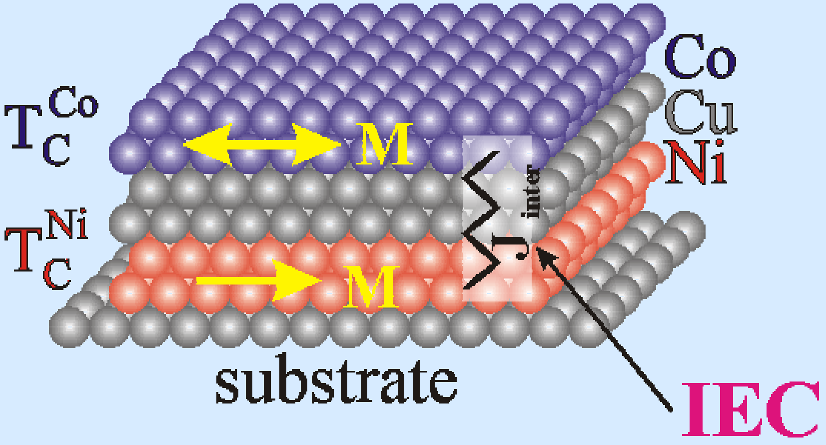
# Interlayer exchange coupling and giant spin fluctuations in ferromagnetic trilayers

**Klaus Baberschke**

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

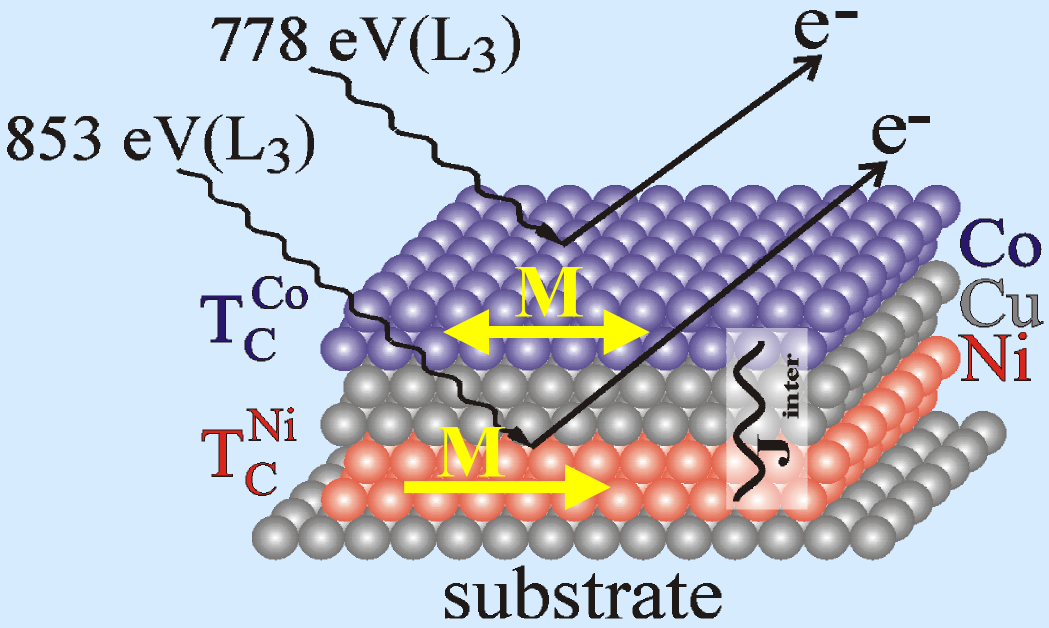
1. Giant shift of $T_C$'s in trilayers
   2D ferromagnet ⇒ $d_{Ni}$ (Jensen)
   effect of spacer ⇒ $d_{Cu}$ (Bruno)
2. Temperature dependence of IEC
3. Oscillatory $T_C$ of a Co film
   QW of a Cu-cap layer



⇒ **http://www.physik.fu-berlin.de/~ag-baberschke**

# 1. Giant shift of $T_C$'s in trilayers

## XMCD element specific magnetizations in trilayers



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

What about element specific Curie-temperatures ?

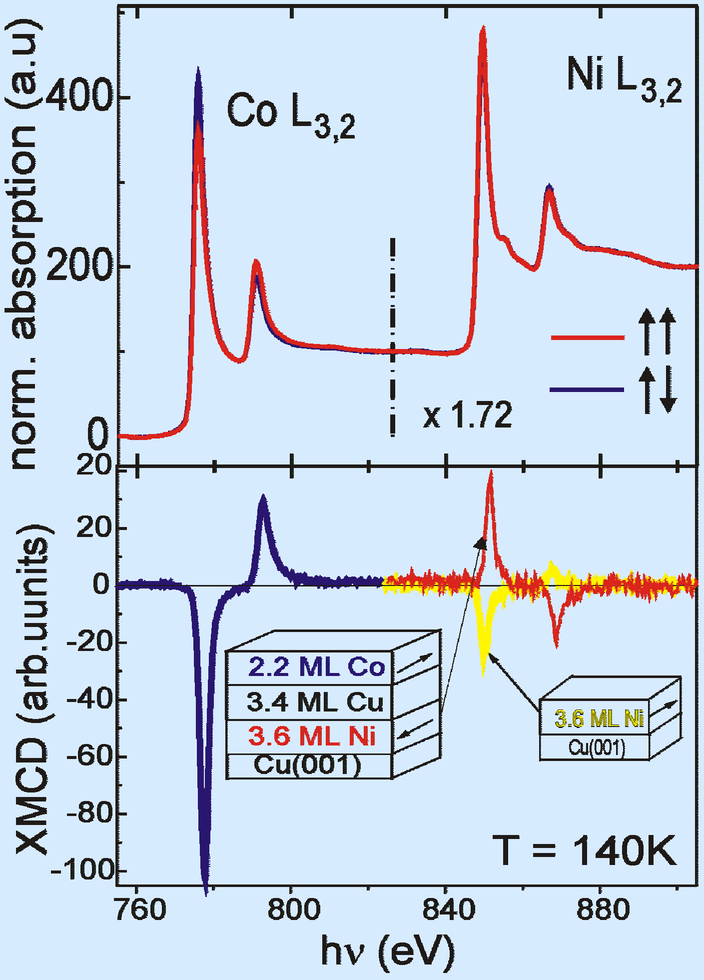
Two trivial limits: (i) $d_{Cu} = 0$ $\Rightarrow$ direct coupling like a Ni-Co alloy

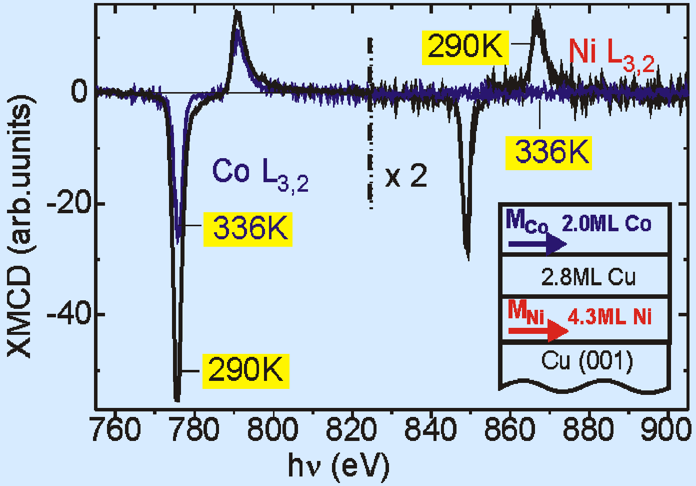
(ii) $d_{Cu}$ = large $\Rightarrow$ no coupling, like a mixed Ni/Co powder

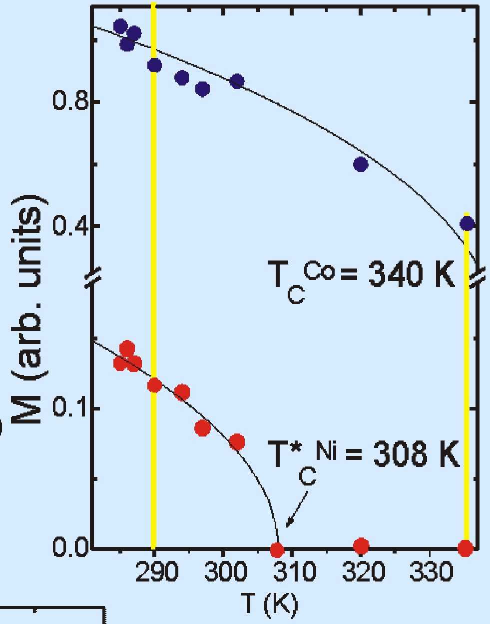
**BUT** $d_{Cu} \approx 2$ ML $\Rightarrow$ **?**

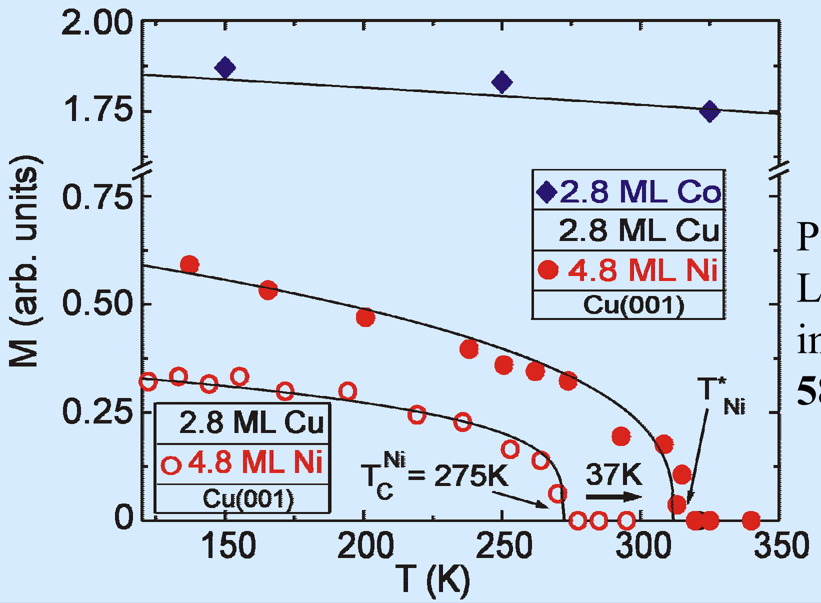
U. Bovensiepen et al., Phys. Rev. Lett. **81**, 2368 (1998)
“*Two susceptibility maxima and element specific magnetizations …*”

# X-ray Magnetic Circular Dichroism



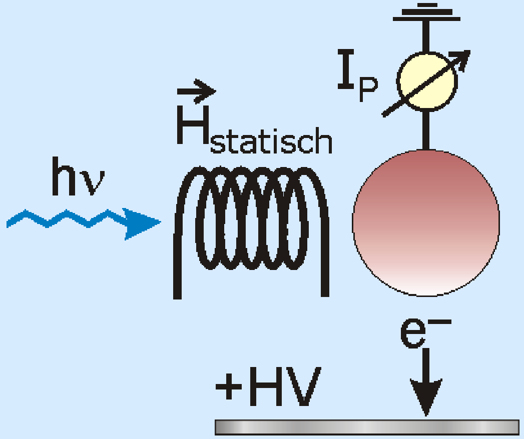




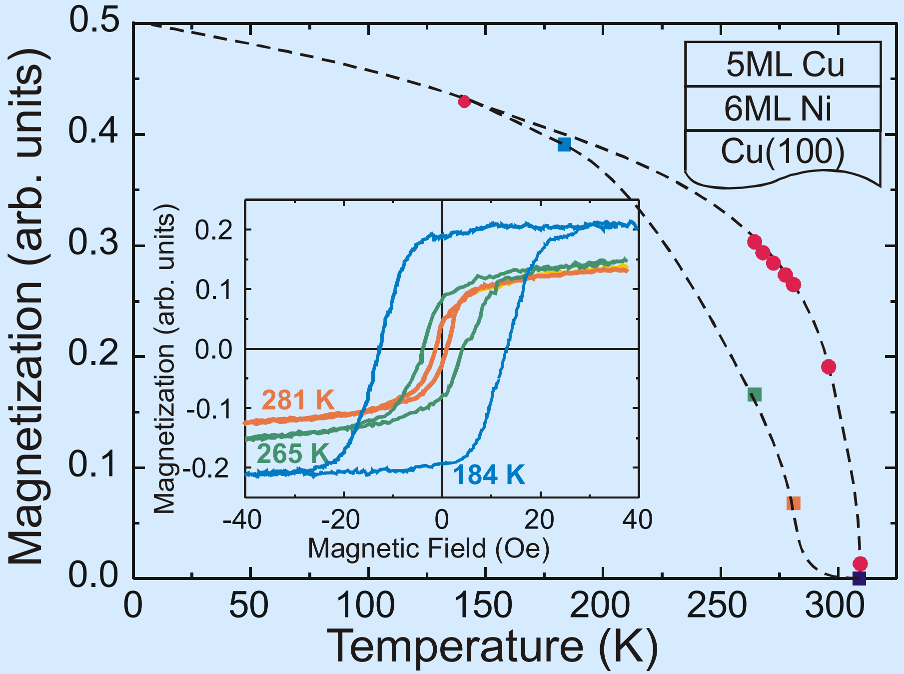


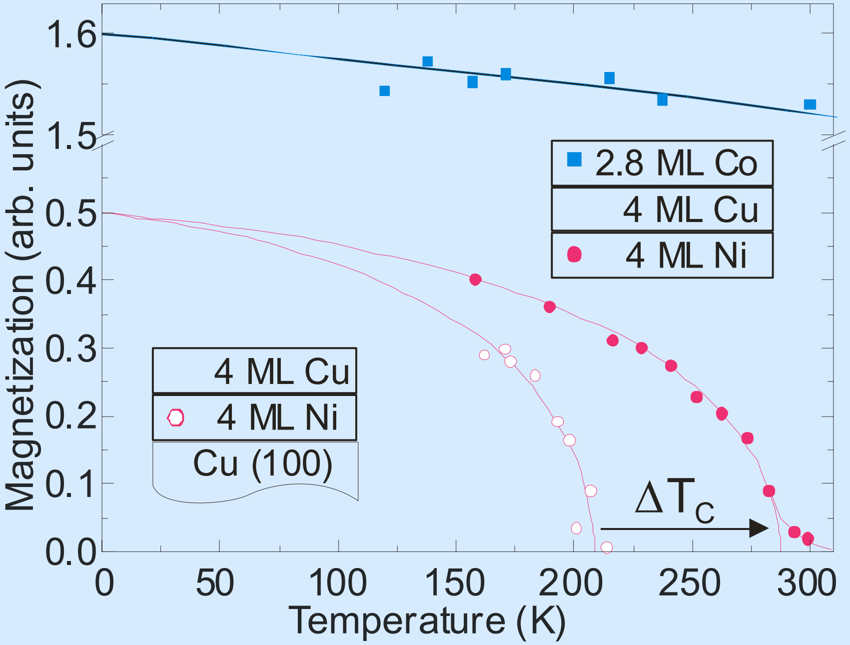
P. Poulopoulos, K. B.,
Lecture Notes
in Physics
**580**, 283 (2001)

