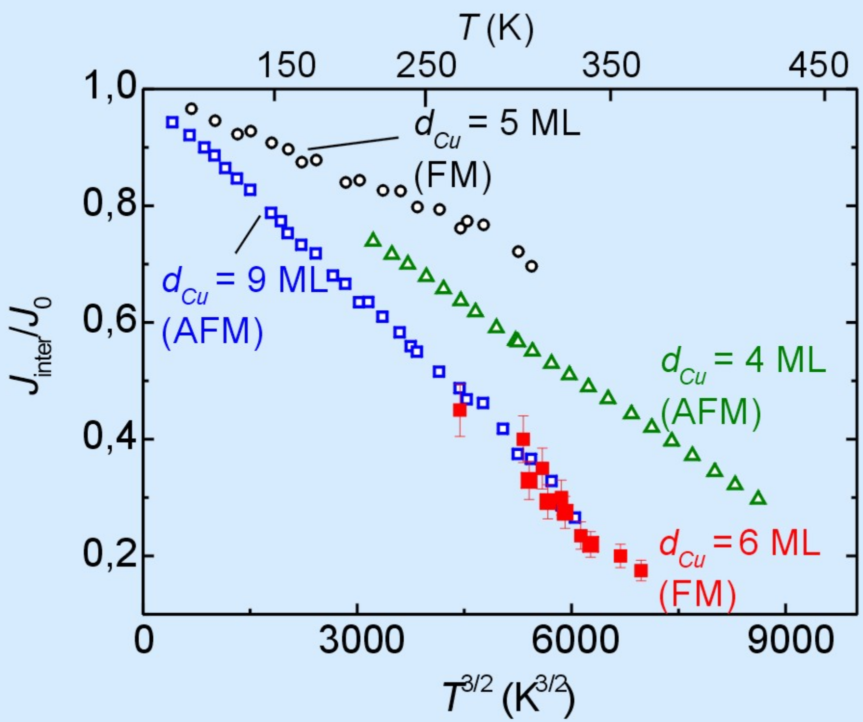
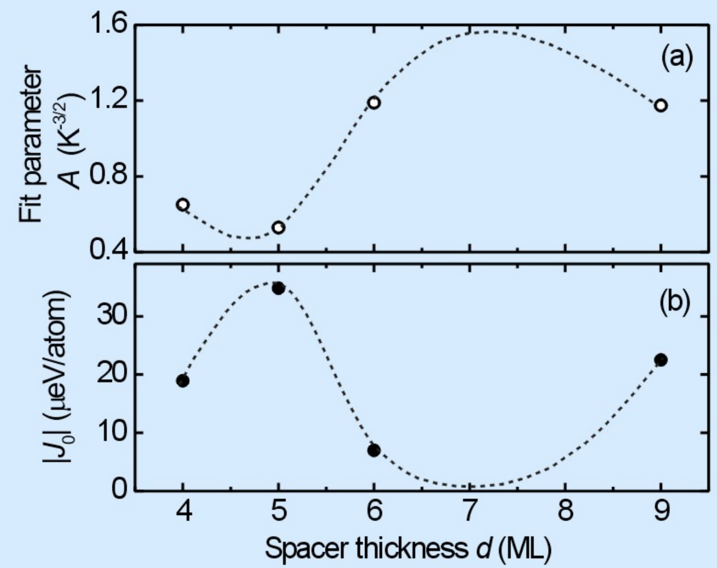
(Received 20 March 2007; revised manuscript received 30 April 2007; published 27 June 2007)



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



A(d) ≠ const.	(interface)
A(d) ≠ linear function	(electronic bandstructure)
A(d) ≈ osc. function	(spin wave excitation)

