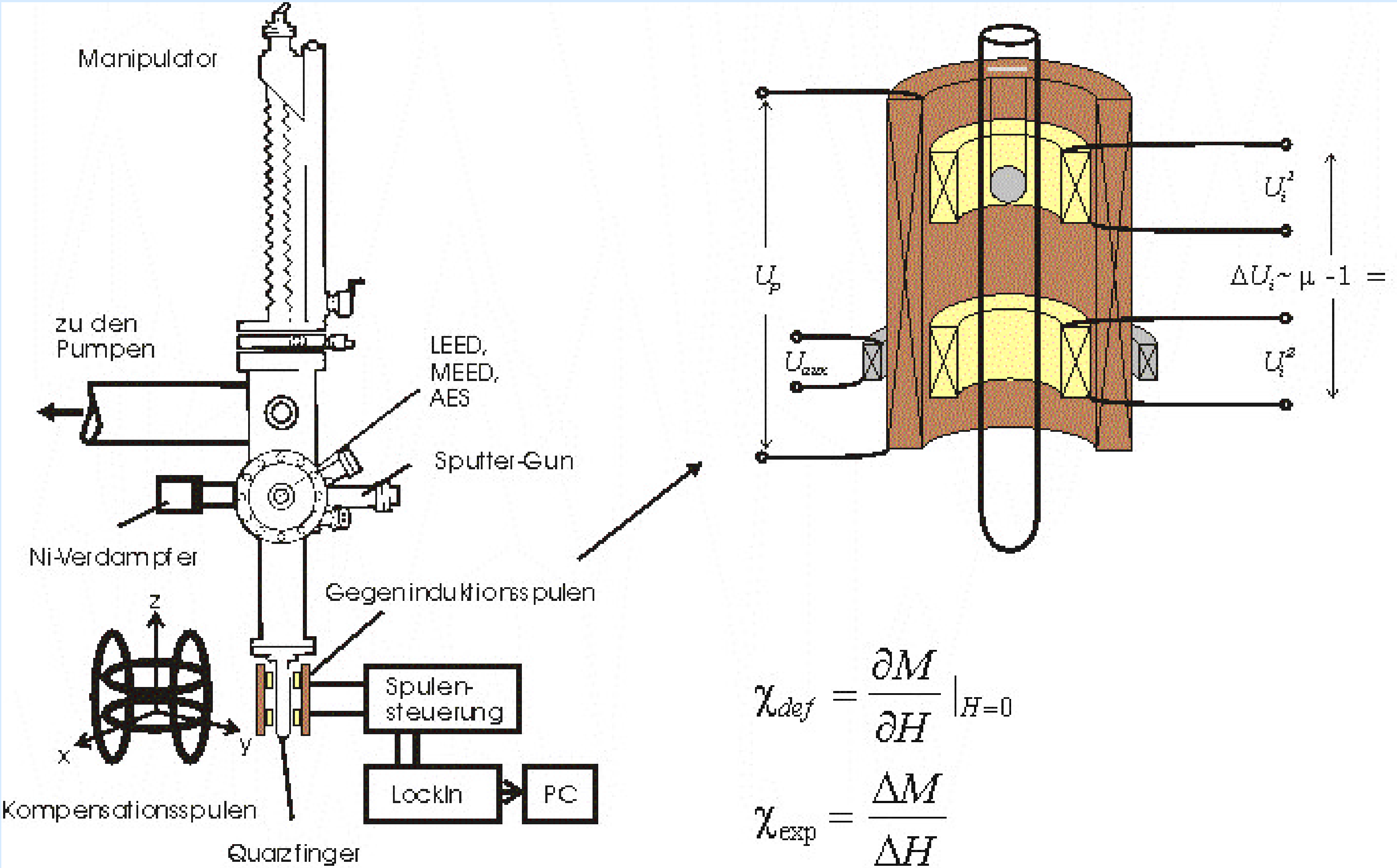
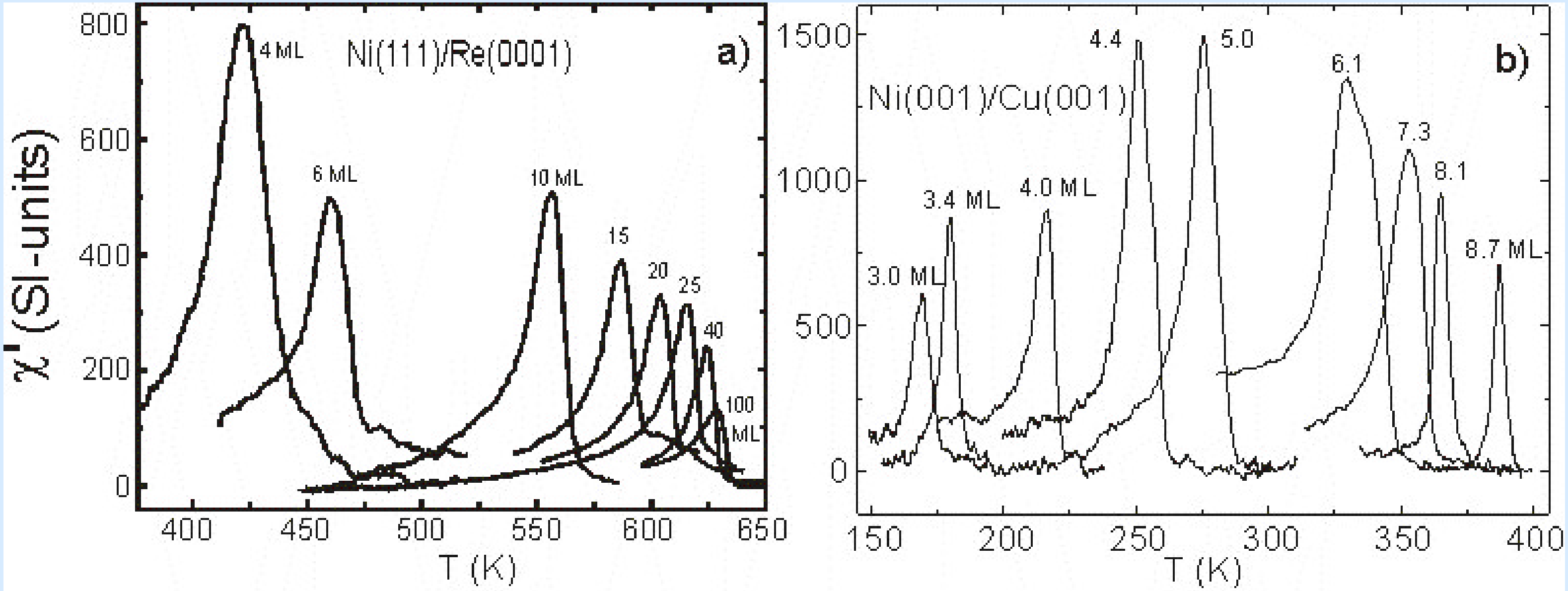
Lecture 3 UHV ac – Susceptibility χ’, χ’’