# Remanence and saturation magnetization



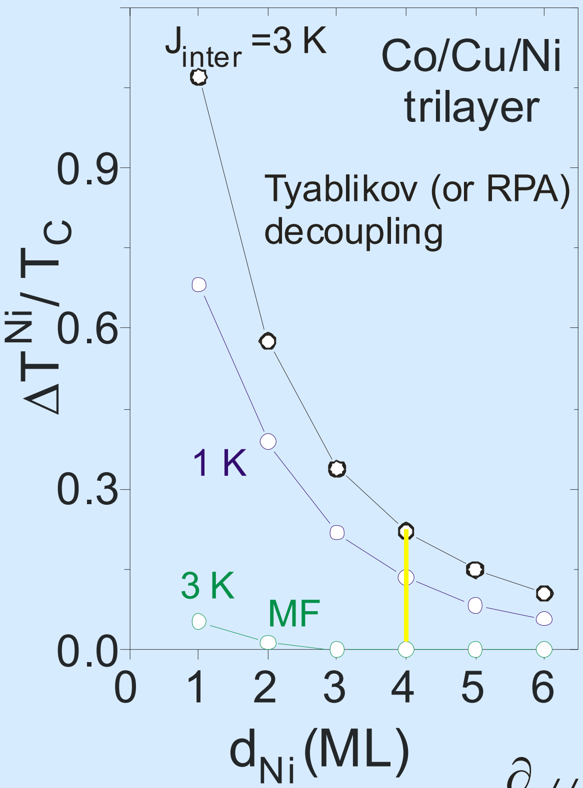
C. Sorg et al.,
XAFS XII, Malmö, June 2003





# Enhanced spin fluctuations in 2D (theory)

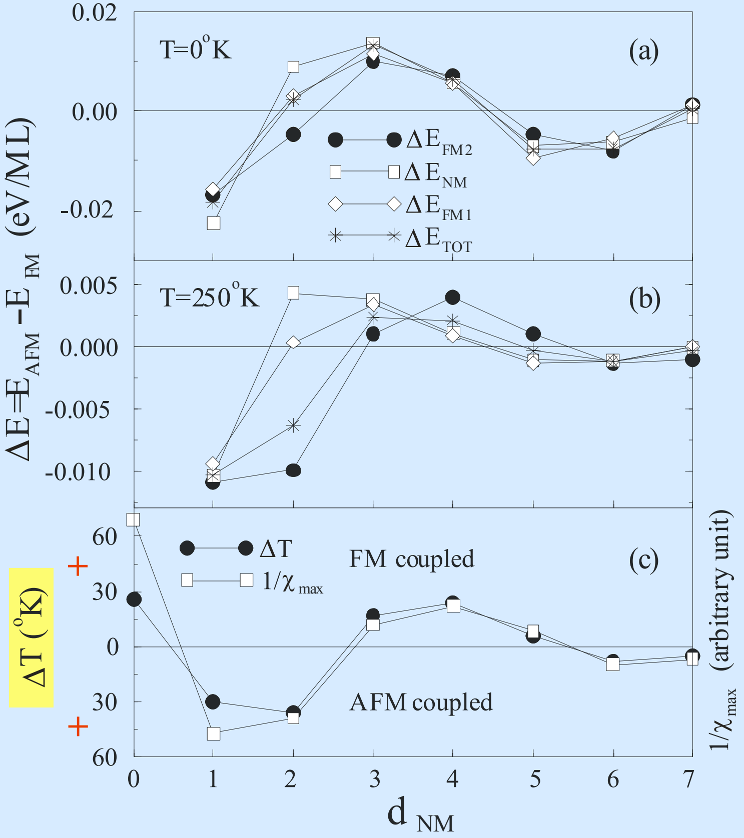
P. Jensen et al. PRB **60**, R14994 (1999)



J. Phys.: Condens. Matter **12** (2000) 2847–2855.

**Theoretical approach to the Curie temperature shift in trilayers**

**J H Wu†, T Herrmann, M Potthoff and W Nolting**



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

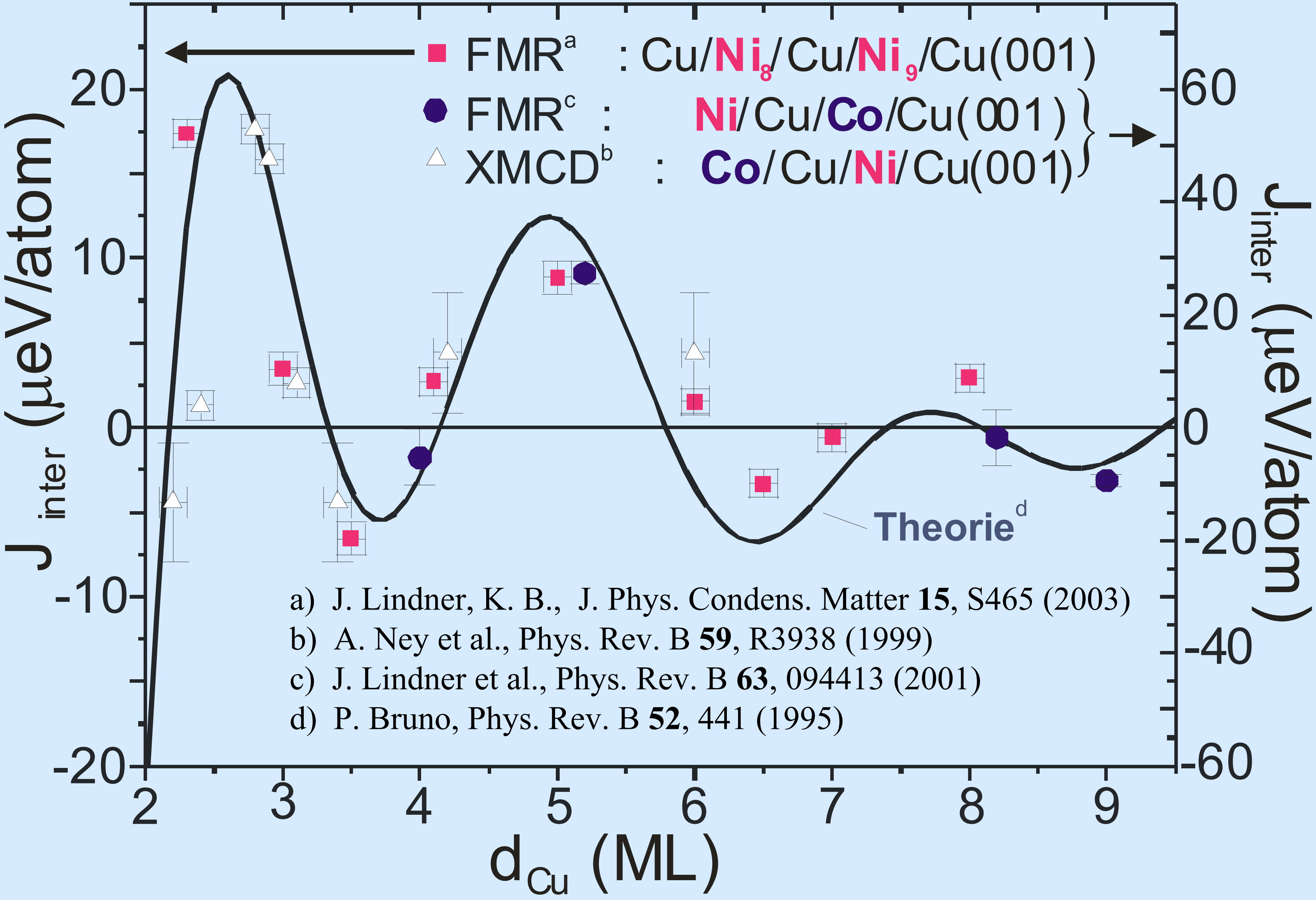
$$S_i^z S_j^+ \approx \langle S_i^z\rangle S_j^+ - \langle S_i^- S_i^+\rangle S_j^+ - \langle S_i^- S_j^+\rangle S_i^+ + \cdots$$

$\longleftarrow$ RPA $\longrightarrow$

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

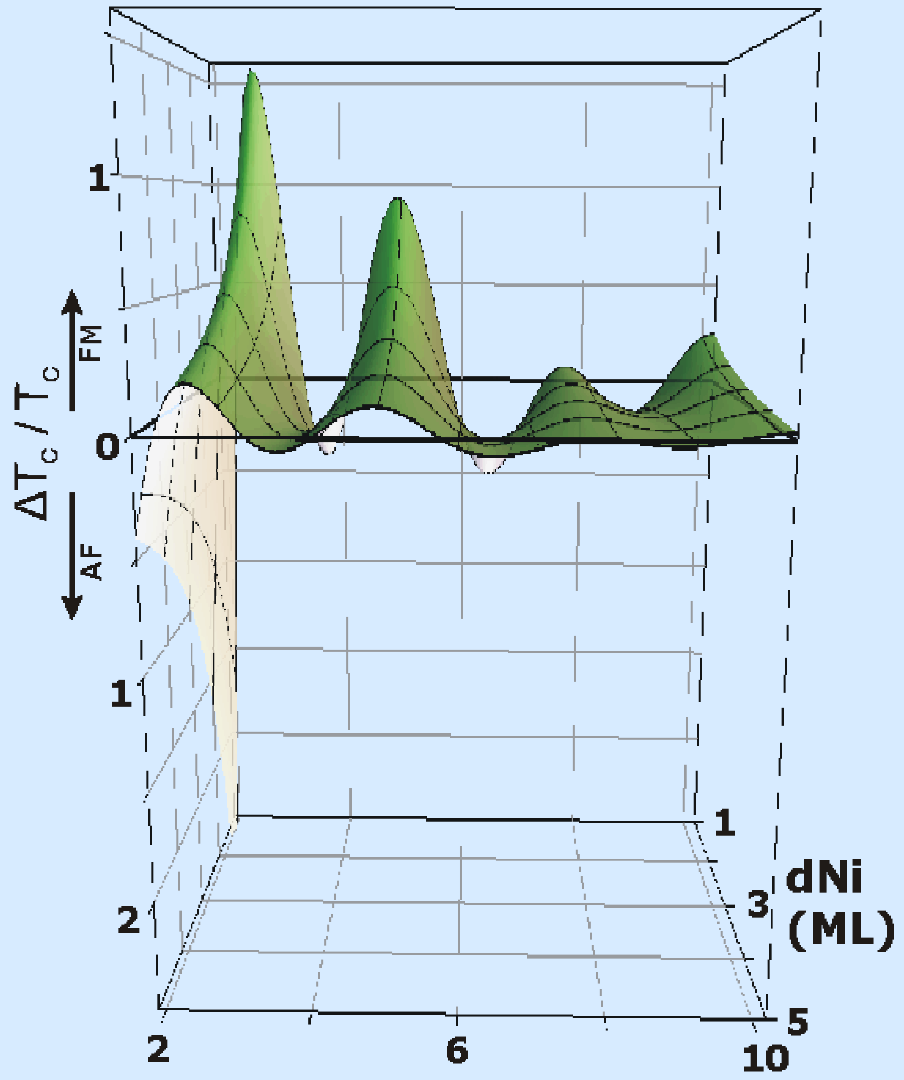
Single band Hubbard model:
Simple Hartree-Fock (Stoner) ansatz is insufficient
Higher order correlations are needed to explain $T_C$-shift