N·H
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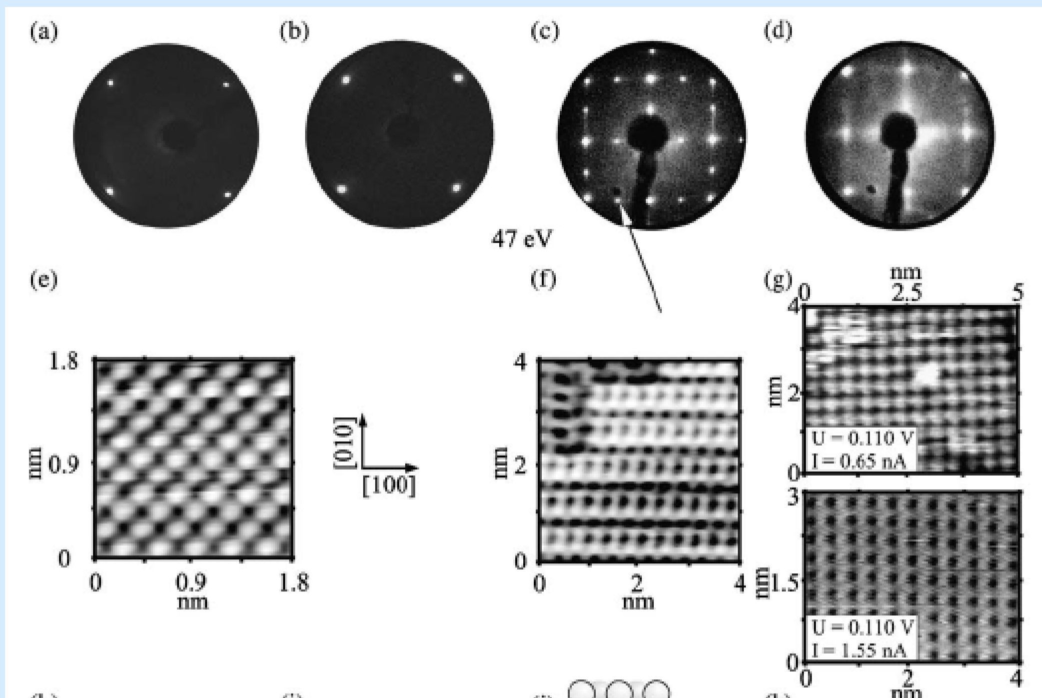
Available online at www.sciencedirect.com
SCIENCE DIRECT®
Surface Science 531 (2003) 53–67
SURFACE SCIENCE
www.elsevier.com/locate/susc

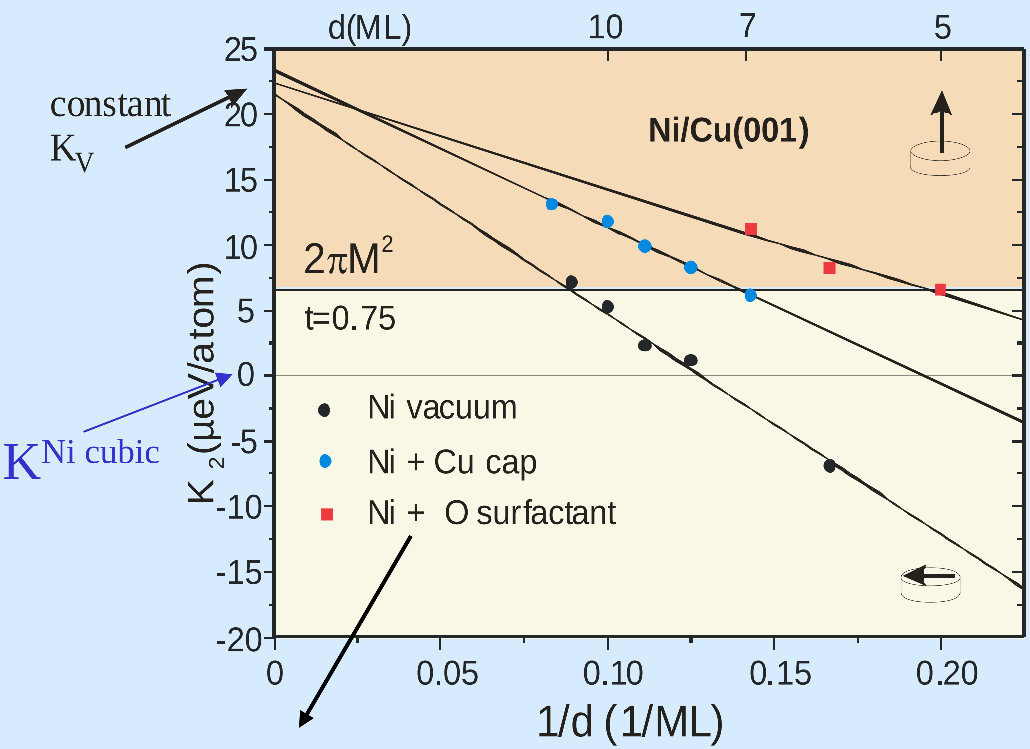
See yesterdays talk by Talat Rahman

Epitaxial growth of Ni on Cu(001) with the assistance of O-surfactant and its magnetism compared to Ni/Cu(001)