$$\chi_{def} = \frac{\partial M}{\partial H}\Big|_{H=0}$$

$$\chi_{exp} = \frac{\Delta M}{\Delta H}$$

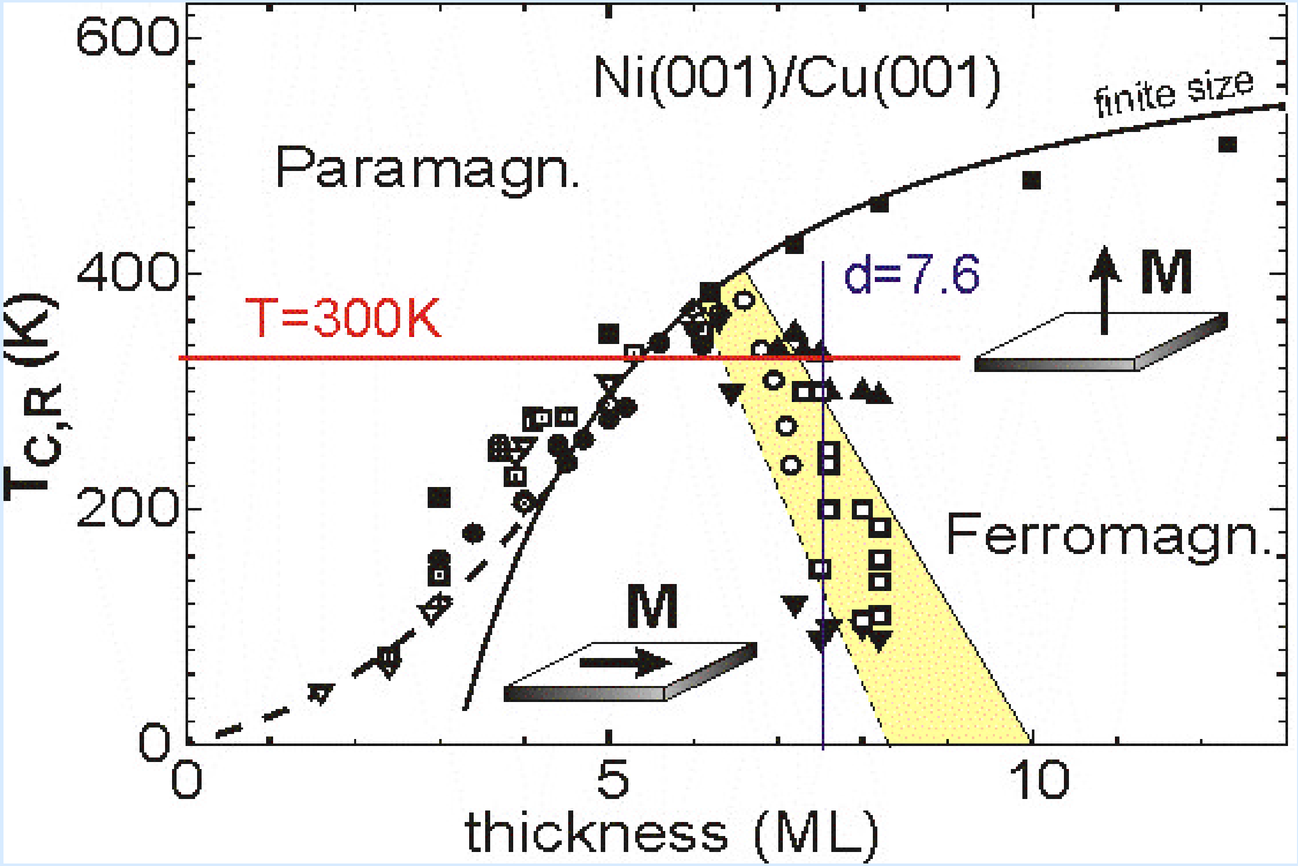
U. Bovensiepen et al., ECOSS 17, Surf. Sci. **402-404**, 396 (1998)



"Magnetism in thin films"

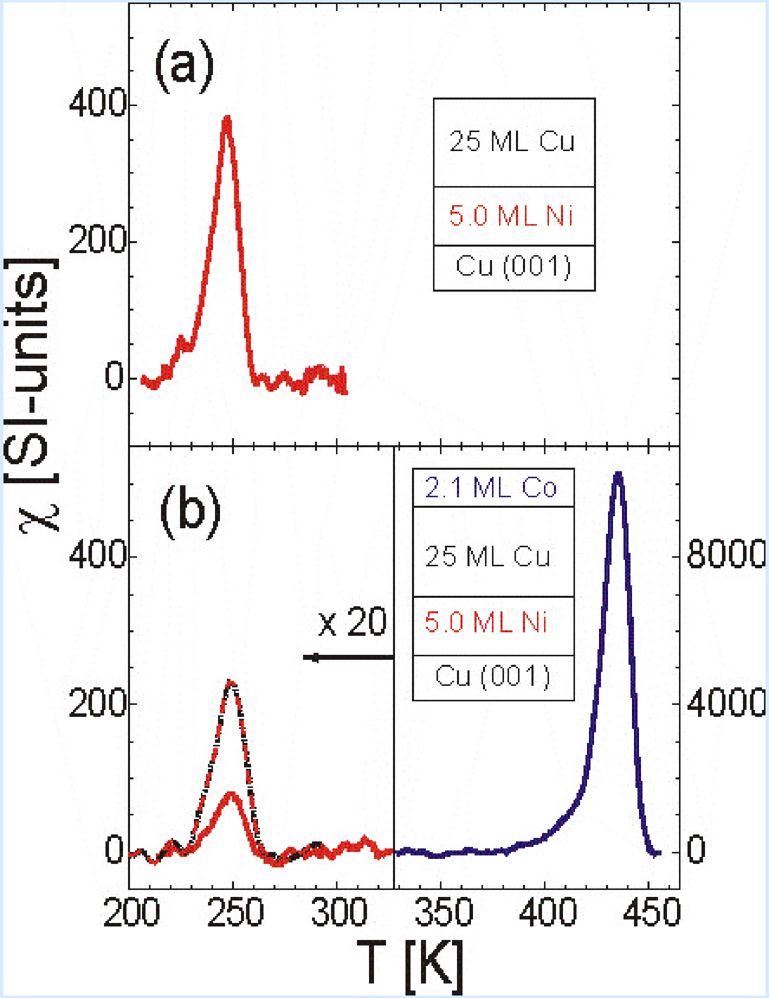
P. Poulopoulos, K. B., J. Phys. Condens. Matter. **11**, 9495 (1999)

For thin films the Curie temperature can be manipulated



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

2 peaks in the ac-susceptibility



see lecture 4

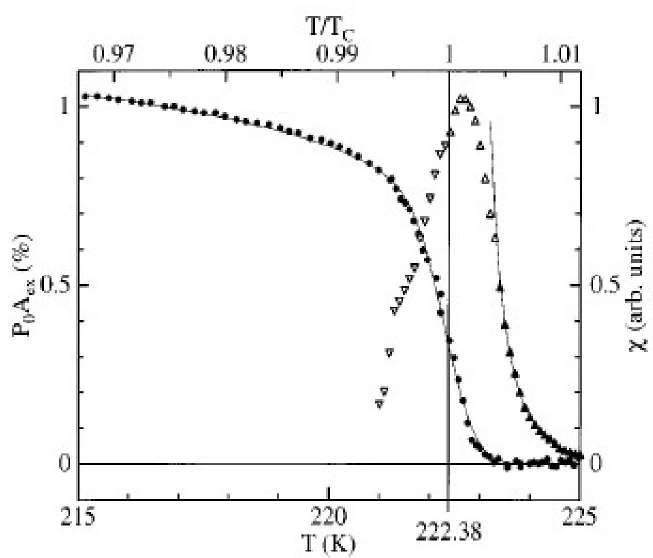
PHYSICAL REVIEW B VOLUME 54, NUMBER 21 1 DECEMBER 1996-I

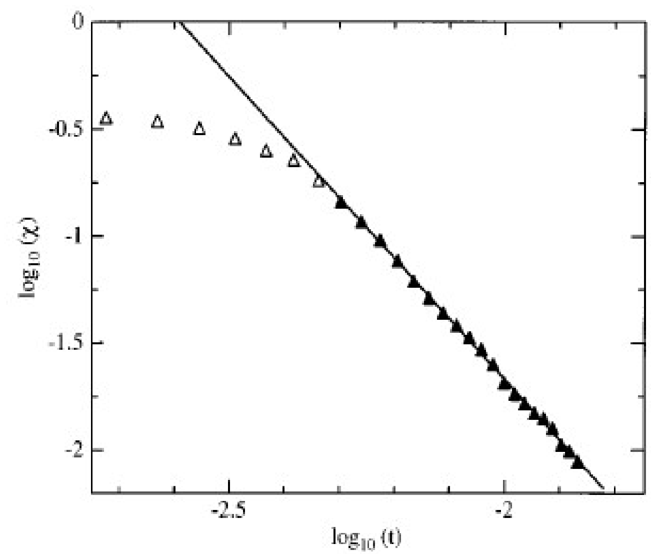
Critical behavior of the uniaxial ferromagnetic monolayer Fe(110) on W(110)