# Interlayer exchange coupling



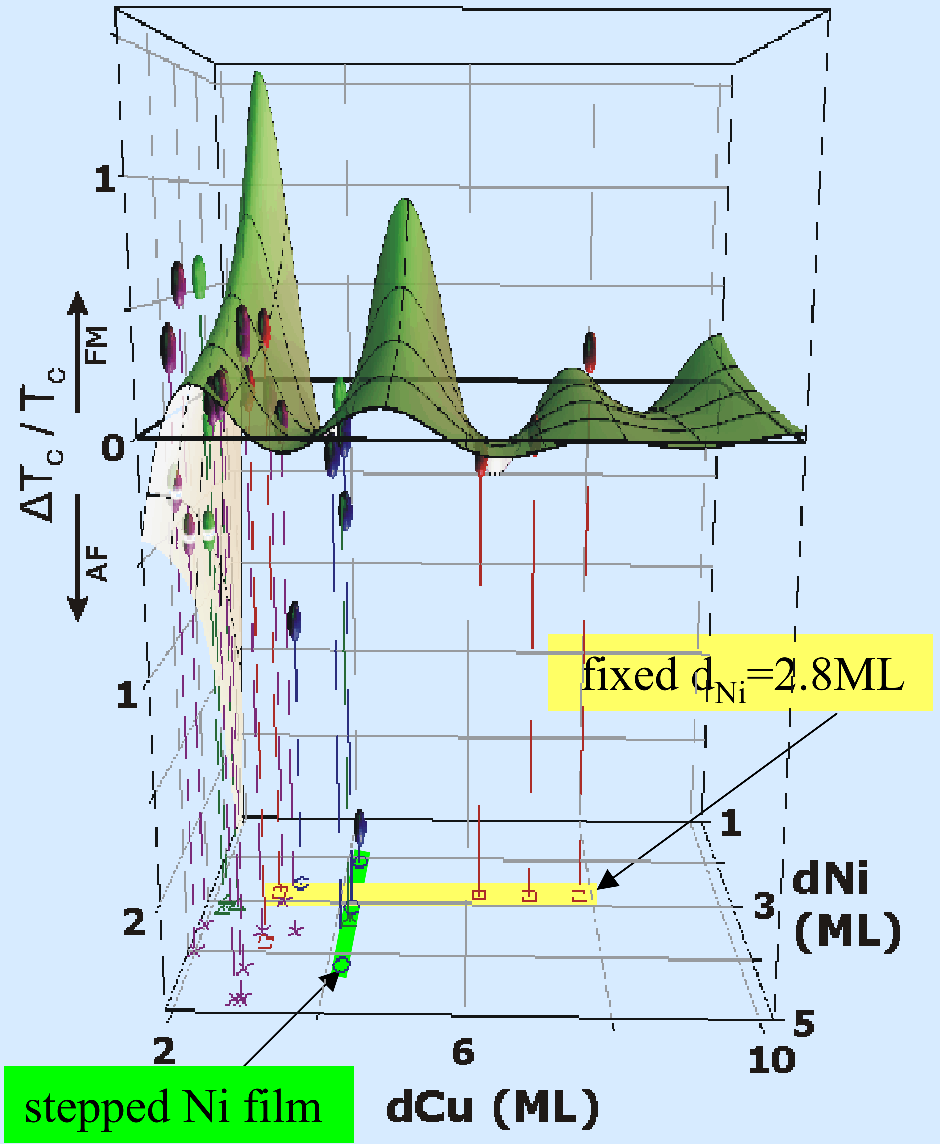
a) J. Lindner, K. B., J. Phys. Condens. Matter **15**, S465 (2003)
b) A. Ney et al., Phys. Rev. B **59**, R3938 (1999)
c) J. Lindner et al., Phys. Rev. B **63**, 094413 (2001)
d) P. Bruno, Phys. Rev. B **52**, 441 (1995)

# Combination of $d_{Ni}$ (Jensen) and $d_{Cu}$ (Bruno) dependence



M. Bernien et al. unpublished

# Combination of $d_{Ni}$ (Jensen) and $d_{Cu}$ (Bruno) dependence



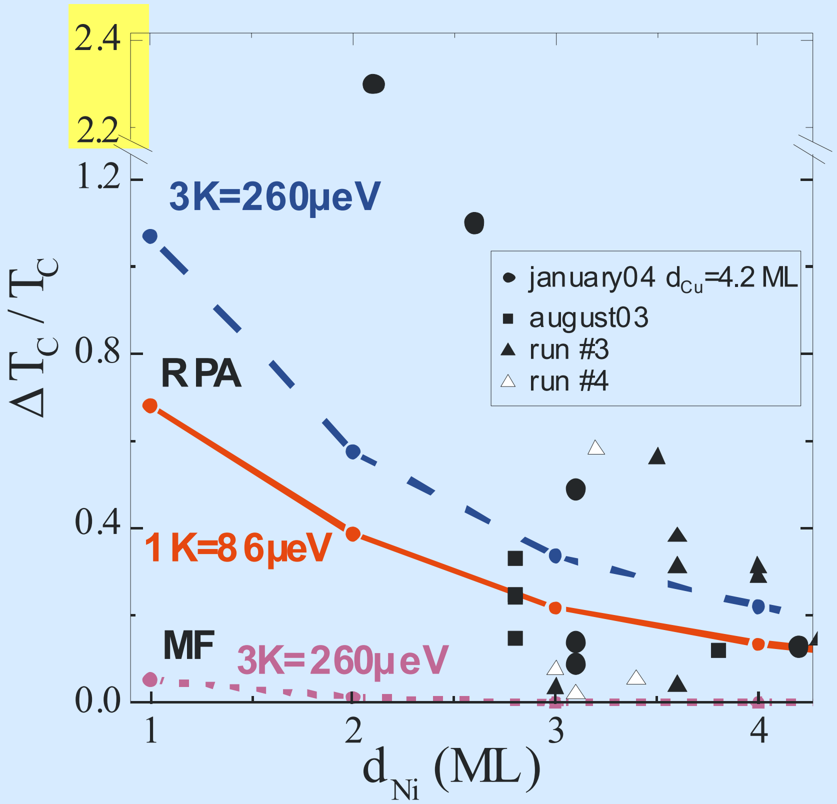
fixed $d_{Ni}$=2.8ML

stepped Ni film

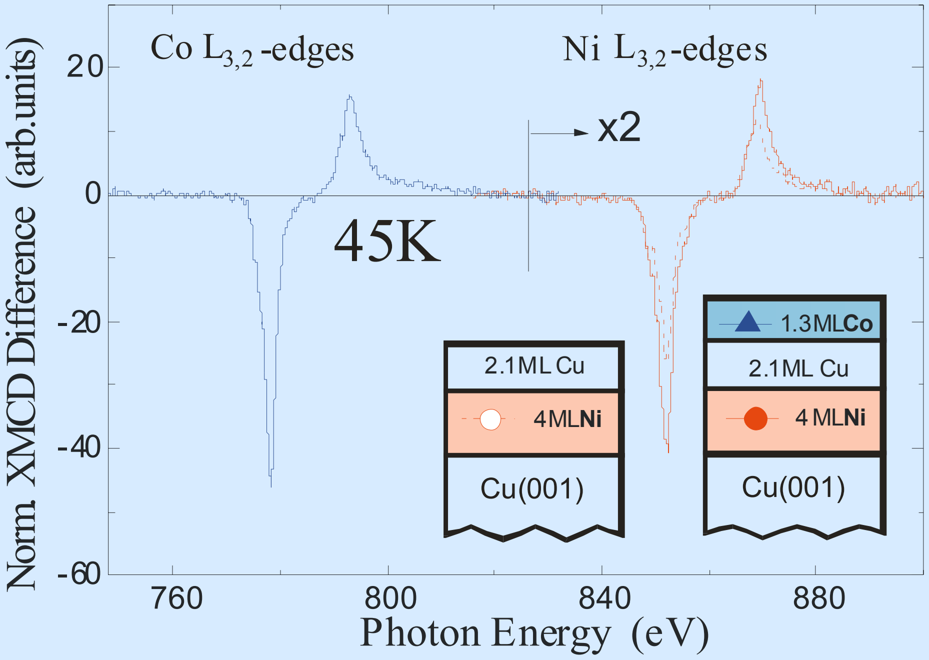
M. Bernien et al. unpublished

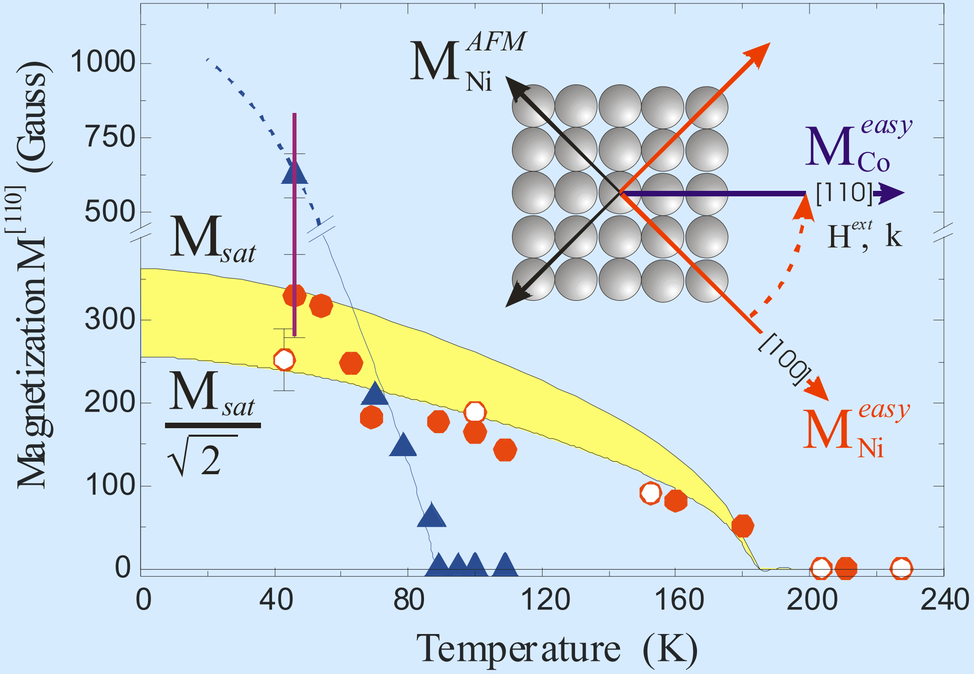
spin fluctuations, $\Delta T_C$ depend on several parameters