R. Nünthel [a], T. Gleitsmann [a], P. Poulopoulos [a,1], A. Scherz [a], J. Lindner [a,*], E. Kosubek [a], Ch. Litwinski [a], Z. Li [a,2], H. Wende [a], K. Baberschke [a], S. Stolbov [b], T.S. Rahman [b]



Manipulation of surface MAE, K_S
by adsorbed molecules, metal cap and surfactant growth



Interface	K_s (μeV/atom)	d_c (ML)
Ni/vacuum	-107	10.8
Ni/Cu	-59	7.6
Ni/CO (van Dijken et al.)	-81	7.3
Ni/H_2 (van Dijken et al.)	-70	6.8
Ni/O (surfactant)	-17	4.9

Changes of K_S shift
the spin reorientation transition d_C

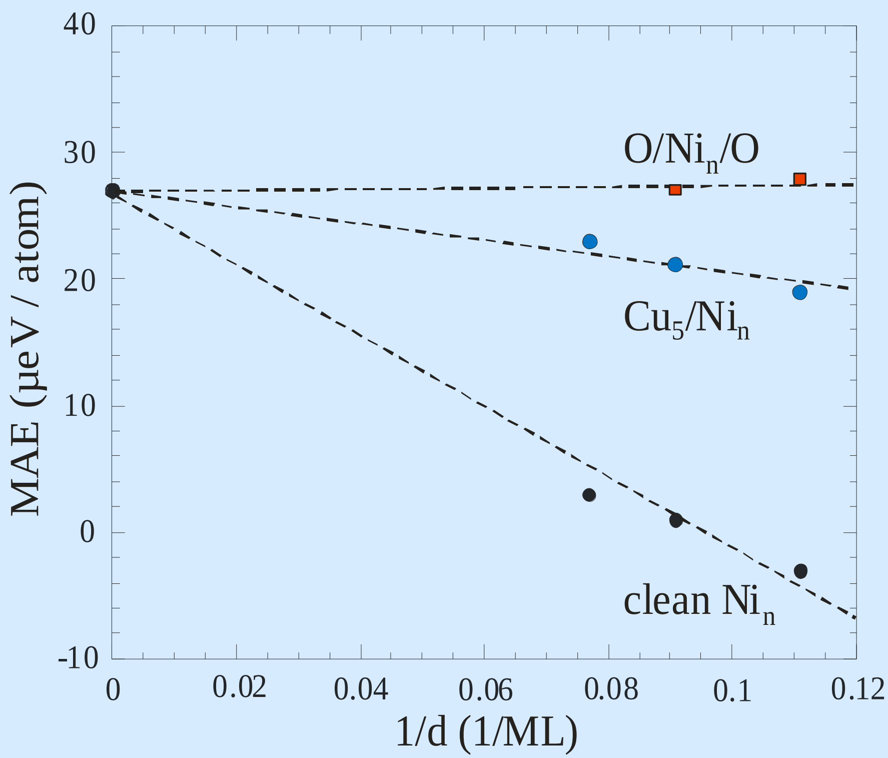
J. Lindner et al. Surf. Sci. Lett. **523**, L65 (2003)