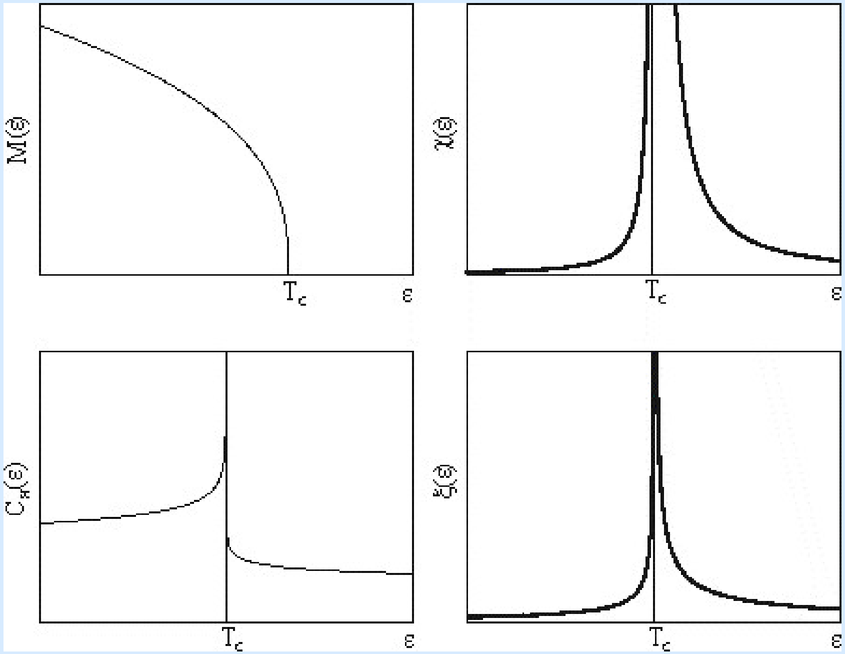
Hans-Joachim Elmers, Jens Hauschild, and Ulrich Gradmann*
Physikalisches Institut, Technische Universität Clausthal, D-38678 Clausthal-Zellerfeld, Germany

(Received 11 July 1996)

The critical behavior of a ferromagnetic monolayer has been investigated experimentally for the case of the thermodynamically stable pseudomorphic monolayer Fe(110) on W(110). The nearly ideal monolayer samples were composed of monolayer Fe(110) stripes, grown by step flow from the atomic steps of the W(110) substrate, with a distribution of stripe widths around a mean value of 40 nm, and virtually infinite length. The magnetic properties were measured by spin-polarized low-energy electron diffraction, which could be done in weak magnetic fields up to 2 Oe. The monolayer samples show uniaxial magnetic anisotropy with the easy axis $[1\bar{1}0]$ in the film plane. Magnetization tails above T_c were shown to be a result of convolution of the critical power law with the monolayer stripe width distribution. Using an appropriate deconvolution, critical power laws could be established for both magnetization M and susceptibility χ, with critical exponents $\beta=(0.134 \pm 0.003)$ and $\gamma=(2.8\pm 0.2)$, corresponding to predictions of a two-dimensional anisotropic Heisenberg model. [S0163-1829(96)03145-1]







$$
\begin{aligned}
M(\varepsilon) &= M_0\,(-\varepsilon)^{\beta}\,, && \varepsilon \to 0^-,\ h = 0 \\
\chi(\varepsilon) &= \chi_0^{\pm}\,|\varepsilon|^{-\gamma}\,, && \varepsilon \to 0^{\pm},\ h = 0 \\
\chi(h) &= D_0'\,|h|^{(1/\delta)-1}\,, && \varepsilon \to 0,\ h = 0^{\pm} \\
C_H(\varepsilon) &= A_0^{\pm}\,|\varepsilon|^{-\alpha}\,, && \varepsilon \to 0^{\pm},\ h = 0 \\
\xi(\varepsilon) &= \xi_0^{\pm}\,|\varepsilon|^{-\nu}\,, && \varepsilon \to 0^{\pm},\ h = 0 \\
M(h) &= D_0^{\pm}\,|h|^{1/\delta}\mathrm{sgn}(h)\,, && \varepsilon \to 0,\ h = 0^{\pm}
\end{aligned}
$$

$$
\begin{aligned}
\alpha &= 2\beta(\delta + 1) \\
\gamma &= \beta(\delta - 1) \\
\alpha + 2\beta + \gamma &= 2 \\
2\beta + \gamma &= \nu D\,,
\end{aligned}
$$

$$
\frac{T_C(d) - T_C(\infty)}{T_C(\infty)} = C_0\, d^{-\lambda}
$$

System [Ref.]	β	γ	χ_0^+/χ_0^-	δ	α	ν	η
MF/Landau [37]	0.5	1	–	3	Sprung	0.5	0
2D–Ising [35]	0.125	1.75	37.69	15	log.	1	0.25
3D–Ising [41]	0.325	1.241	4.8–5.07	4.816	0.11	0.63	0.032
3D–XY [41]	0.345	1.316	–	4.810	-0.008	0.705	0.033
3D–Heisenberg [41,42]	0.3645	1.3866	5.41	4.803	-0.116	0.7054	0.034
Volumen							
Fe [43]	0.389	1.33	–	4.35	-0.1	–	–
Co [44]	0.42	1.23	–	–	0.65	–	
Ni [45]	0.394	1.337	–	4.39	–	–	–
Gd [46]	0.37	1.25	–	4.39	–	–	–
Fe/W(110)							
1 ML [10]	0.134	2.8	–	–	–	–	–
1.7 ML [13]	0.13	1.74	–	14	–	–	–
Fe/W(100)							
1.6 ML [11]	0.22	5	–	–	–	–	–
Cr_3Fe [47]	0.31	1.39	–	5.5	–	–	–
$(Fe_2/V_5)_{50}$ [18,48]	0.31	1.72*	–	–	–	–	–
Ni/Cu(100)							
1.6 ML [49]	0.26	–	–	–	–	–	–
4.2 ML [48]	0.38	–	–	–	–	–	–
5 ML [49]	0.36	–	–	–	–	–	–
Ni/W(110)							
2–4 ML [39,40]	0.13	–	–	–	–	–	–
7.5 ML [39,40]	0.29	–	–	–	–	–	–
6.5–8 ML [15,29]	–	1.24	–	–	–	–	–
Gd/W(110)							
100 ML [9,50]	–	1.235	–	–	–	–	–

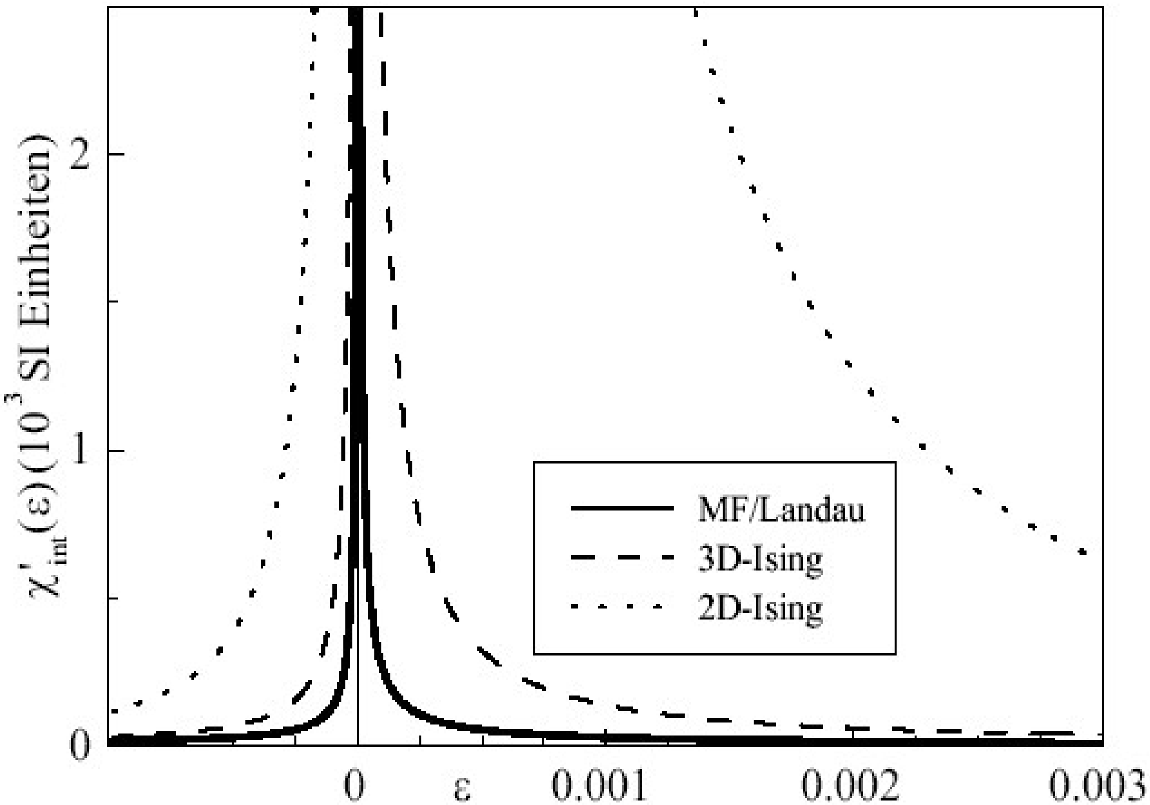
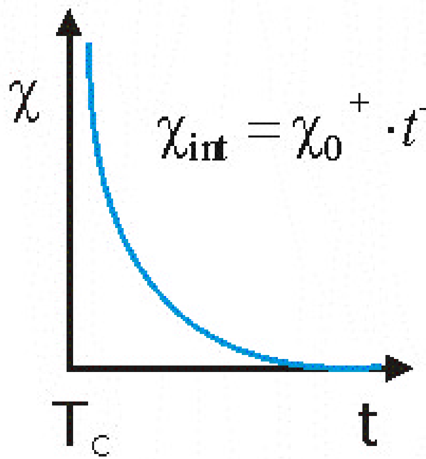