$d_{Ni}$ $d_{Cu}$ $d_{Co}$ and more



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



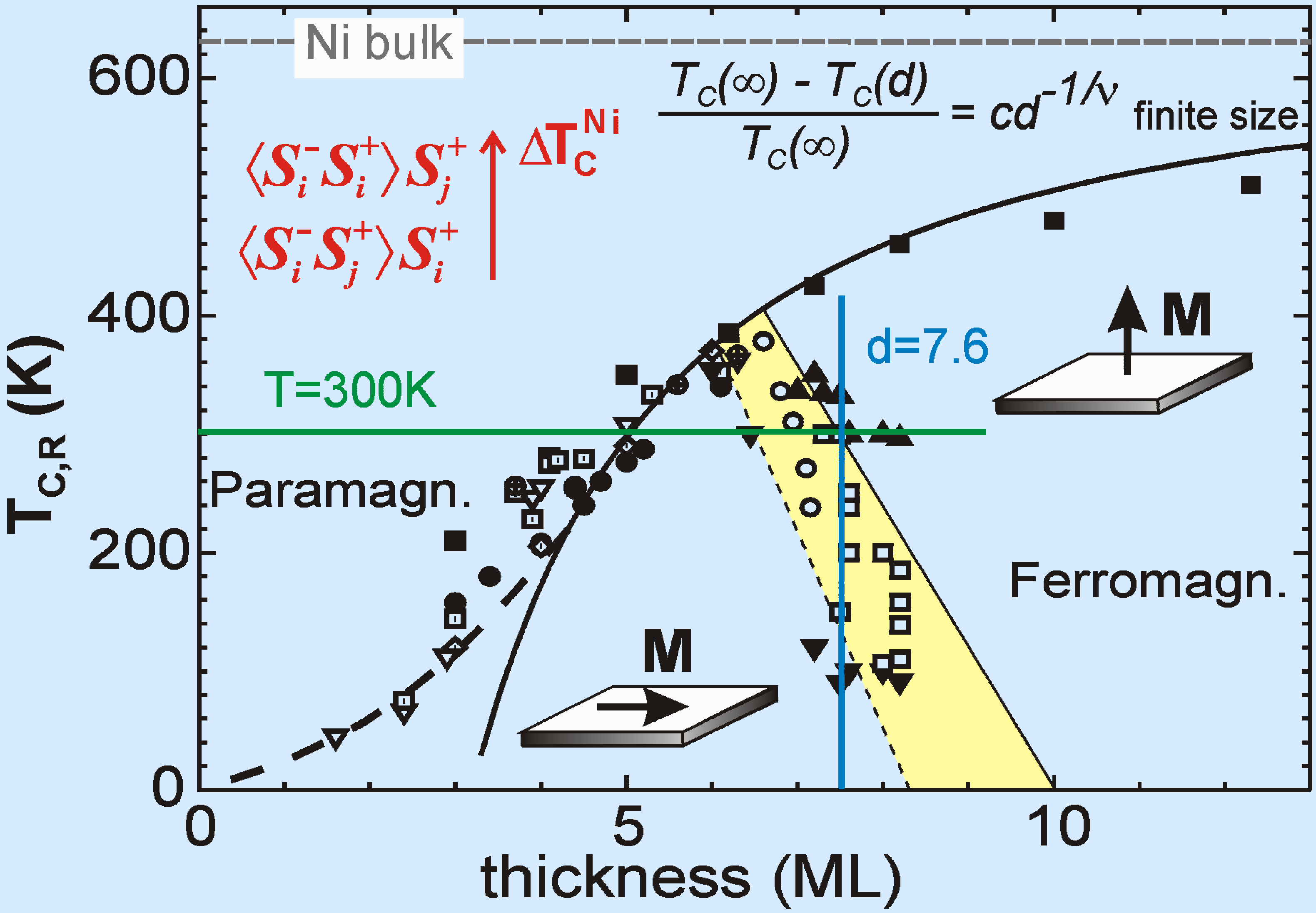


Two order parameter of $T_C^{Ni}$ and $T_C^{Co}$

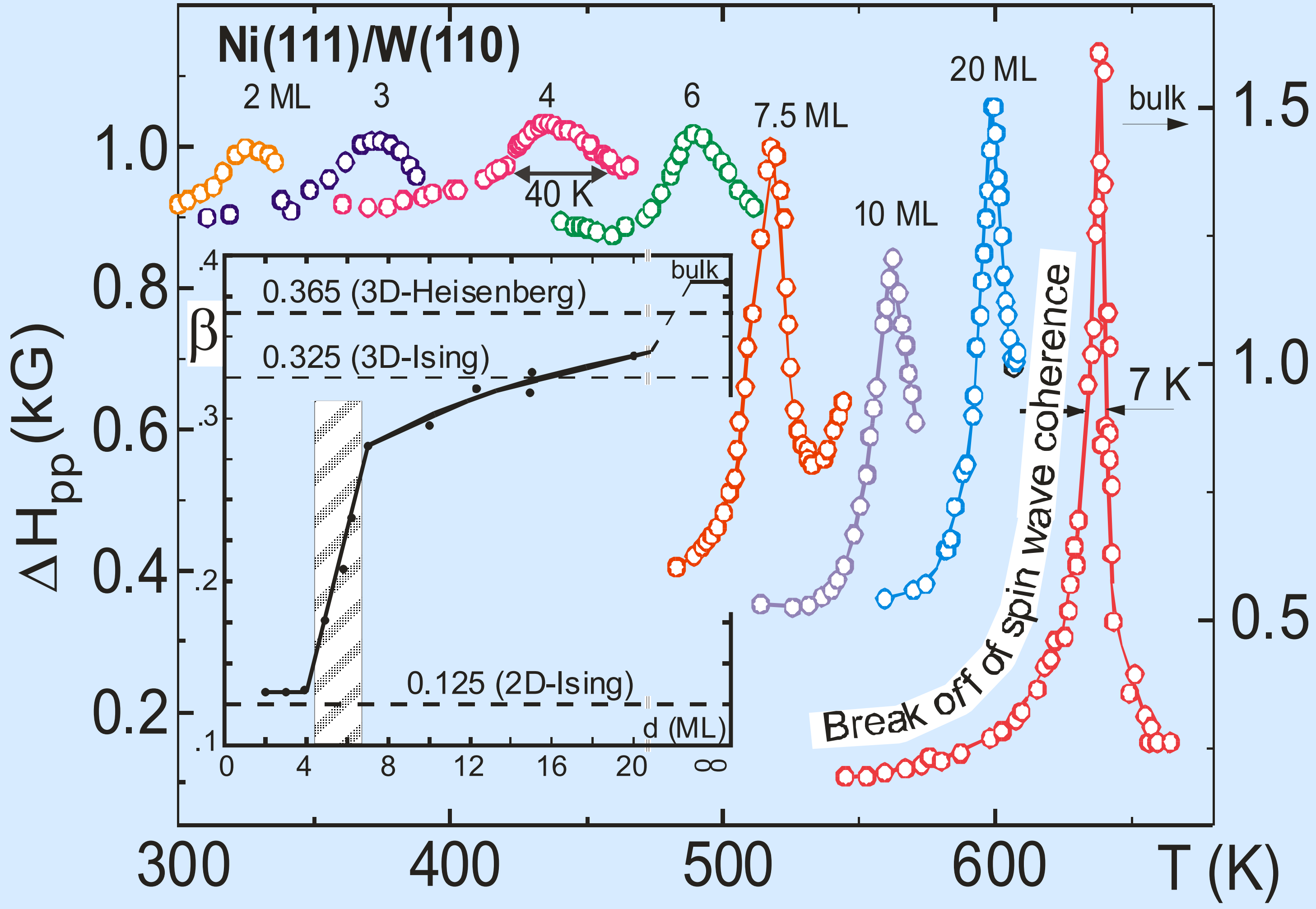
A further reduction in symmetry happens at $T_C^{low}$

A. Scherz, F. Wilhelm, P. Poulopoulos, H. Wende and K. Baberschke
*Element-specific Magnetization Curves and Crossover in Co/Cu/Ni/Cu(001) Trilayers Studied by XMCD*
XAFS XI Japan, July 2000, J. Synchrotron Rad. **8**, 472 (2001)

# Beyond the Molecular Field Approximation



# Spin fluctuation in Ni thin films. Magnetic resonance linewidth diverges at $T_C$



Yi Li and K. Baberschke, Phys. Rev. Lett., **68**, 1208 (1992)

# Summary

Spin dynamics at interfaces and nanostructures
may not be explained in a simple picture of
spin-up, spin-down MF band structures.

Higher order spin-spin correlations
are important in 1D and 2D structures.

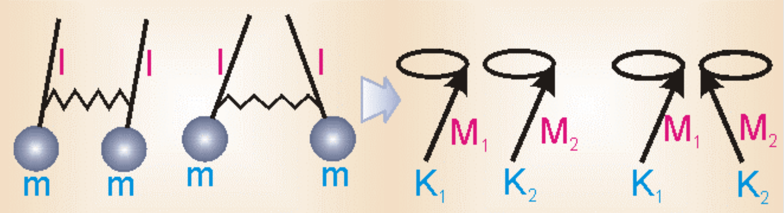
New results in ***Theomag-group Fysik, UU*** ?!

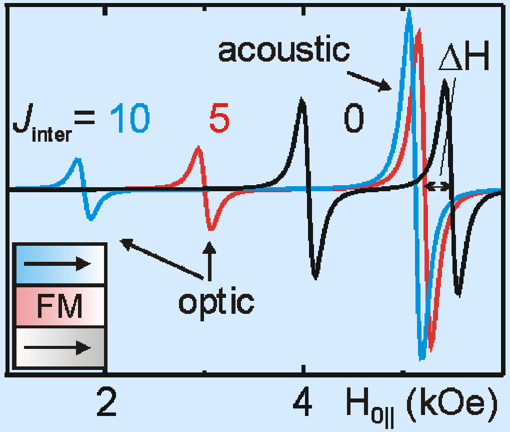
# 2. Temperature dependence of IEC

## Spin dynamics in coupled films

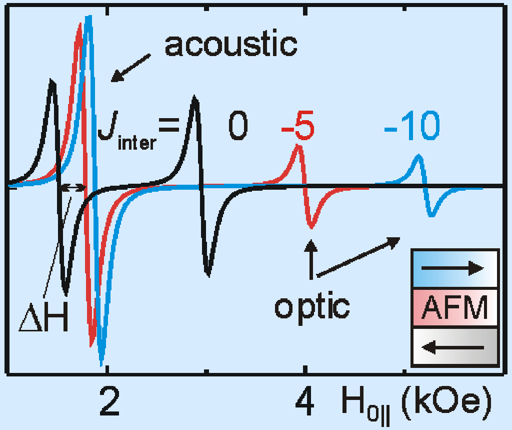
Landau-Lifshitz-Gilbert-Equation

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

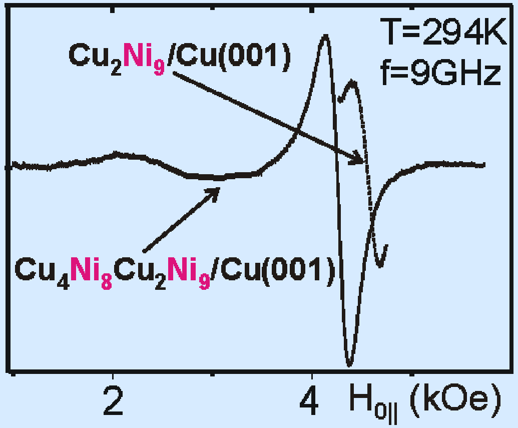




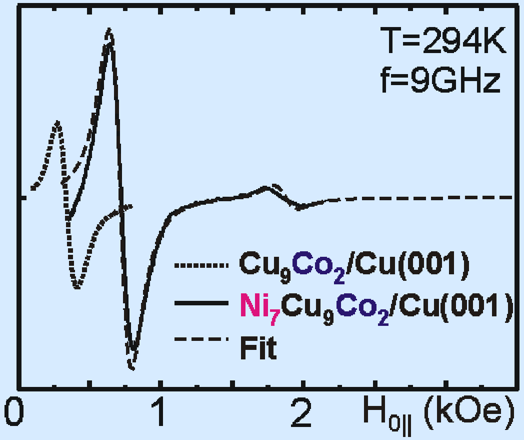
theory



**FMR**

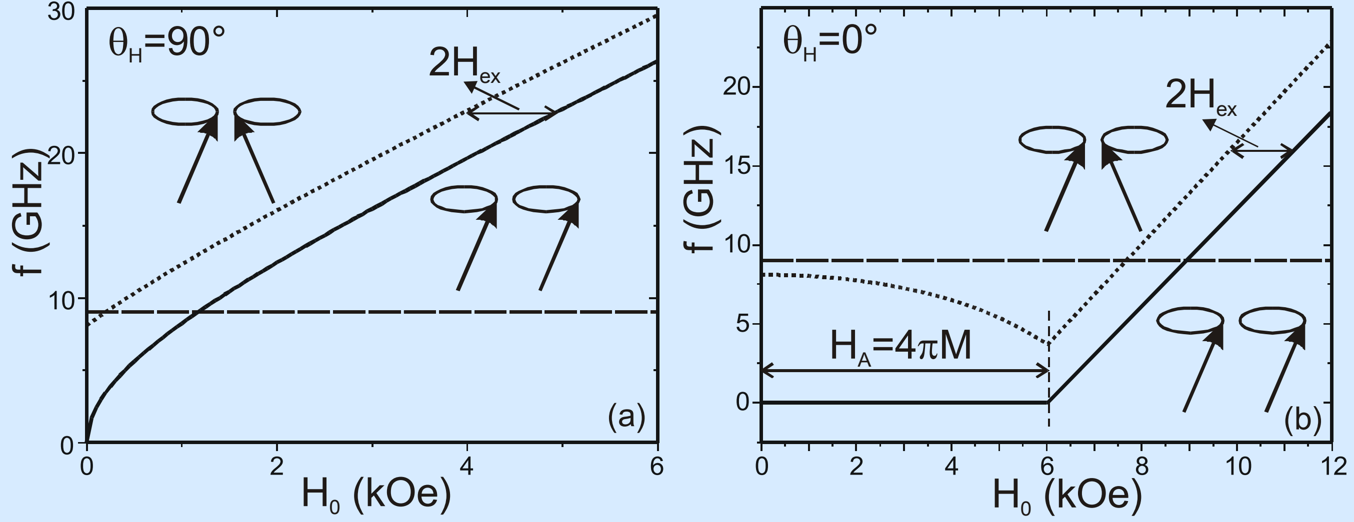


*in-situ*
UHV-experiment

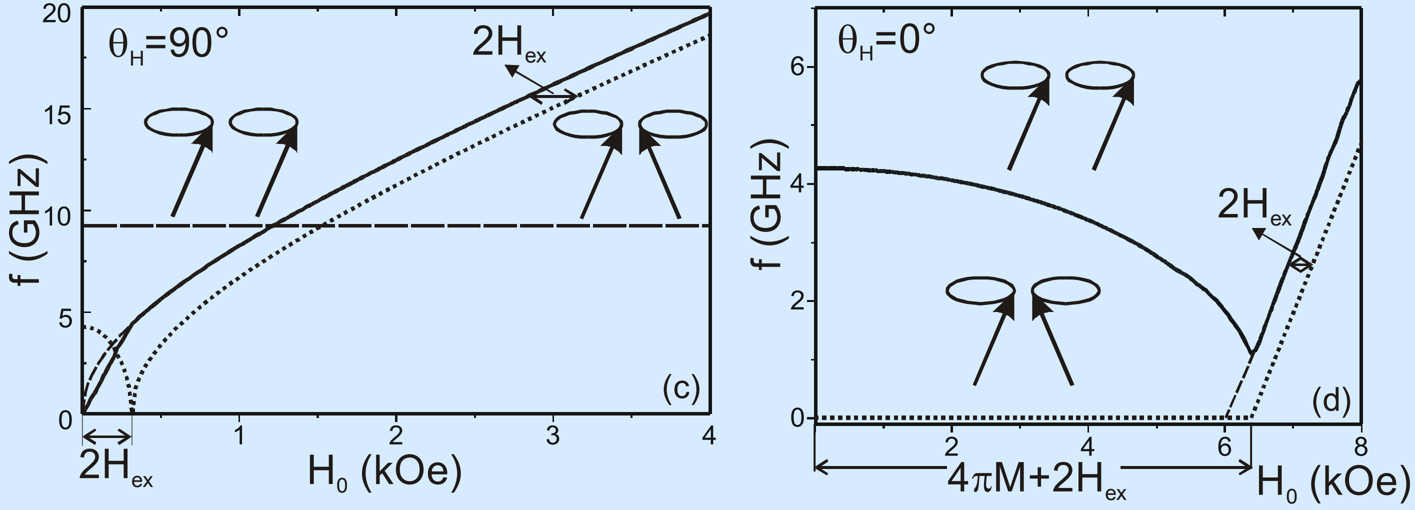


J. Lindner, K. B. Topical Rev., J. Phys. Condens. Matter **15**, R193-R232 (2003)

# Ferromagnetically coupled system



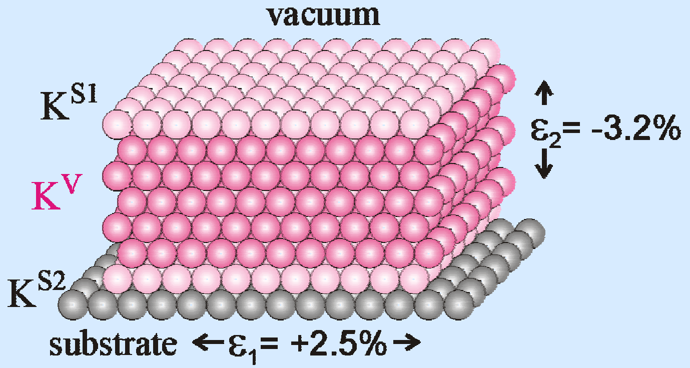
# Antiferromagnetically coupled system



*in-situ* UHV-FMR measures FM **and** AFM
and determines $J_{inter}$ **in absolute units**, e.g. μeV/atom