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

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

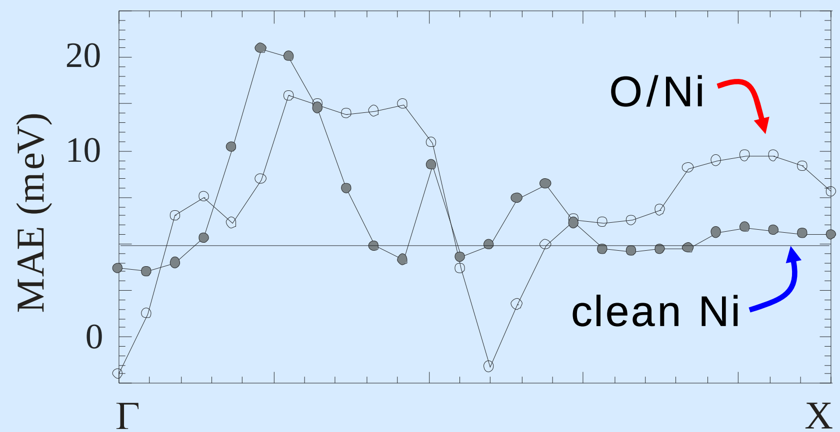
Results of ab initio calculations

R. Q. Wu & coworkers *Phys. Rev. Lett.* **92**, 147202 (2004)



Ni$_n$ slabs, n = 9, 11, 13:
clean, Ni$_n$Cu$_5$ superlattice, and c(2x2) O/Ni$_n$ on each side

MAE along $\overline{\Gamma}\overline{X}$ axis



O-induced surface state seen in the vicinity of $\overline{X}$-point is responsible for change in **MAE**

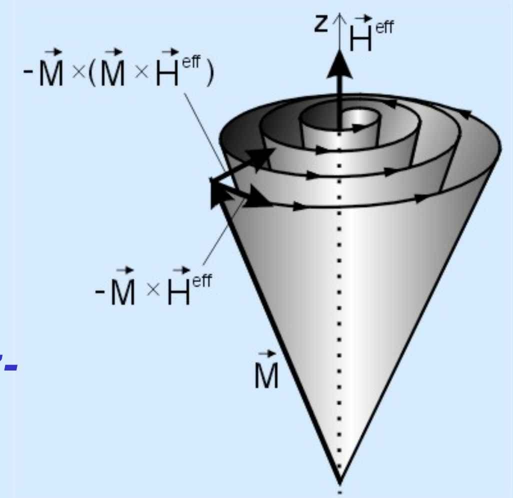
Spin Dynamics: Damping and Scattering

Landau-Lifshitz-Gilbert equation(1935)

$$\frac{d\mathbf{m}}{dt} = -\gamma\,\mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha\,\mathbf{m} \times \frac{d\mathbf{m}}{dt}$$

Gilbert damping

|M|=const.
M spirals on a sphere into z-axis



Bloch-Bloembergen Equation (1956)

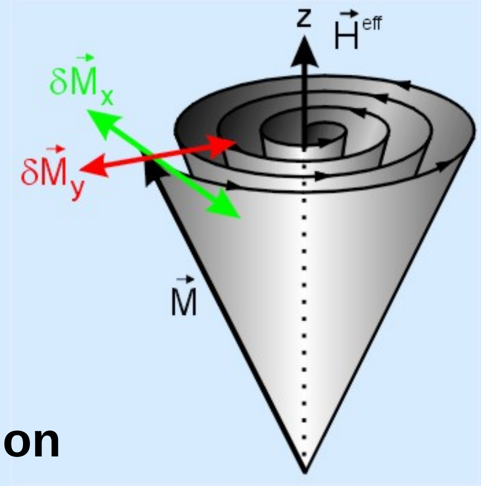
$$\frac{dm_z}{dt} = -\gamma(\,\mathbf{m} \times \mathbf{H}_{\text{eff}}\,)_z - \frac{m_z - M_S}{T_1}$$

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

spin-lattice relaxation *(longitudinal)*

spin-spin relaxation *(transverse)*

M_z=const.