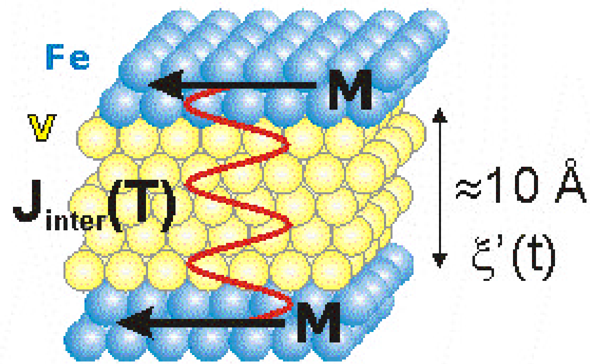
Abbildung 2.2: Simulation der temperaturabhängigen Suszeptibilität nach Glg. (2.15). Dargestellt ist die interne Suszeptibilität $\chi'_{int}(\varepsilon)$ in absoluten Einheiten als Funktion der reduzierten Temperatur für die Molekularfeld-theorie ($\gamma = 1$) und das 2D– ($\gamma = 1.75$) und 3D–Ising–Modell ($\gamma = 1.25$) mit $\chi_0^+ = 0.024$ bestimmt für $(Fe_2/V_5)_{50}$ (s. Kap. 5). χ_0^- ergibt sich durch Berücksichtigung des entsprechenden Amplitudenverhältnisses (Tab. 2.2).

3a Susceptibility and critical exponent γ



γ = 2D / 3D ?

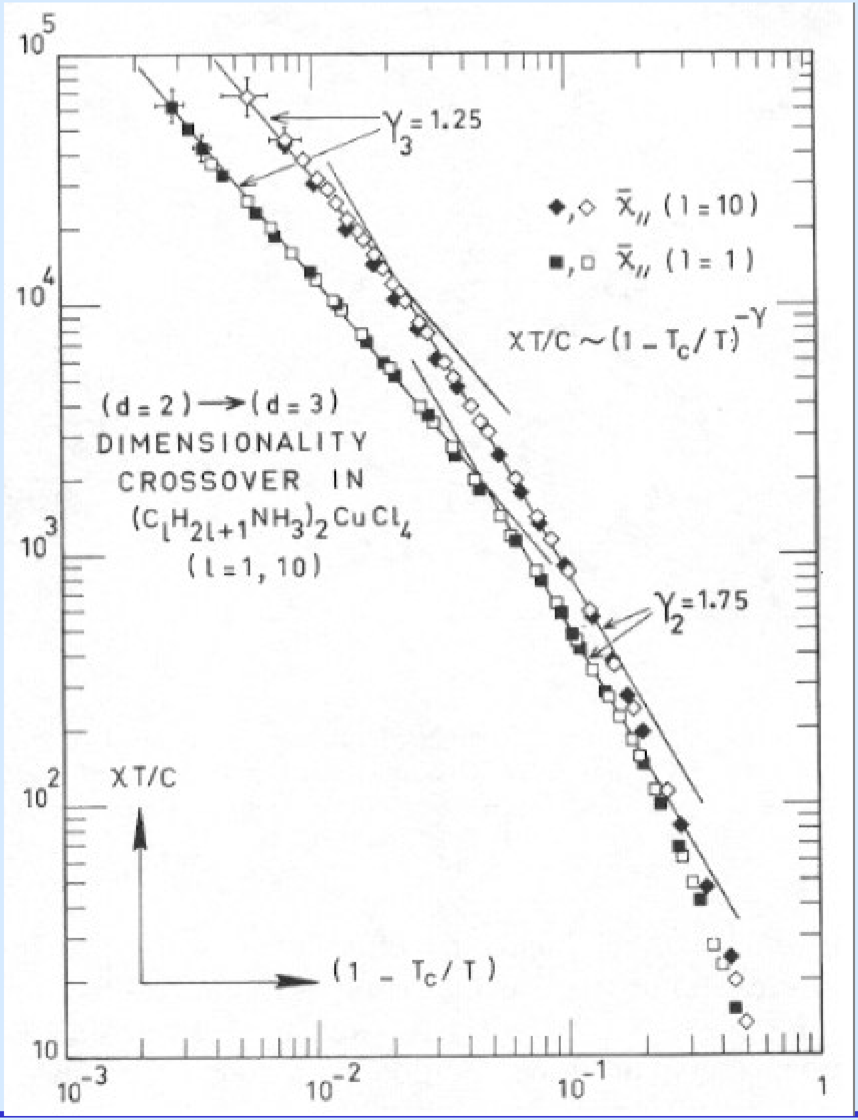
$$\frac{\chi_1}{\chi_2} = \left(\frac{\xi_1}{\xi_2}\right)^{\gamma/\nu}$$



Earlier works

- Co/Cu/Ni/Cu(001)
  *U. Bovensiepen et al., PRL **81**, 2368 (1998)*
- Cr, Nb / $(Tb_{0.27}Dy_{0.73})_{0.32}Fe_{0.68}$
  3D - Heisenberg: γ = 1.38 / 2D - Ising: γ = 1.75
  *Ch. V. Mohan et al., J. Magn. Magn Mater. **182** (1998), 287-296*