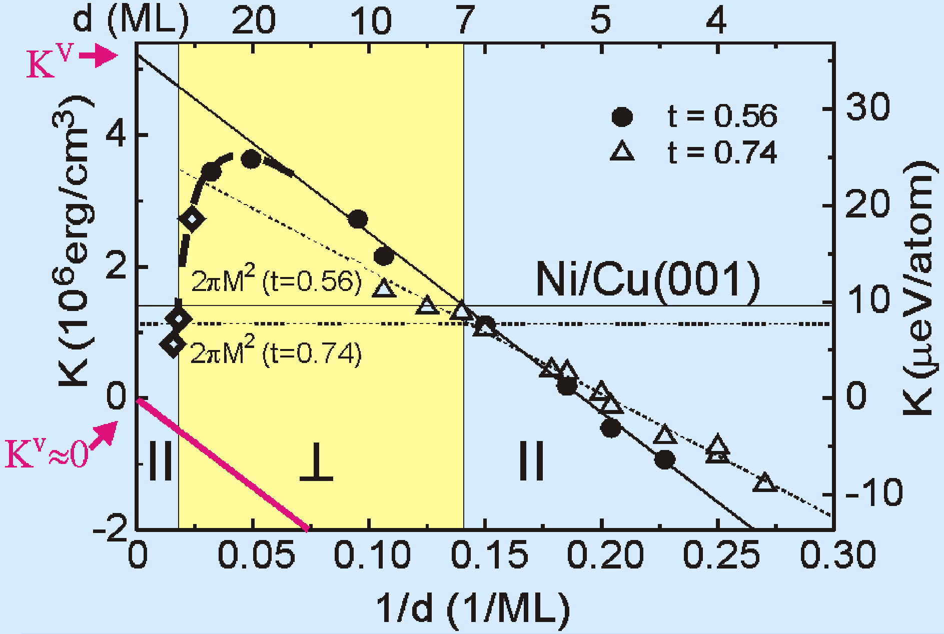
# Full trilayer grows in fct structure

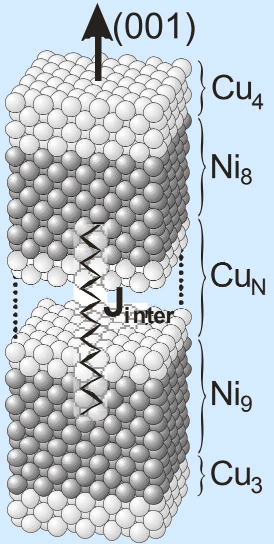
## “volume”, “surface” and “interface” MAE

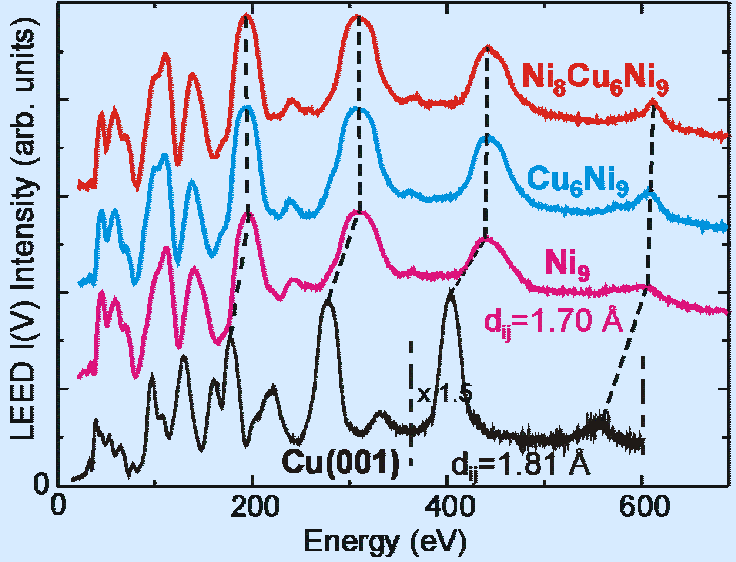


$$K_i = K_i^V + 2\frac{K_i^S}{d}$$

$t=T/T_C(d)$



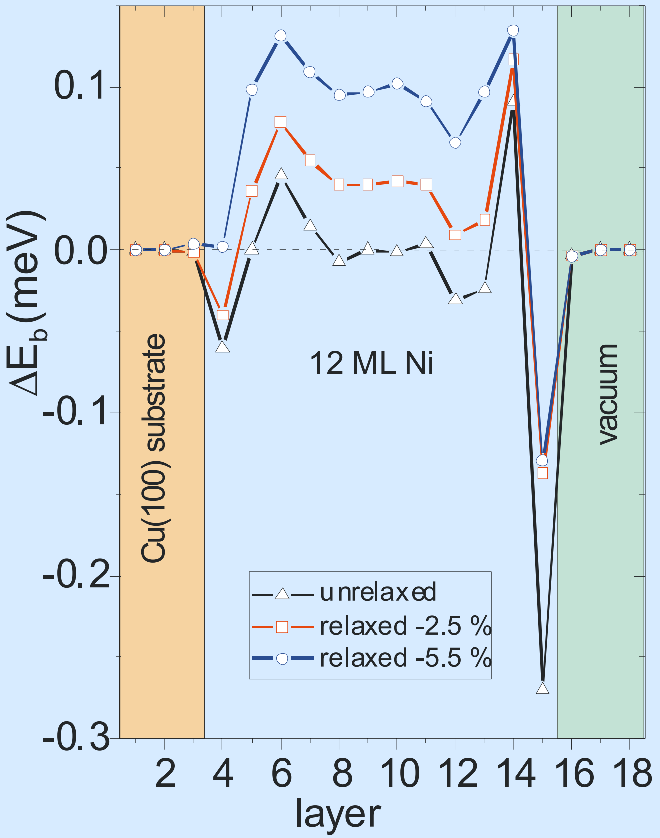




K.B. JMMM, **272-276,** 1130 (2004)

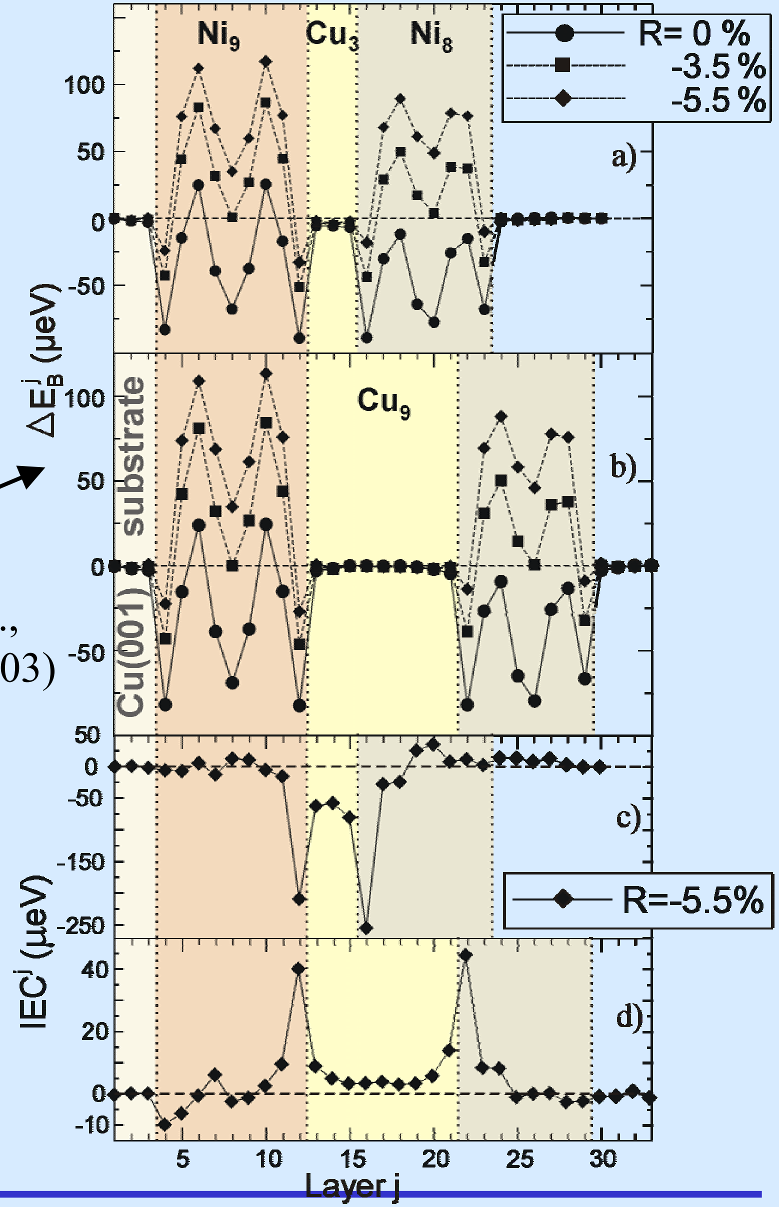
# SP-KKR calculation for rigit fcc and relaxed fct structures

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 in n-2 layers.

Are the calculated IEC and the measured $J_{inter}$ identical?

$$E = \sum_{i=1}^{2} (2\pi M_i^2 - K_{2\perp,i}) d_i \cos^2\theta_i - J_{inter} \frac{\overline{M}_1 \cdot \overline{M}_2}{M_1 M_2}$$

Experiment measures Δ free energy and projects it on a macroscopy Heisenberg model

---

Theory uses microscopic magnetic moments $m_i$ with site selectic $J_{ij}$

$$\langle E\rangle = \left\langle \sum_{i,j} J_{ij} \frac{\overline{m}_i \cdot \overline{m}_j}{m_i m_j} \right\rangle \sim \left\langle J \sum_{i,j} \frac{\overline{m}_i \cdot \overline{m}_j}{m_i m_j} \right\rangle \qquad \langle J\rangle \left\langle \sum_{i,j} \frac{\overline{m}_i \cdot \overline{m}_j}{m_i m_j} \right\rangle \Leftrightarrow J_{inter} \frac{\overline{M}_1 \cdot \overline{M}_2}{M_1 M_2}$$

They are related only via the approximations $J_{ij} \rightarrow \langle J \rangle$