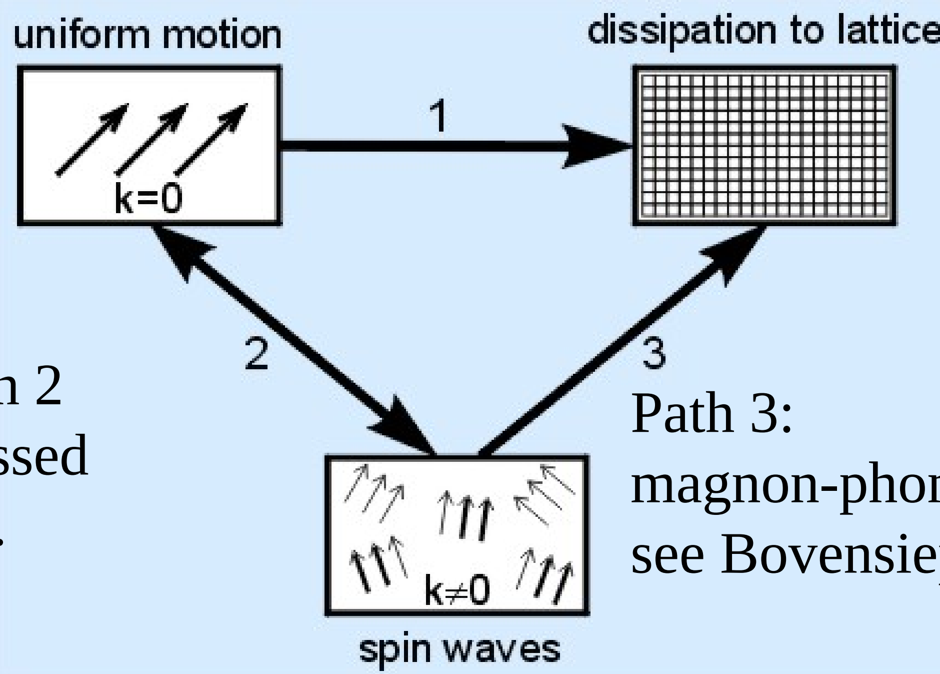


Gilbert damping versus magnon-magnon scattering.

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) is modeled/fitted.

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

Path 3:
magnon-phonon scattering,
see Bovensiepen PRL 2008

FMR Linewidth - Damping

Landau-Lifshitz-Gilbert-Equation

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

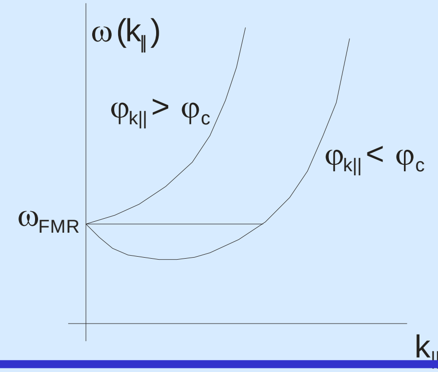
viscous damping,
energy dissipation

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

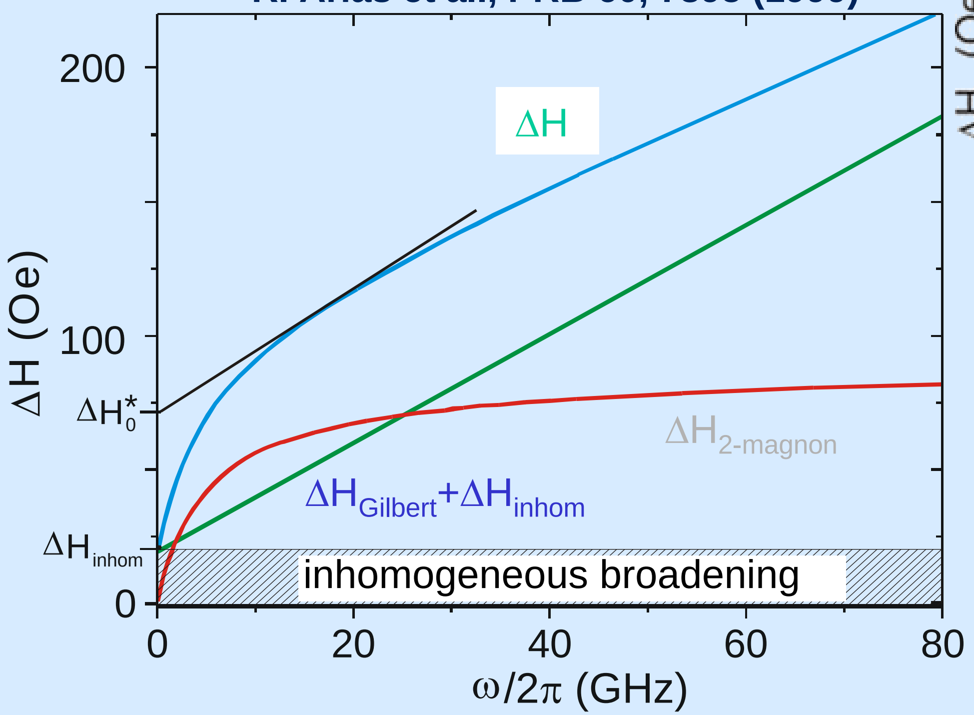
Which (FMR)-publication has checked (disproved) quantitatively this analytical function?