Dimensional crossover

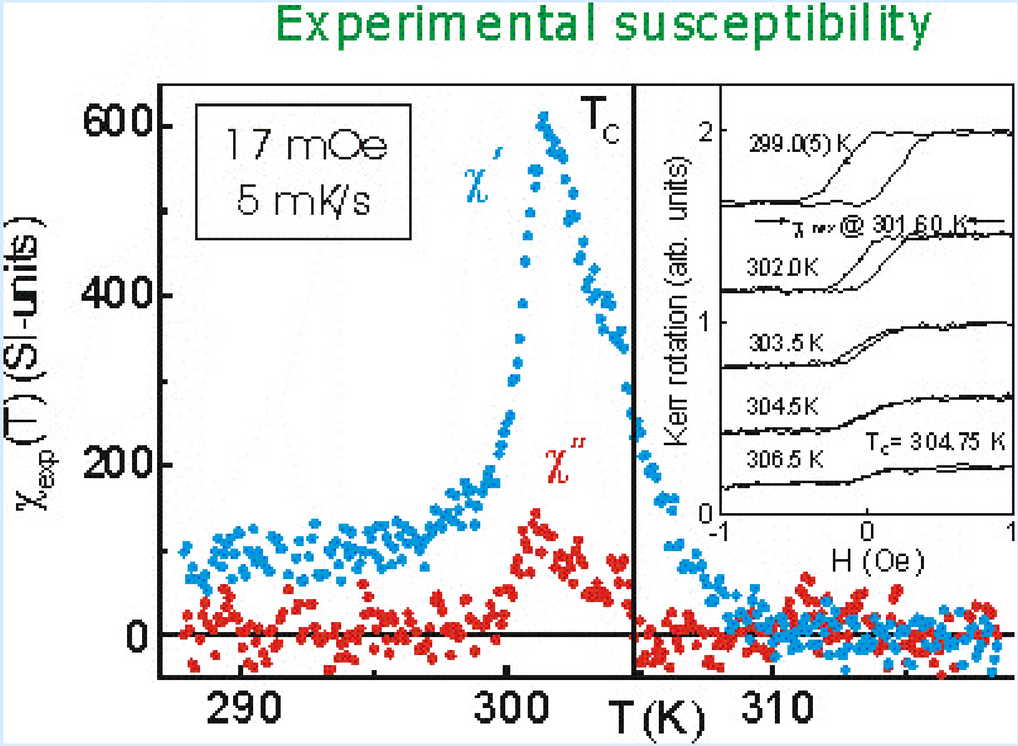


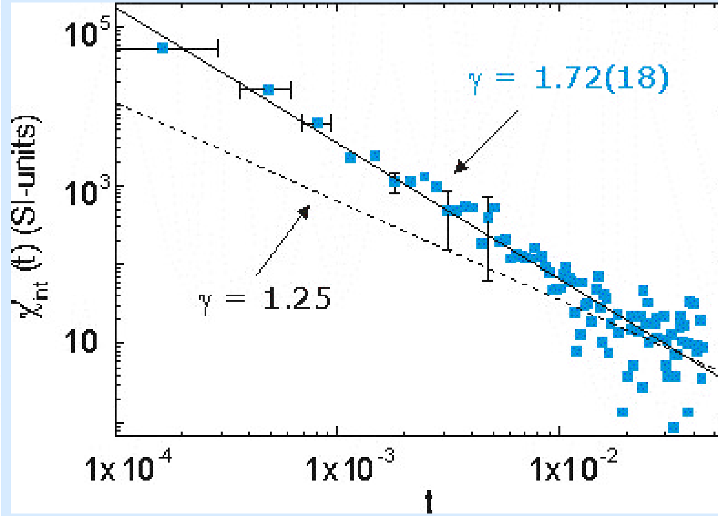
L.J. de Jongh and H.E. Stanley, Phys. Rev. Lett. 36, 817 (1976)

L.J. de Jongh, Physica 82B, 247 (1976)

L.J. de Jongh and A.R. Miedema, Adv. Phys. 23, 1 (1974)

$(Fe_2 / V_5)_{50}$ (001): critical behavior at T_C





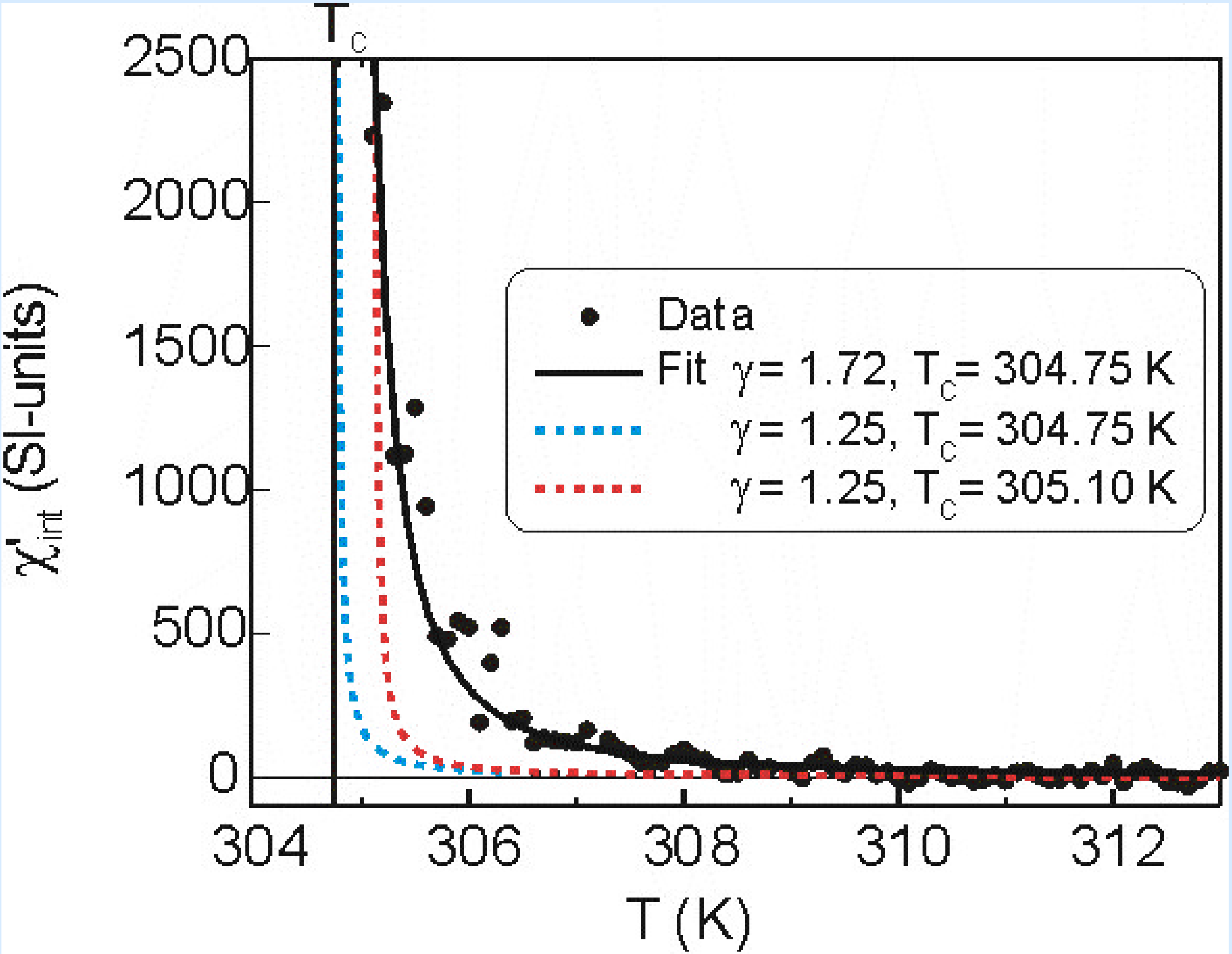
$$\chi_{exp} = \left(\frac{1}{\chi_{int}} + N_{\parallel} \right)^{-1}$$

T_c=304.75(5) K , $t = \frac{T - T_c}{T_c}$

N≈ thickness / diameter ≈10^{-3}

$$\chi_{int}(t) = \chi_0^{+} \cdot t^{-\gamma}$$

Forced manipulation of T_C and γ

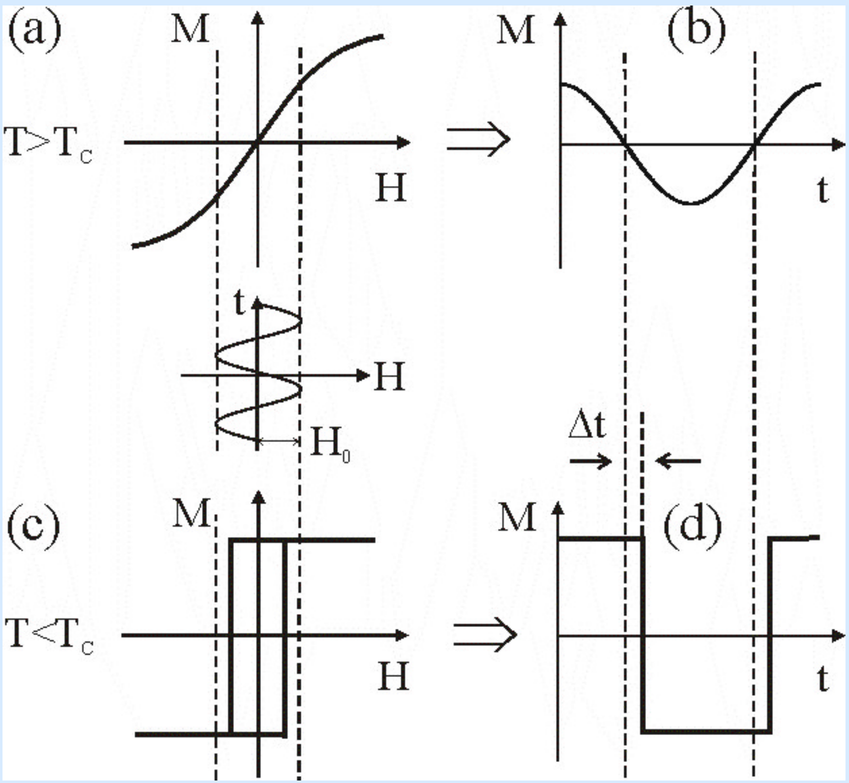


50 K < T < 650 K
ΔT = 3-5 mK/s
$\Delta T/T_C$ ~ 10^{-4}

PRB **65**, 220404 (2002)