**Conclusion:** **IEC $\propto$ $J_{inter}$**
but necessarily not identical

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

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

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

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

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

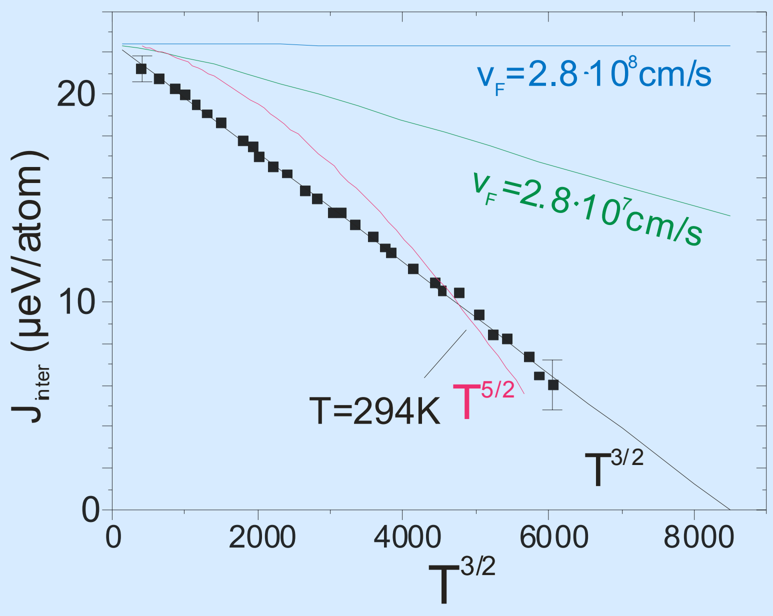
**$Ni_7Cu_9Co_2/Cu(001)$**

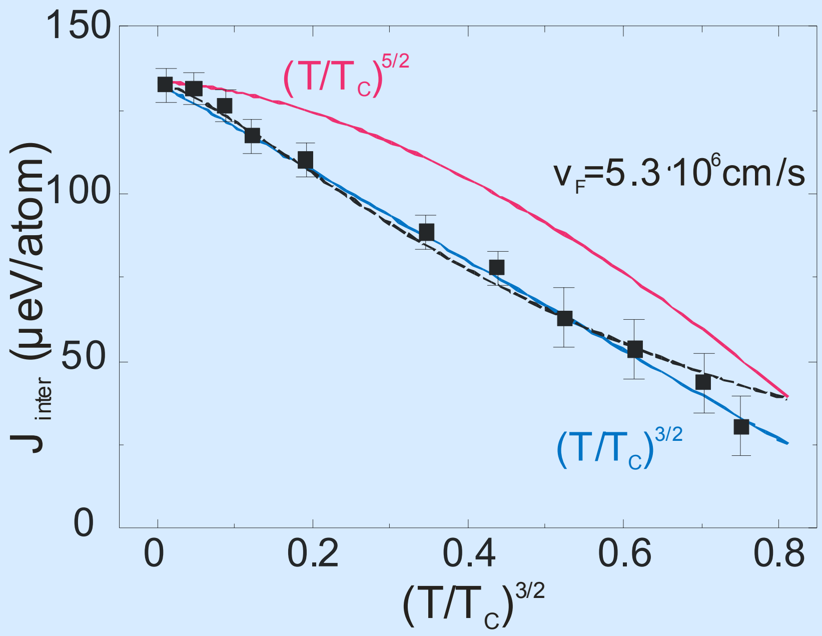
T=55K - 332K

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

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

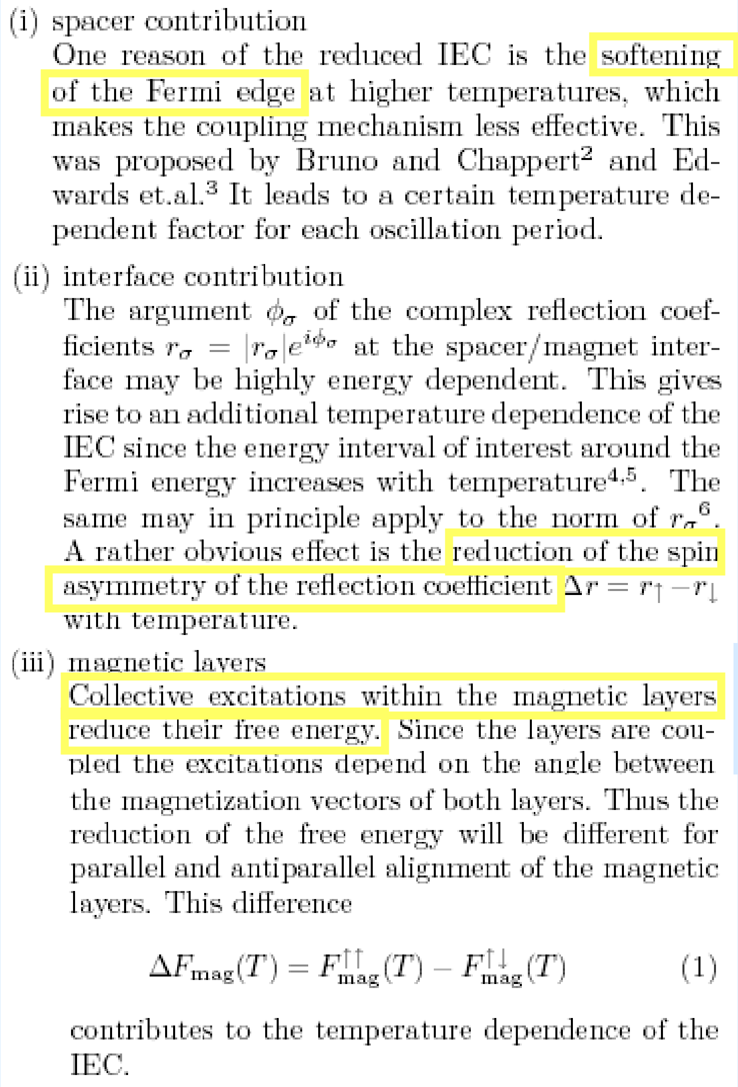
T=15K - 252K, $T_C$=305K





# On the origin of temperature dependence of interlayer exchange coupling in metallic trilayers

S. Schwieger and W. Nolting
*Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, 12489 Berlin*



(i) spacer contribution
One reason of the reduced IEC is the softening of the Fermi edge at higher temperatures, which makes the coupling mechanism less effective. This was proposed by Bruno and Chappert[2] and Edwards et.al.[3] It leads to a certain temperature dependent factor for each oscillation period.

(ii) interface contribution
The argument $\phi_\sigma$ of the complex reflection coefficients $r_\sigma = |r_\sigma| e^{i\phi_\sigma}$ at the spacer/magnet interface may be highly energy dependent. This gives rise to an additional temperature dependence of the IEC since the energy interval of interest around the Fermi energy increases with temperature[4,5]. The same may in principle apply to the norm of $r_\sigma$[6]. A rather obvious effect is the reduction of the spin asymmetry of the reflection coefficient $\Delta r = r_\uparrow - r_\downarrow$ with temperature.

(iii) magnetic layers
Collective excitations within the magnetic layers reduce their free energy. Since the layers are coupled the excitations depend on the angle between the magnetization vectors of both layers. Thus the reduction of the free energy will be different for parallel and antiparallel alignment of the magnetic layers. This difference

$$\Delta F_{\mathrm{mag}}(T) = F^{\uparrow\uparrow}_{\mathrm{mag}}(T) - F^{\uparrow\downarrow}_{\mathrm{mag}}(T) \qquad (1)$$

contributes to the temperature dependence of the IEC.

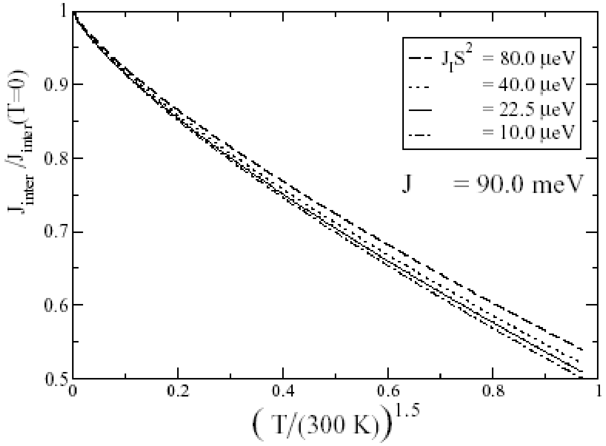


FIG. 3: Temperature dependent factor of $J_{\mathrm{inter}}$ plotted against temperature for different zero temperature couplings $J_I S^2$.

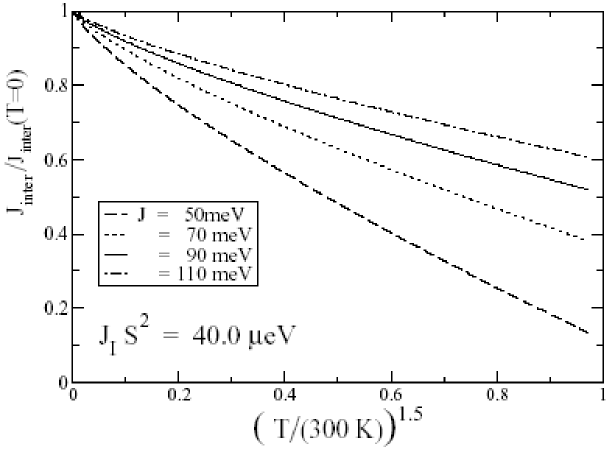
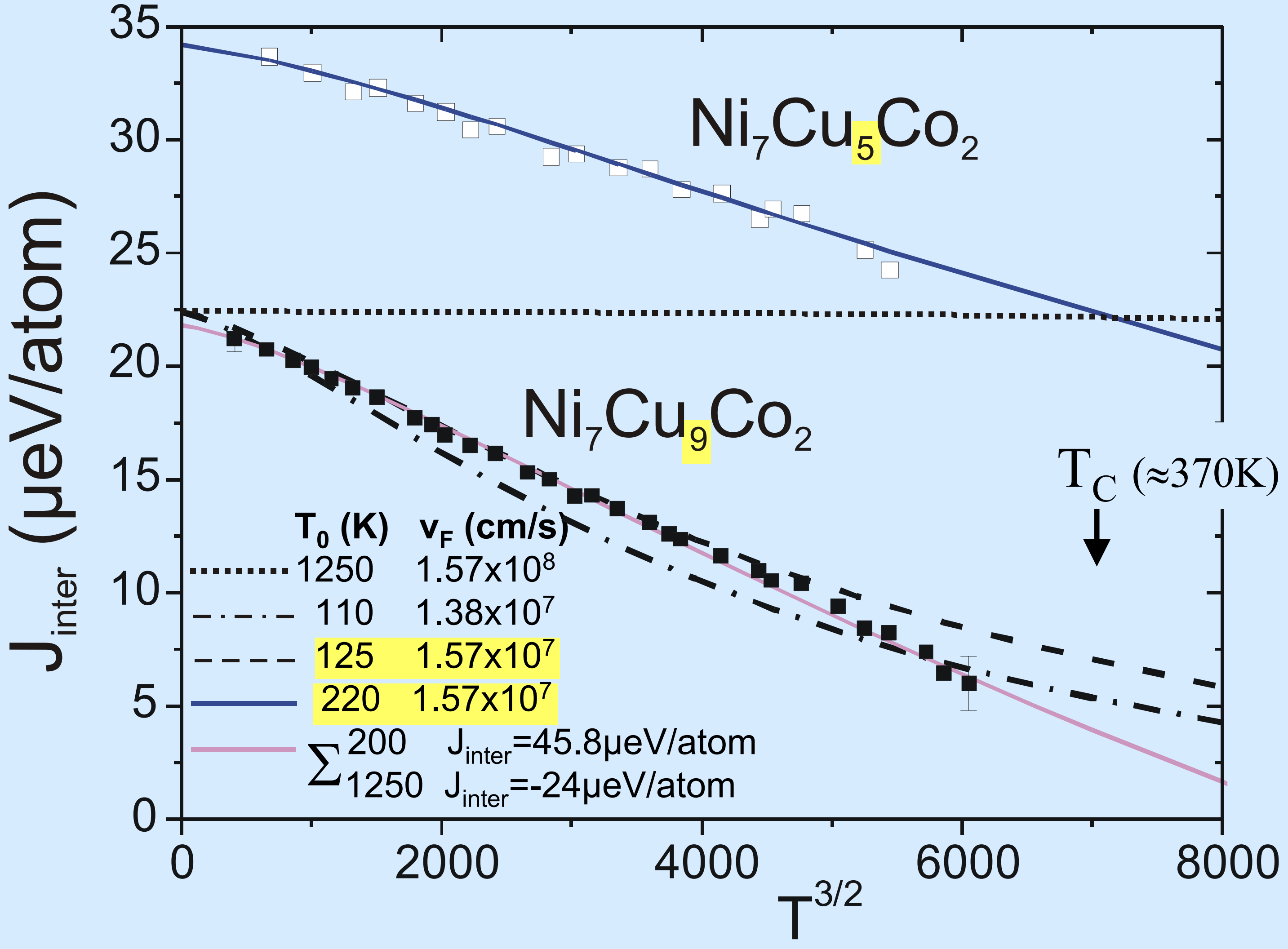


FIG. 4: Temperature dependent factor of $J_{\mathrm{inter}}$ plotted against temperature for different intra-layer couplings $J$

# $J_{inter}$ (T) for different $d_{Cu}$



$$\frac{220}{125} \approx \frac{9}{5}$$

K. Lenz et al. unpublished

# FMR line width ⇔ spin-wave damping

## Landau-Lifshitz-Gilbert-Equation

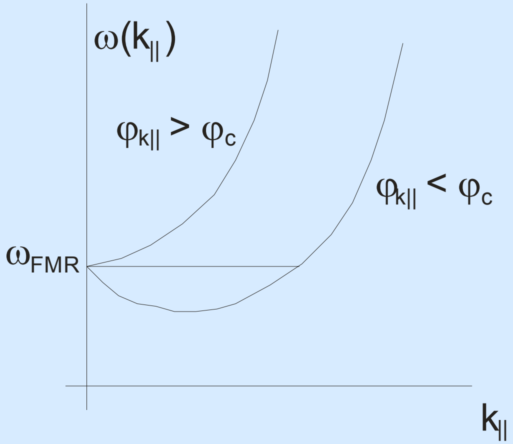
$$\frac{1}{\gamma}\frac{\partial M}{\partial t} = -(M \times H_{eff}) + \frac{G}{\gamma M_S^2}\left(M \times \frac{\partial M}{\partial t}\right)$$

## 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

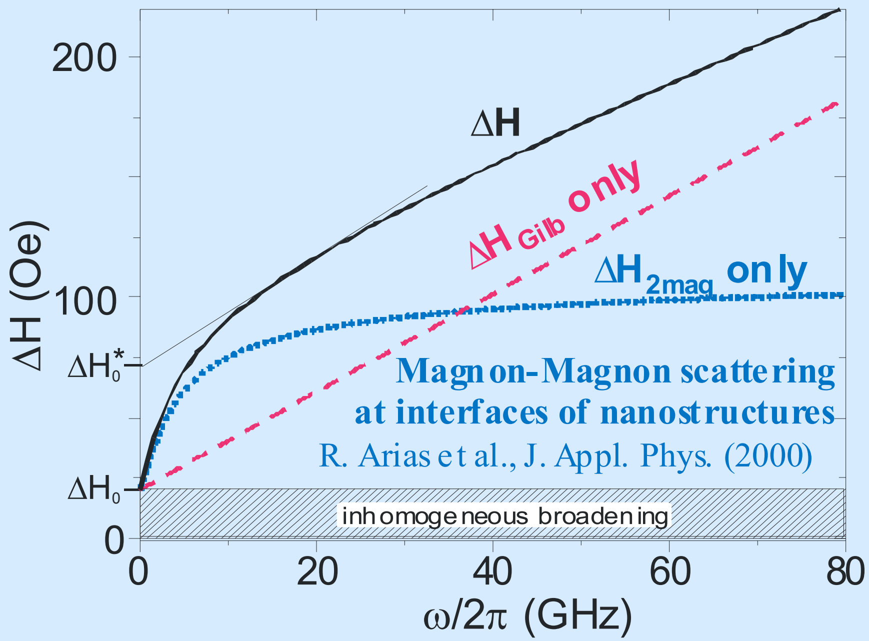


$$\Delta H^{2Mag}(\omega) = \Gamma \arcsin\sqrt{\frac{[\omega^2+(\omega_0/2)^2]^{1/2} - \omega_0/2}{[\omega^2+(\omega_0/2)^2]^{1/2} + \omega_0/2}}$$