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

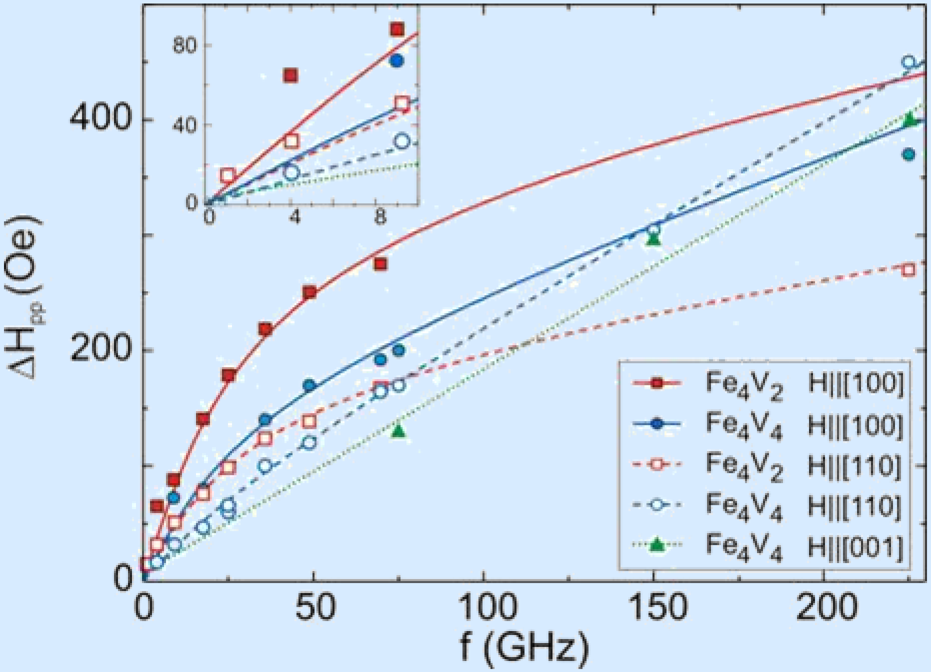
$$\Delta H_{2-\mathrm{magnon}}(\omega) = \Gamma \arcsin\sqrt{\frac{\sqrt{\omega^2+(\omega_0/2)^2}-\omega_0/2}{\sqrt{\omega^2+(\omega_0/2)^2}+\omega_0/2}}$$

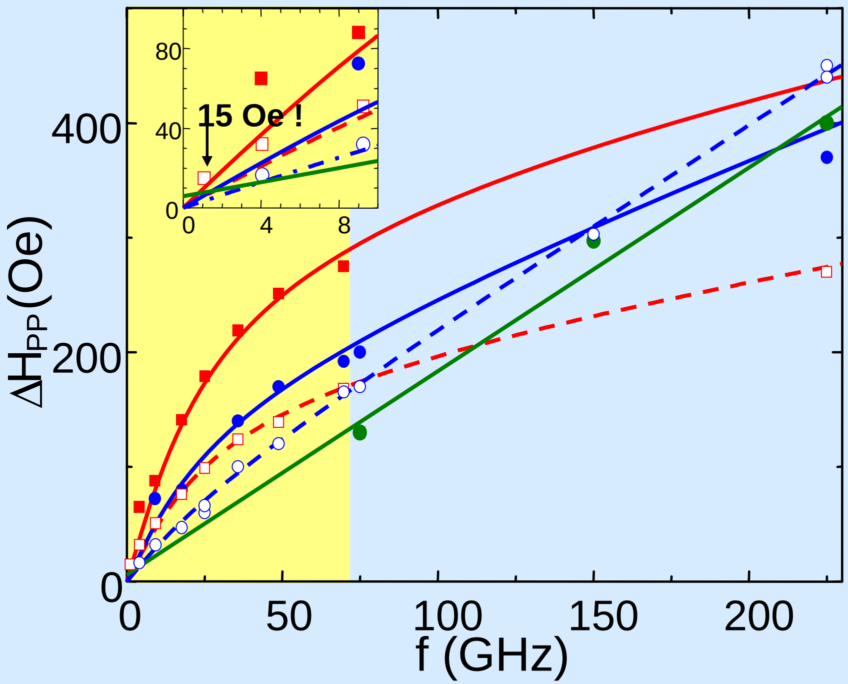
with $\omega_0 = \gamma M_{\mathrm{eff}}$

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 (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})	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

G ≈ isotropic dissipation and
Γ ≈ anisotropic spin wave scattering

Angular- and frequency-dependent FMR on

Fe_3Si binary Heusler structures epitaxially grown on MgO(001)

d = 40nm

Kh. Zakeri et al.