3b Higher harmonics of the ac susceptibility in ultrathin film ferromagnets

C. Rüdt et al., Phys. Rev. B **69**, 014419 (2003) and ICM 2003



$$\chi_n(T) = \chi'_n(T) + i\chi''_n(T)$$

$$M_n(T) = 1/\tau_0 \int_0^{\tau_0} dt\, M(T,H)\, \exp(i\, n\, \omega_0\, t)$$

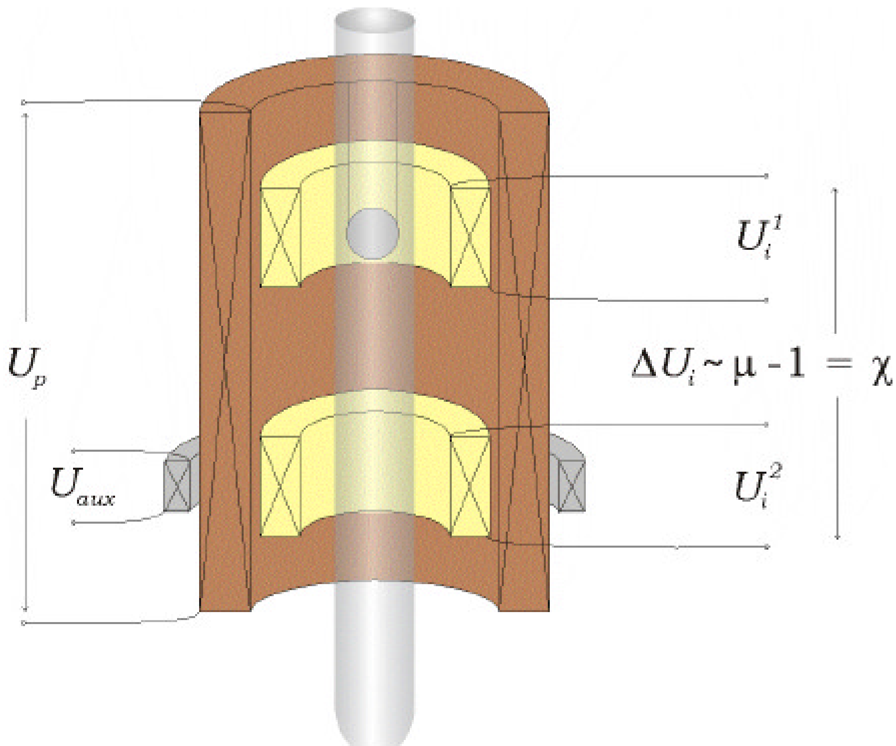
Sketch of the field-, temperature-, and time-dependent magnetization M(H,T,t) subject to an oscillating magnetic field H(t). (a) and (b) represent the paramagnetic case for T>T_C, whereas (c) and (d) show the ferromagnetic response for T<T_C. The phase-shift Δt between the oscillating magnetic field H(t) and the response function M(T,t) due to hysteretic effects is indicated (d). τ_0 is the oscillation period.

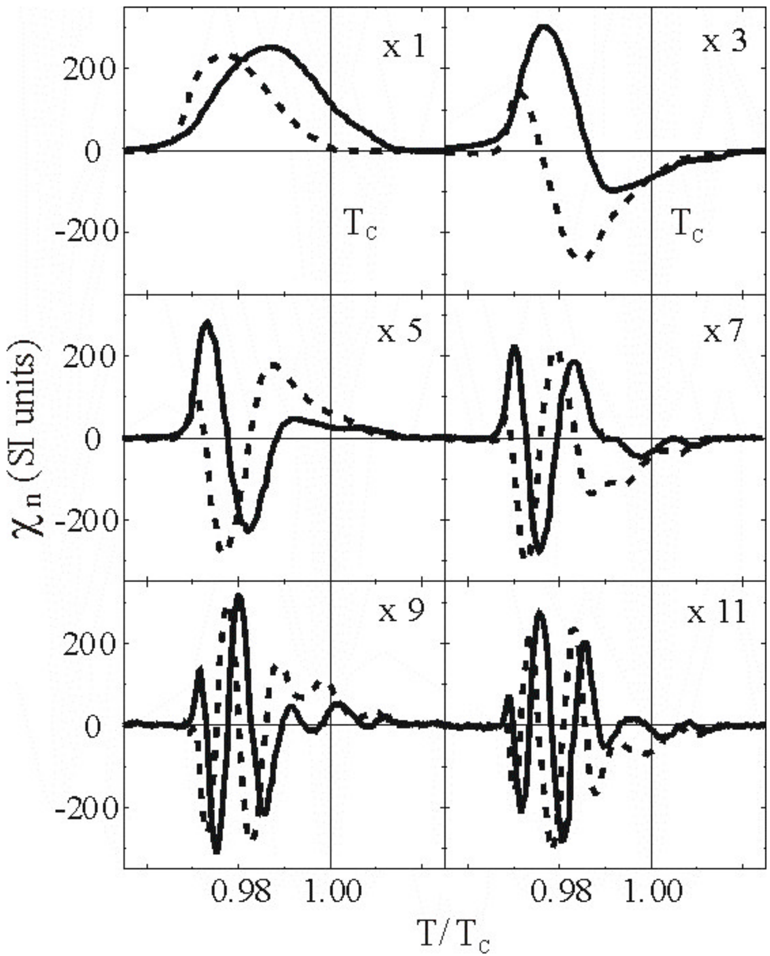
Measurement of higher harmonics

$$\chi_{def} = \frac{\partial M}{\partial H}\Big|_{H=0}$$

$$\chi_{exp} = \frac{\Delta M}{\Delta H}$$

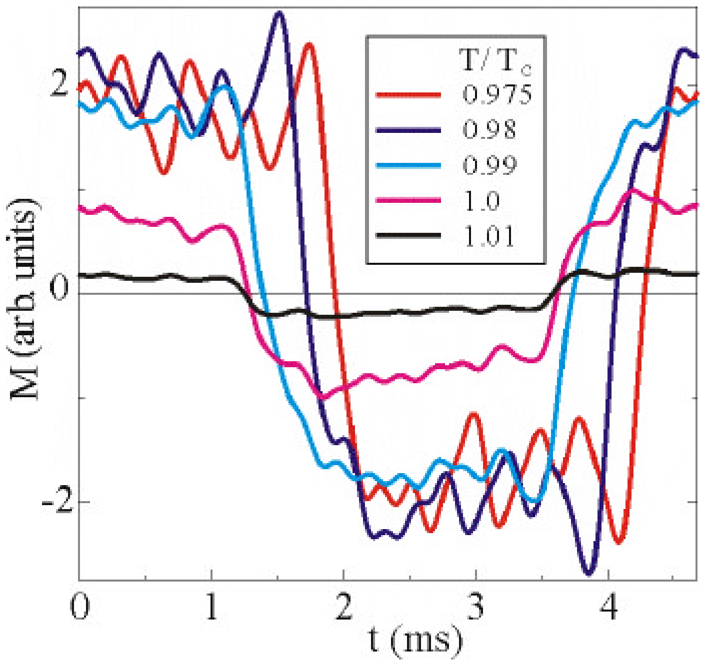
- $\chi(T,H,\omega)$
- quasistatic 213 Hz
- 10 mOe < H_0 < 1.6 Oe