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

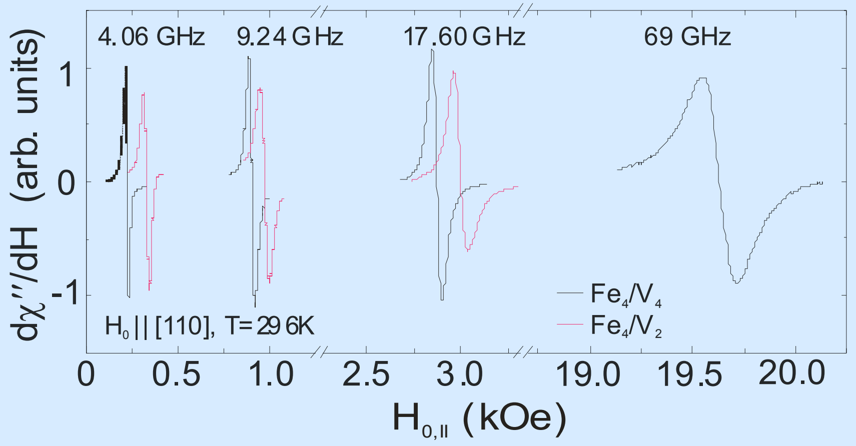
# ‘Non-Gilbert-Type’ spin-wave damping

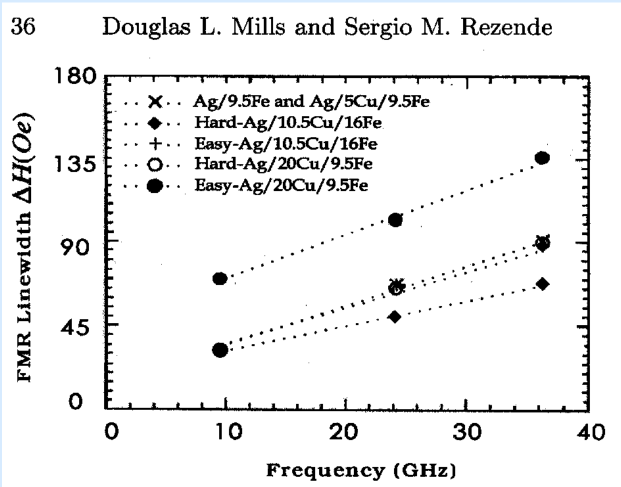
J. Lindner et al.
Phys. Rev. B **68**, 060102(R) (2003)



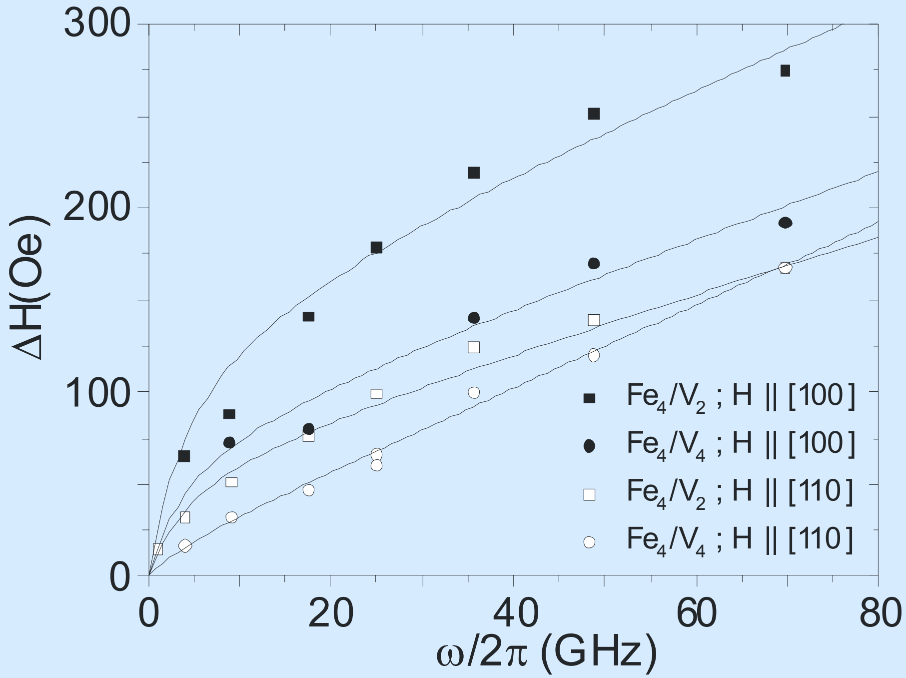
Magnon-Magnon scattering at interfaces of nanostructures

R. Arias et al., J. Appl. Phys. (2000)





36 Douglas L. Mills and Sergio M. Rezende

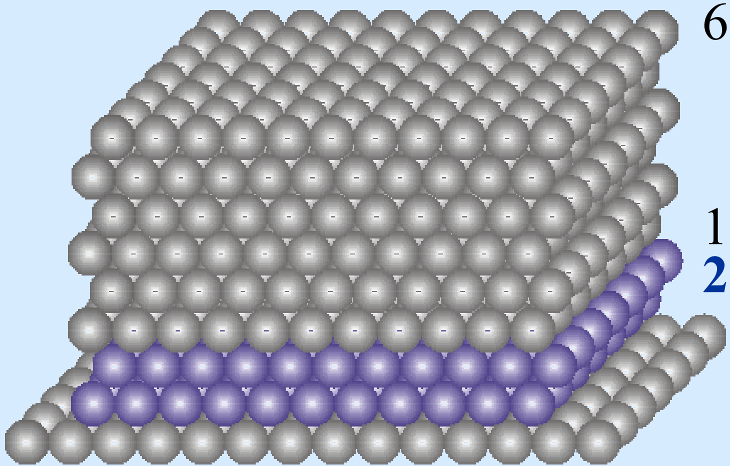


# Summary

- FMR provides IEC, MAE, etc. in absolute energy units, i.e. μeV/particle.
- More complete theory of spin wave dynamics at elevated temperatures is needed.
- Simple D•k$^2$ dispersion law may not be always sufficient.

For '*Spin Dynamics in Confined Magnetic Structures*' the LL equation of motion may give incomplete information. Not all scattering processes can be treated as a macroscopic viscosity parameter.

# 3. Oscillatory $T_C$ of a Co film with Cu-cap



6 ML Cu

1 ML Cu

**2-3 ML Co**

**$T_C \approx 300\text{-}400K$**

Cu-substrate

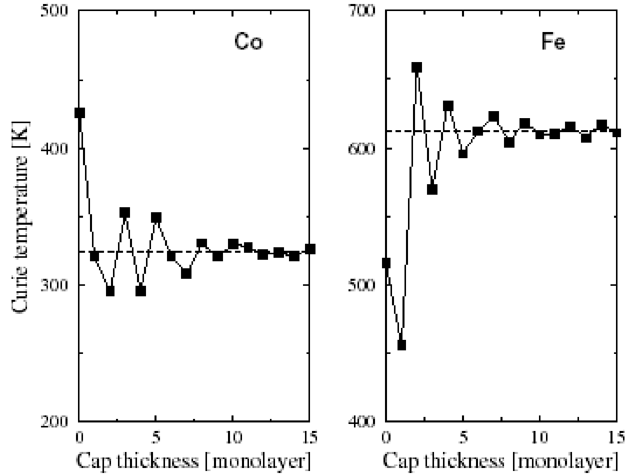
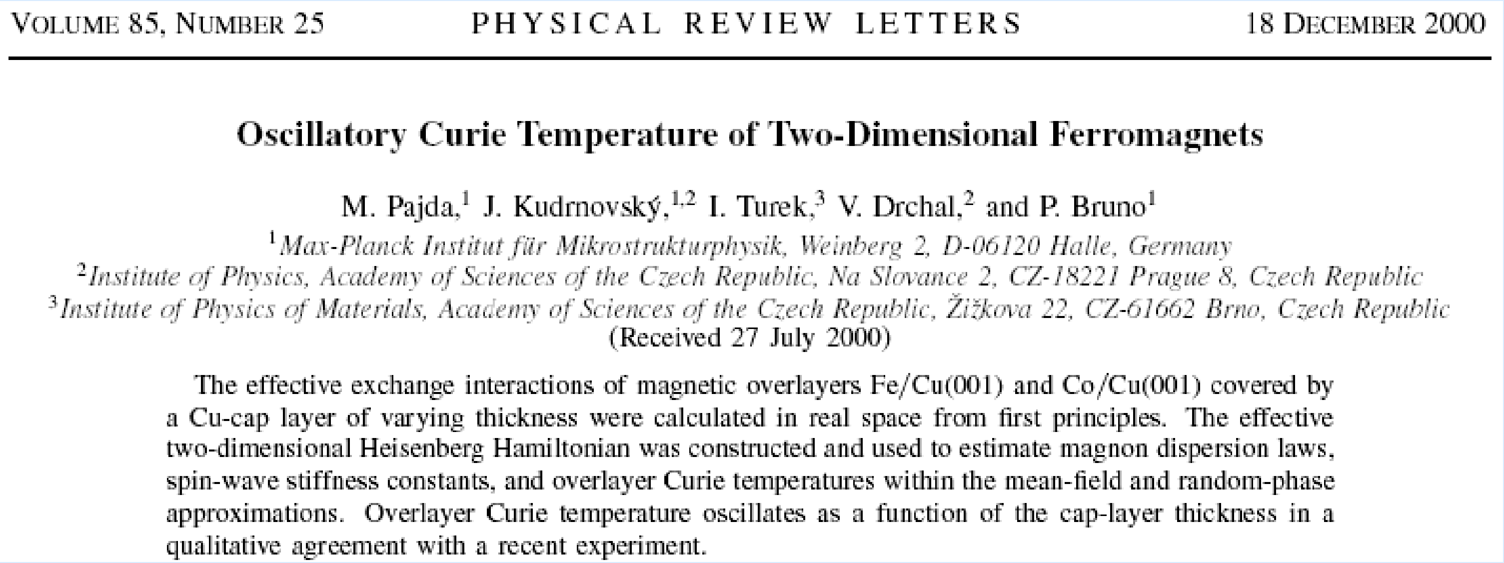


FIG. 3. $T_c^{\mathrm{RPA}}$ of Co (left) and Fe (right) overlayers on a fcc-Cu(001) substrate covered by a cap layer of varying thickness. The dashed lines represent the embedded layer limit (infinite cap thickness) while the limit of zero cap thickness corresponds to the uncovered overlayer.



VOLUME 85, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 2000

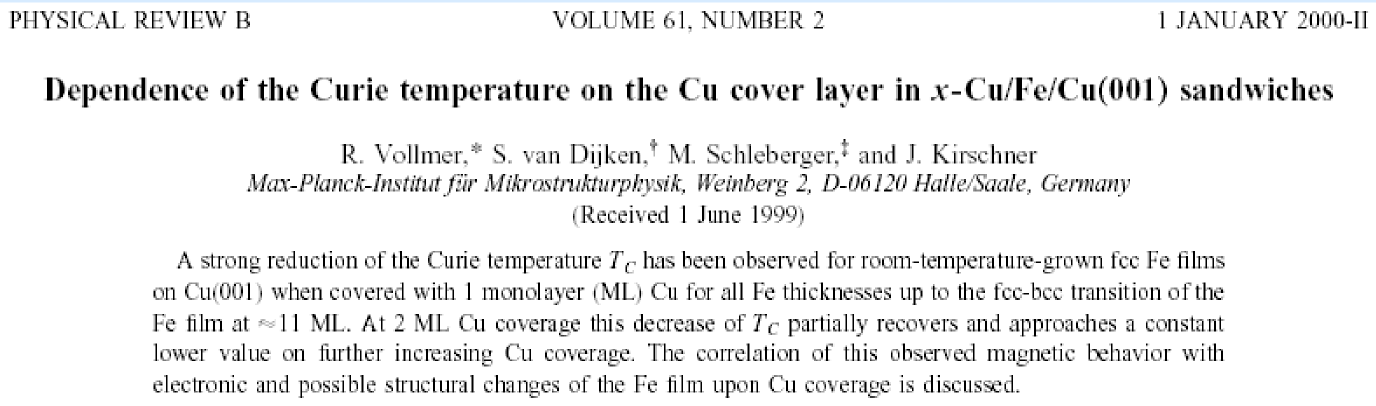
## Oscillatory Curie Temperature of Two-Dimensional Ferromagnets

M. Pajda,[1] J. Kudrnovský,[1,2] I. Turek,[3] V. Drchal,[2] and P. Bruno[1]

[1] *Max-Planck Institut für Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany*
[2] *Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, CZ-18221 Prague 8, Czech Republic*
[3] *Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Žižkova 22, CZ-61662 Brno, Czech Republic*

(Received 27 July 2000)

The effective exchange interactions of magnetic overlayers Fe/Cu(001) and Co/Cu(001) covered by a Cu-cap layer of varying thickness were calculated in real space from first principles. The effective two-dimensional Heisenberg Hamiltonian was constructed and used to estimate magnon dispersion laws, spin-wave stiffness constants, and overlayer Curie temperatures within the mean-field and random-phase approximations. Overlayer Curie temperature oscillates as a function of the cap-layer thickness in a qualitative agreement with a recent experiment.