PRB **76**,104416 (2007)

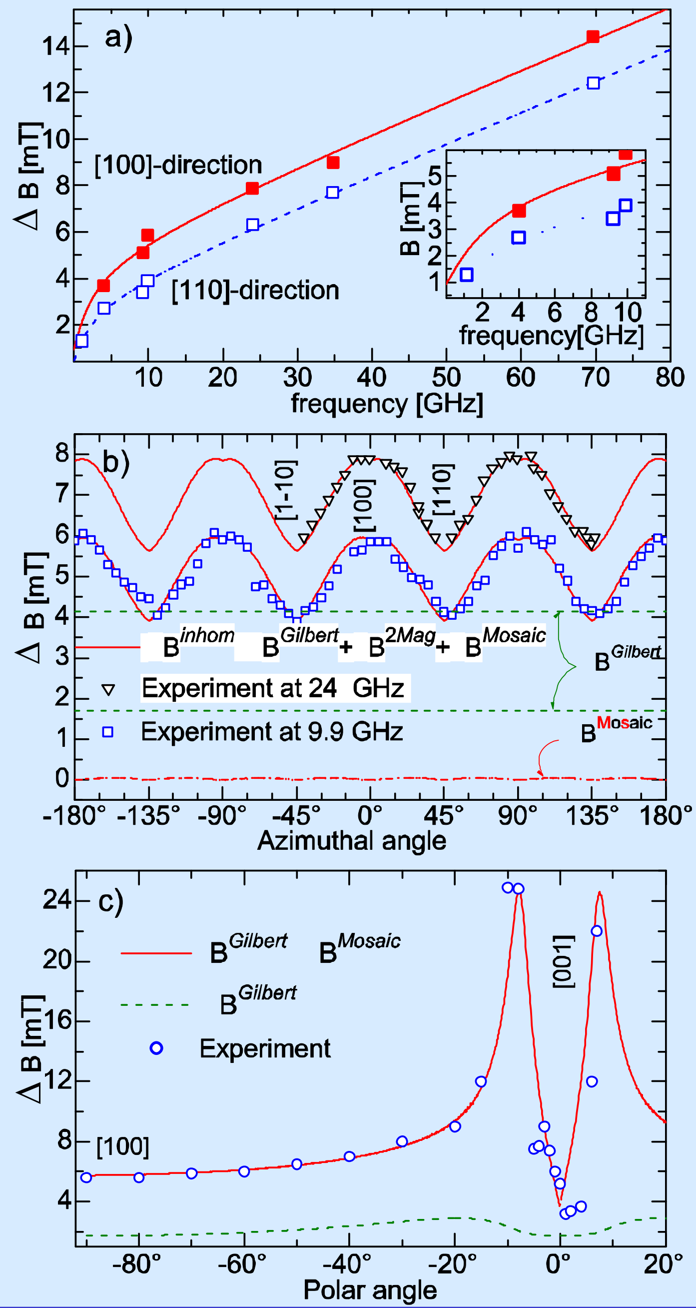
PRB **80**, 059901 (2009)