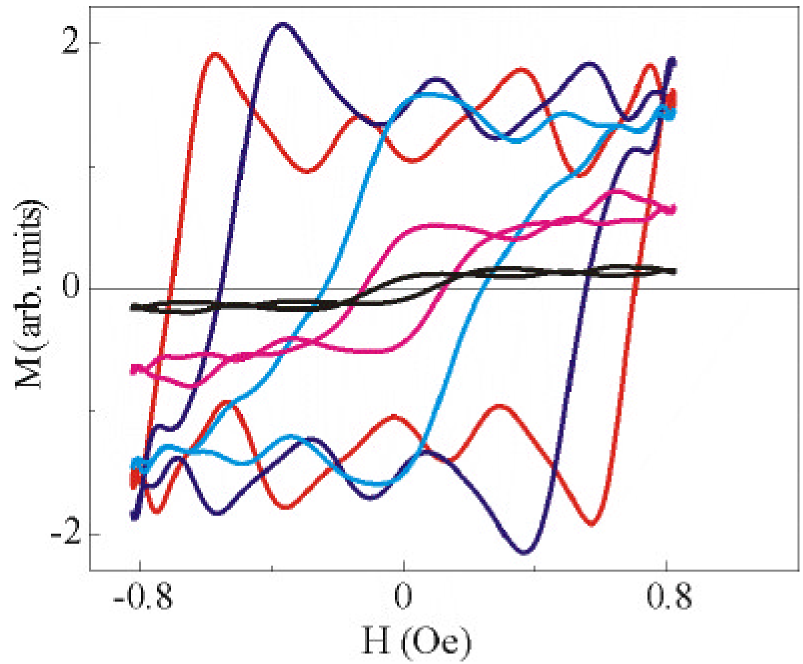


Hysteresis close to T_C

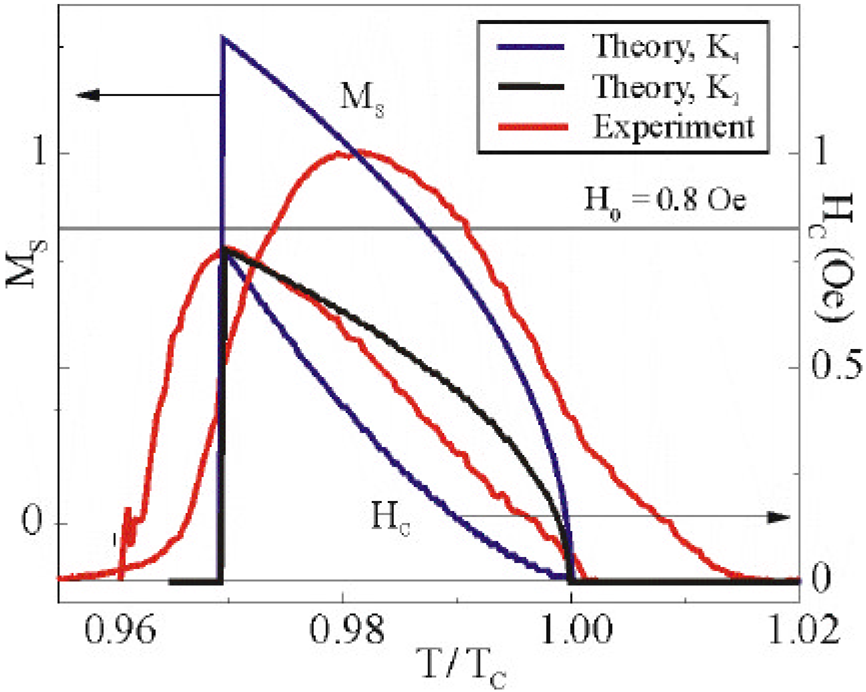
$$M(T,t) = H_0 \sum_{-\infty}^{\infty} \chi_n(T,\omega_0)\, \exp(-in\omega_0 t)$$



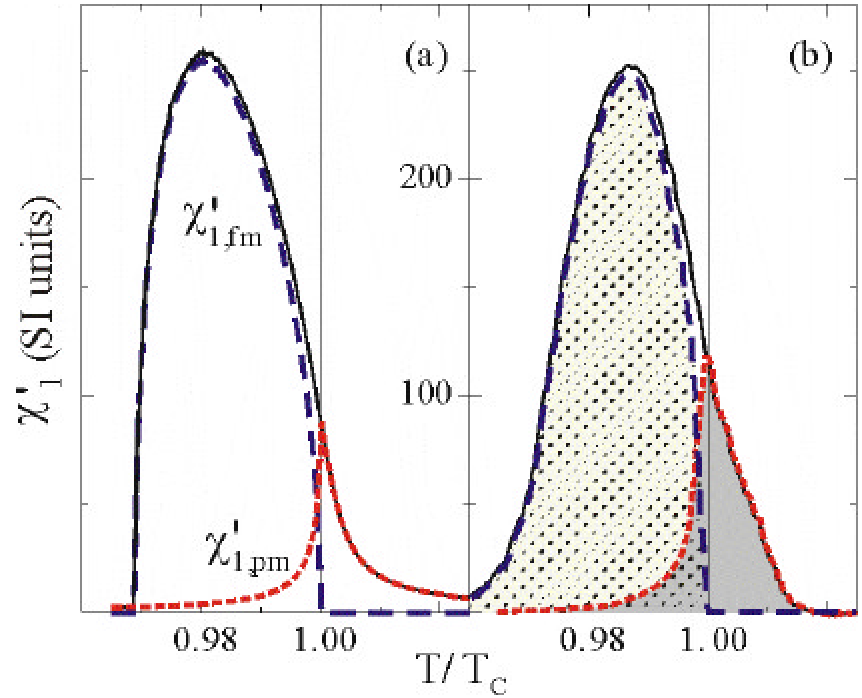
Time-dependent magnetizations M(t) calculated via a Fourier analysis of the measured susceptibility coefficients $\chi_n(T)$, for reduced temperatures $0.975<T/T_C<1.01$. Fourier coefficients up to order n=11 have been used.



Hysteresis loops M(H) for different reduced temperatures T/T_C.



Comparison of theoretically and experimentally determined saturation magnetization $M_S(T)$, normalized to unity (left axis), and the coercive field $H_C(T)$ in units of Oe (right axis) as a function of the reduced temperature T/T_C. $H_C(T)$ has been calculated for both a uniaxial (K_2) and a quartic (K_4) in-plane anisotropy.



Separation of the first harmonic coefficient $\chi'_1(T)=\chi'_{1,fm}(T)+\chi'_{1,pm}(T)$ into a ferromagnetic (blue) and a paramagnetic part (red). (a) theory and (b) experiment. In (b) the para- and ferromagnetic contributions are only drawn schematically (hatched areas).

3c Oscillatory Curie temperatures

Oscillatory Curie Temperature in Ultrathin Ferromagnets: Experimental Evidence

C. Rüdt*, A. Scherz[!] and K. Baberschke

Motivation

Experiment - ac susceptibility of Cu/Co/Cu(100)

Proof of an oscillatory T_c

Summary

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.

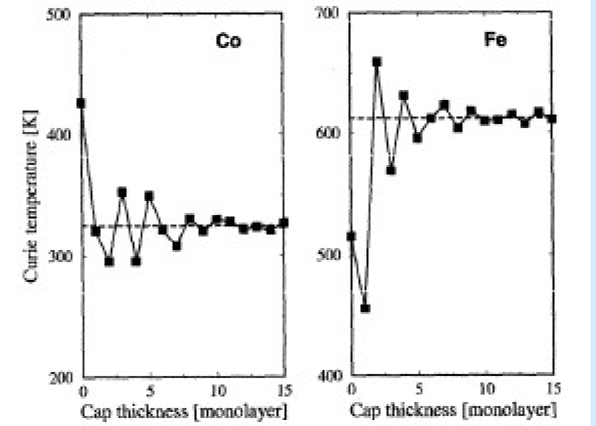


FIG. 3. T_c^{RPA} of Co (left) and Fe (right) overlayers on a fcc-Cu(001) substrate covered by a cap layer of varying thickness. The dashed lines represent the embedded layer limit (infinite cap thickness) while the limit of zero cap thickness corresponds to the uncovered overlayer.

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

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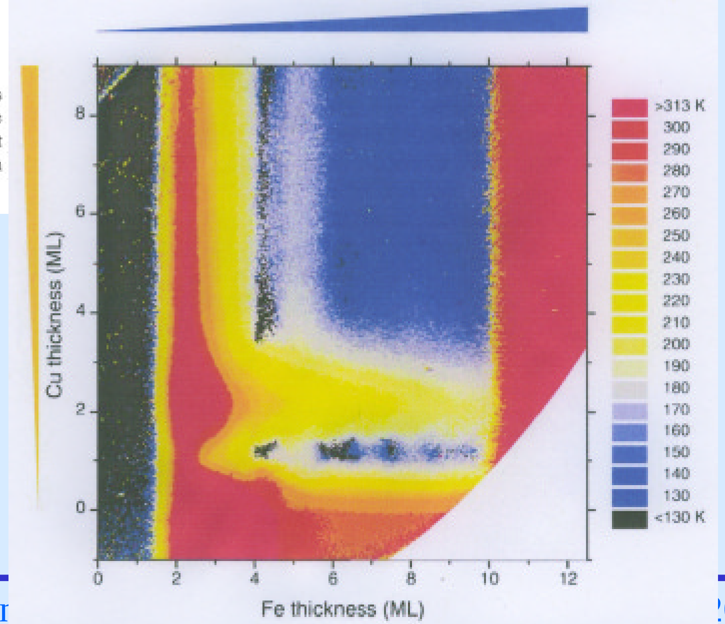
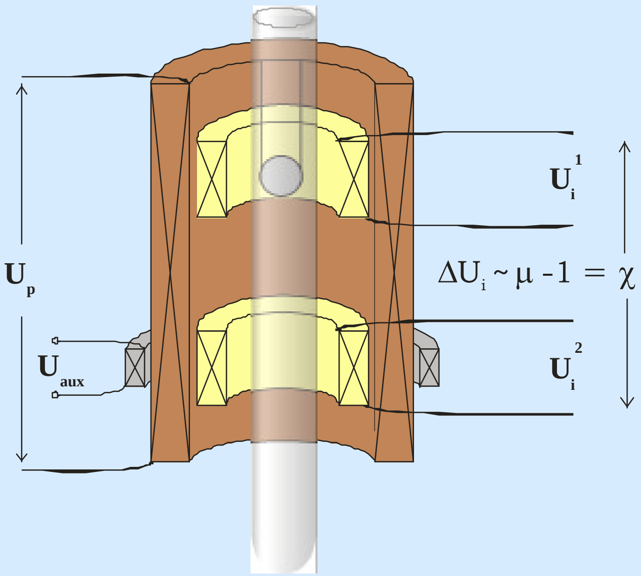
(Received 1 June 1999)

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.