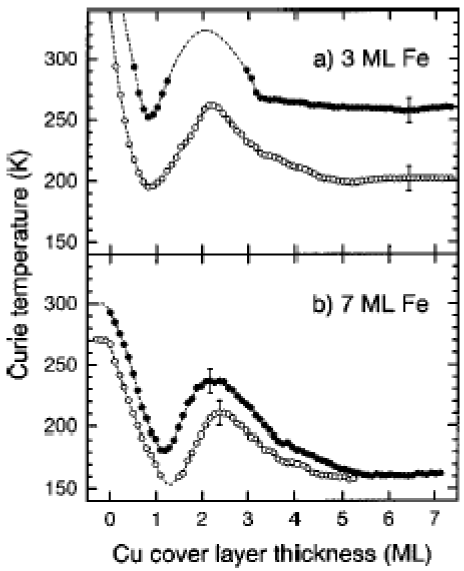
PHYSICAL REVIEW B VOLUME 61, NUMBER 2 1 JANUARY 2000-II

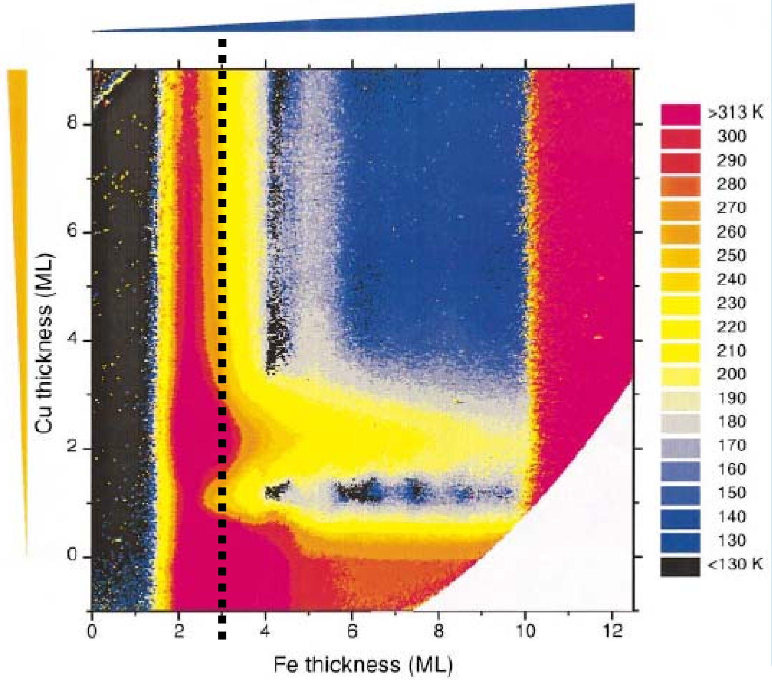
### Dependence of the Curie temperature on the Cu cover layer in *x*-Cu/Fe/Cu(001) sandwiches

R. Vollmer,* S. van Dijken,† M. Schleberger,‡ and J. Kirschner
*Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, D-06120 Halle/Saale, Germany*

(Received 1 June 1999)

A strong reduction of the Curie temperature $T_C$ has been observed for room-temperature-grown fcc Fe films on Cu(001) when covered with 1 monolayer (ML) Cu for all Fe thicknesses up to the fcc-bcc transition of the Fe film at ≈11 ML. At 2 ML Cu coverage this decrease of $T_C$ partially recovers and approaches a constant lower value on further increasing Cu coverage. The correlation of this observed magnetic behavior with electronic and possible structural changes of the Fe film upon Cu coverage is discussed.





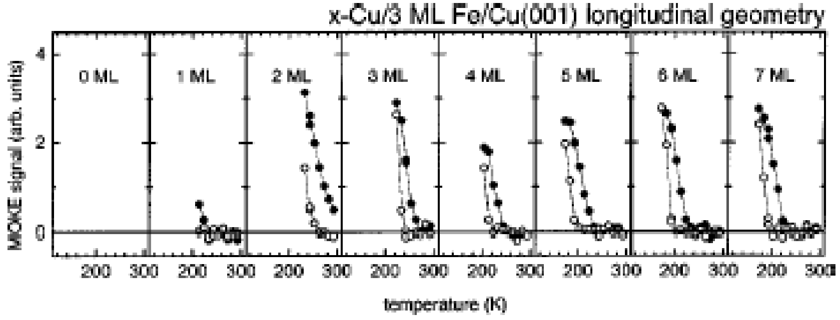


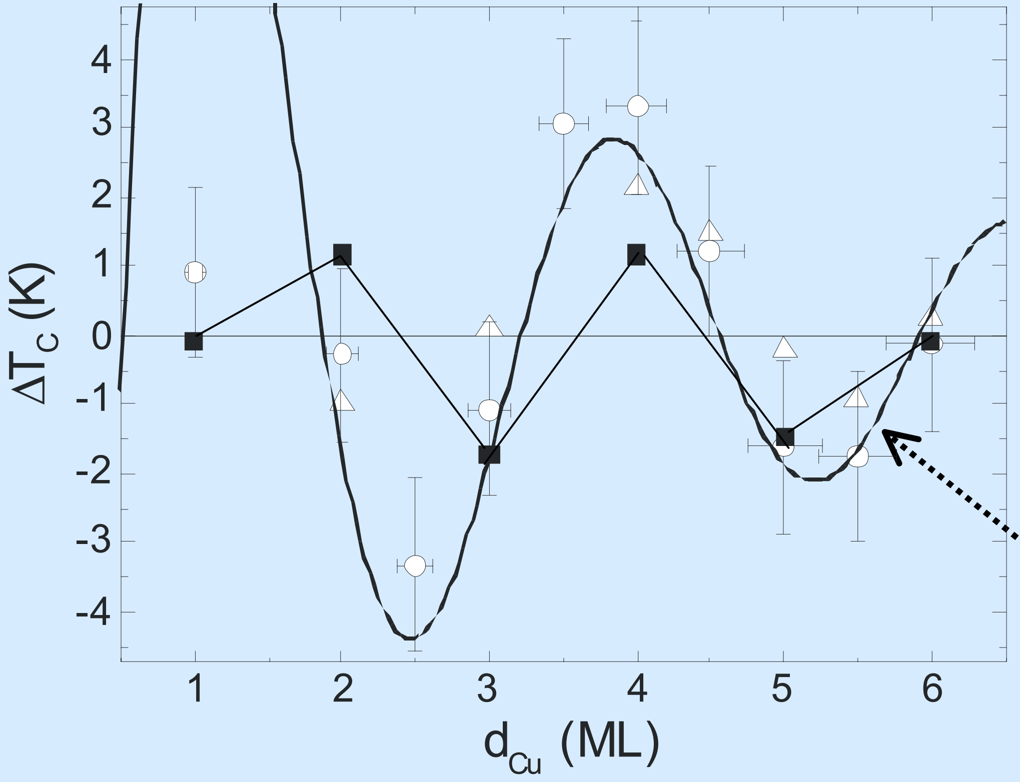
FIG. 8. Same as Fig. 2 in the longitudinal Kerr geometry. Due to the insufficient external field component normal to the surface in this geometry the magnetization direction of the Fe film could not be reversed below ≈180 K.

FIG. 7. (Color) Color map of the Curie temperatures from a Cu/Fe/Cu(001) double wedge. The Kerr data for this image were obtained by a Kerr-imaging setup as described in Ref. 59 with a maximum external field of $H = \pm 300$ Oe. The Curie temperature in the light gray area in the lower right corner is not determined because these points correspond to coordinates outside of the crystal. (While the Fe and Cu wedges were grown at an angle of 74° with respect to each other, the data in this figure are transformed to an orthogonal coordinate system.)

# Oscillatory Curie Temperature in Ultrathin Ferromagnets: Experimental Evidence

C. Rüdt, A. Scherz, K. Baberschke
*Institut für Experimentalphysik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin, Germany*

submitted



ac-susceptibility measurements with consecutive evaporation of Cu-layers

○ = 2.2 ML Co
△ = 2.5 ML Co
■ = M. Pajda et al. PRL **85**, 5424 (2000)
(down scaled)

$$\Delta T_C(d) = \frac{A}{d}\sin(\frac{2\pi}{\Lambda}d + \Phi); \quad \Lambda = 2.7 \text{ ML}$$

**However, there are other additional effects on $T_C$**

# Three mechanisms influence $T_C$

1. The magnetic moment of the top layer changes

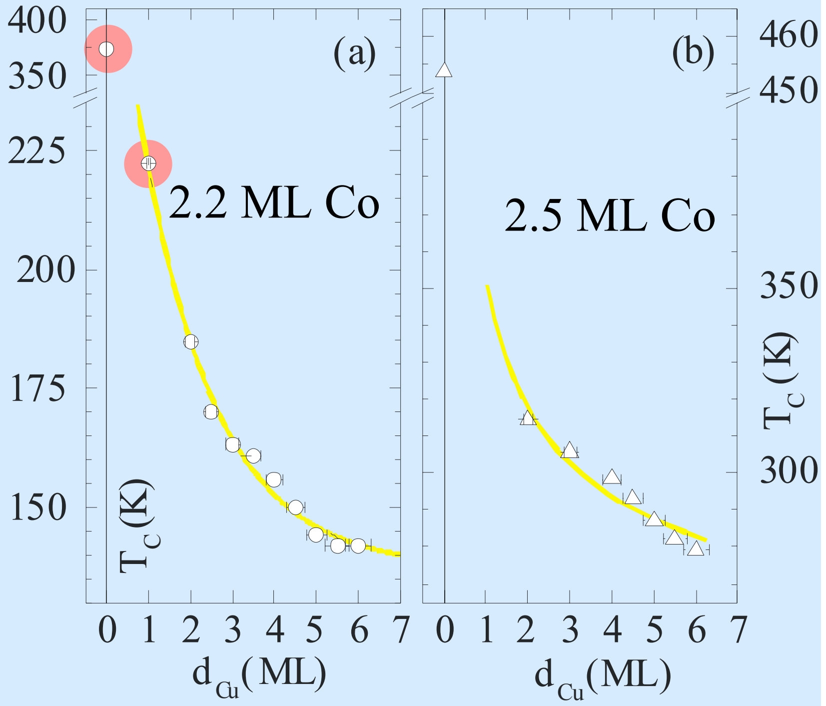
vacuum: $\mu_{Co}$ +32% enhanced

Cu-interface: $\mu_{Co}$ –17% reduced

*UHV-SQUID, A. Ney et al. EPL,* ***54****, 820 (2001)*

$T_C \propto \langle \mu^2 \rangle$

$Co_2/Cu(100)\ T_C^0=370K \Rightarrow Cu/Co_2/Cu(100)\ T_C^0=220K$



2. Hybridization, electronic band structure at Cu/Co interface

*ARUPS* $Cu_{2\text{-}8}/Co_{20}$ *changes effective mass of QW states*

*P. Johanson et al. PRB* ***50****, 8954 (1994)*

*monotonic decay of* $T_C$

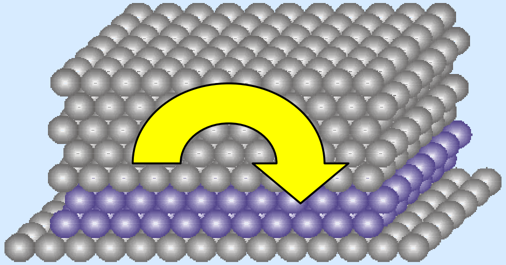
3. QW effects

# Summary

Is a „small“ oscillatory amplitude in $T_C$ plausible ? Yes !

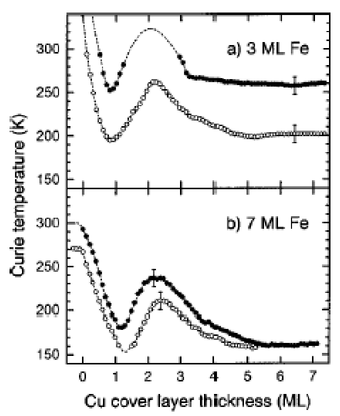
We know from FMR in trilayers that

$$\Delta T_C^{*} \approx 100\text{K} \Leftrightarrow J_{inter} = 50\mu\text{eV/atom}$$
$$\Delta T_C^{cap} \approx 4\text{K} \Leftrightarrow J_{cap} \approx 2\mu\text{eV (FMR)}$$



Vollmer et al. observed a strong decrease of $T_C$ by 120K ...

Vollmer et al. write „ ... delocalized QW states ... may be less important …, since we did not see further oscillations ...“



# Conclusion

- *In-situ* experiments + step-by-step preparation in UHV are important.
- XMCD measures element specific M
- FMR measures J absolute and f(T)
- Oscillatory $T_C$ upon capping, QW states are experimentally verified, but amplitude is small.

  C. Rüdt, A. Scherz, and K. B.
  "*Oscillatory Curie Temperature in Ultrathin Ferromagnets: Experimental Evidence*"
  submitted

K. B. "*The magnetism of ultrathin trilayers: A playground to study fundamentals*"
J. Magn. Magn. Mater. **272-276**, 1130 (2004)

- The magnetism of nanostructures is a prototype case, which shows the close collaboration between theory and experiment.

**Theory:** O. Eriksson UU; P. Weinberger, TU Vienna; R. Wu, D.L. Mills, UCI;
J.J. Rehr, UW; H. Ebert, LMU; K.H. Bennemann, FUB; W. Nolting, HUB

# Acknowledgement

**BESSY-crew:** H. Wende, A. Scherz, C. Sorg, N. Ponpandian, M. Bernien

**Lab. experiments:** K. Lenz, T.Toliński, E. Kosubek, C. Rüdt, (J. Lindner, R. Nünthel)

***Support:*** BMBF (BESSY), DFG (lab.)

⇒ **http://www.physik.fu-berlin.de/~ag-baberschke**