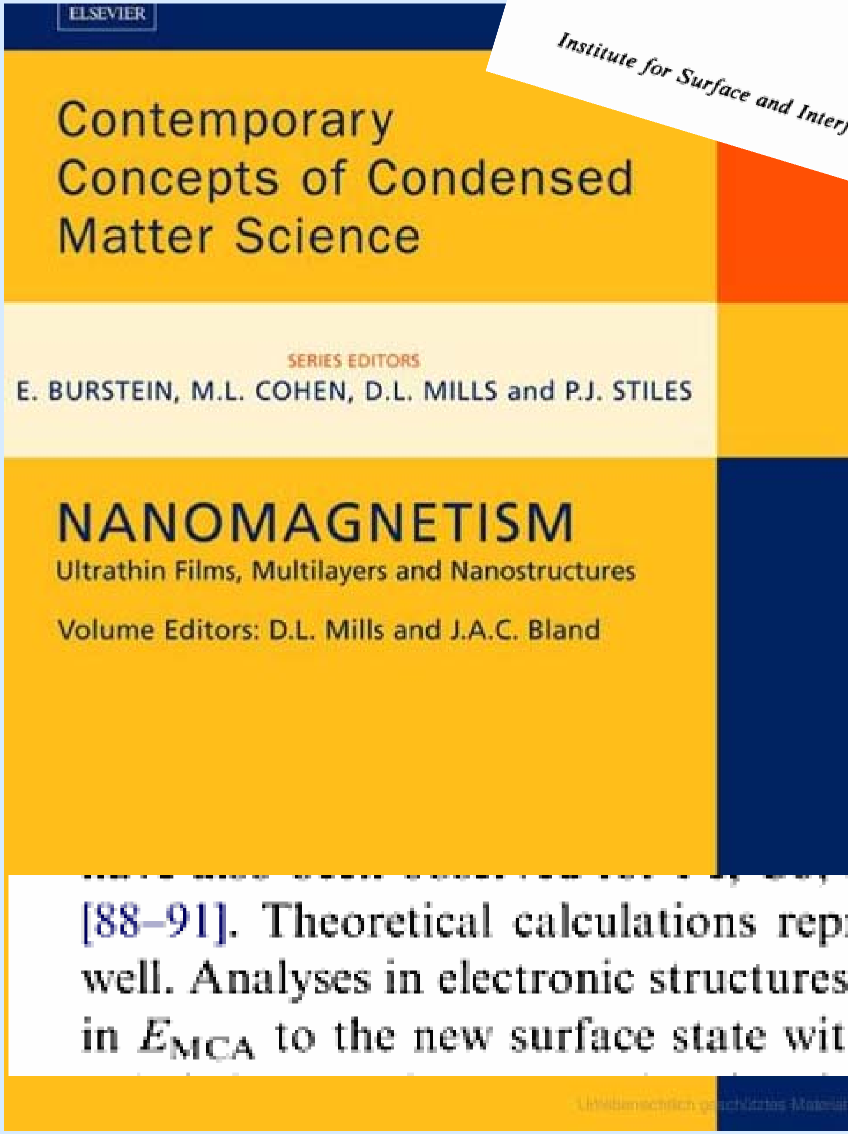
Angular dependence at 9 and 24 GHz

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

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

A phenomenological effective *Gilbert damping parameter* gives very little insight into the microscopic relaxation and scattering .





PHYSICAL REVIEW B VOLUME 38, NUMBER 16 1 DECEMBER 1988-I

RAPID COMMUNICATIONS

Ferromagnetism of ultrathin films

Myron Bander and D. L. Mills
Institute for Surface and Interface Science and Department of Physics, University of California, Irvine, California 92717
(Received 10 August 1988)

$$T_2 = T_3 / \ln\left(\frac{3\pi}{4}\frac{T_3}{K}\right)$$

[88–91]. Theoretical calculations reproduced the trend of experimental data very well. Analyses in electronic structures furthermore attributed the O-induced change in E_{MCA} to the new surface state with the d_{xz} feature caused by the O adlayer.


Doug, we wish you all the best !

Magnetism of ultrathin Ferromagnets: Theory and Experiment

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Ultrathin films of few atomic layers thickness only, are a new type of “designer materials”. They have no counterpart in bulk magnetism; they offer the opportunity to study new fundamental aspects of magnetism: The critical temperature Tc changes as function of the thickness from Tcbulk to zero. Modification of the n.n. distance by few hundreds of Å may change the magnetic part of the free energy by orders of magnitude. In multilayer ferromagnetic- and antiferromagnetic-coupling can be manipulated via the spacer thickness. The unusual static properties as well as dynamic characteristics (magnons) are investigated by theory and experiment. Recent specific example will be discussed[1,2]. This field of low dimensional magnetism demonstrates the very successful collaboration between theory and experiment, and gives some insight for the fundamental understanding of magnetism.

1 D. L. Mills and S. M. Rezende in Spin dynamics in confined magnetic structures II Topics in Applied Physics vol. 87, p.27 Springer 2003

2 K. Baberschke in Handbook of magnetism and advanced magnetic materials vol. 3, p.1617 John Wiley & Sons 2007

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