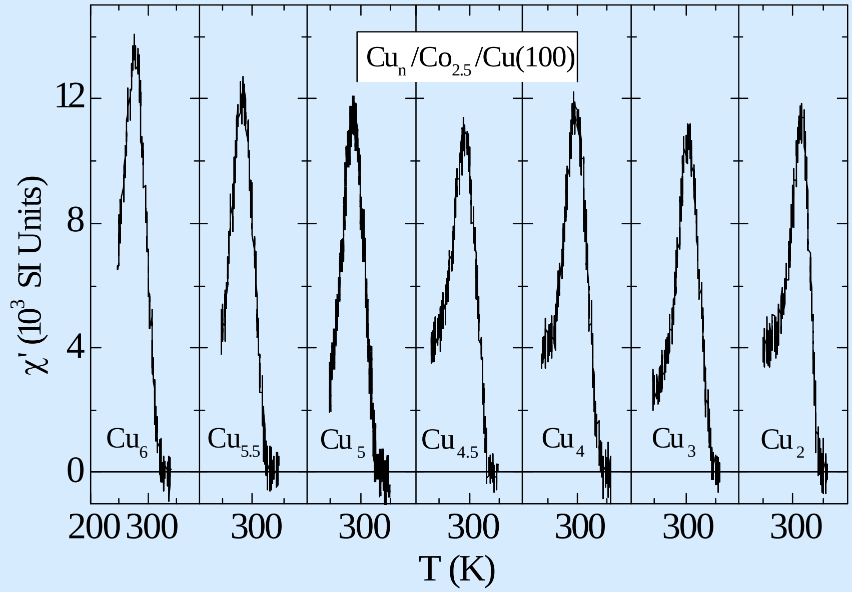
ac Susceptibility of $Cu_n/Co/Cu(100)$

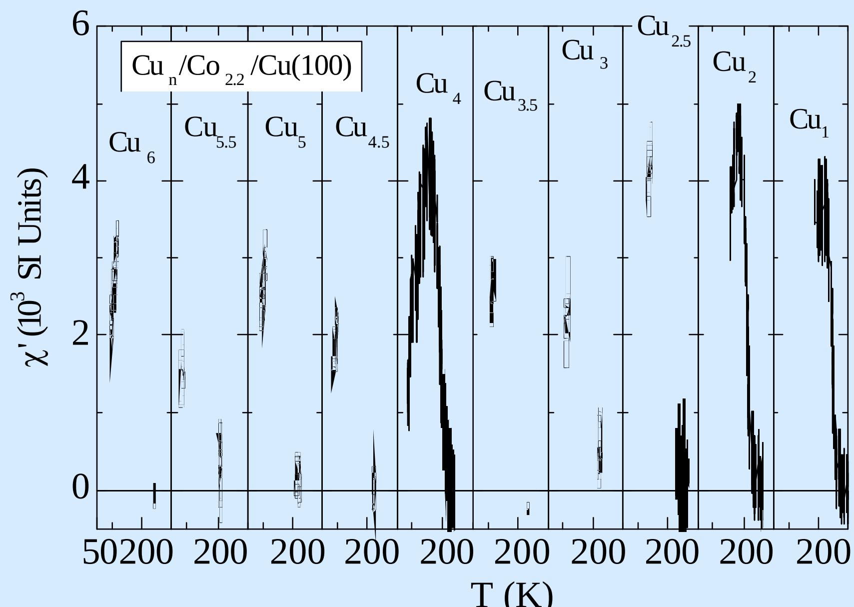


$$c_{def} = \frac{\partial M}{\partial \hat{H}}\Big|_{H=0}$$

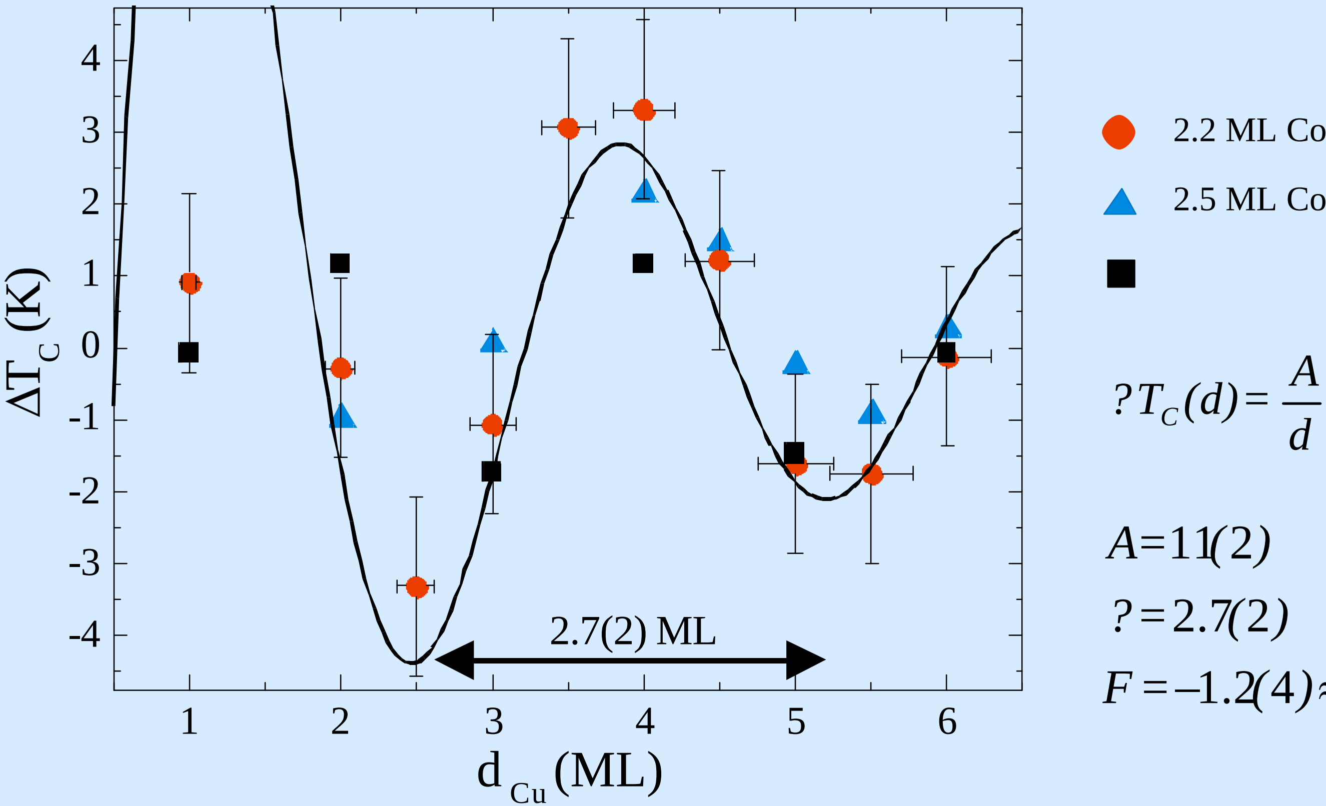
$p = 4\times10^{-11}$ mbar
17 mOe $< H_{ac} < 1.6$ Oe
$\omega_0 = 213$ Hz
compensation < 10 mOe

50 K < T < 650 K
$\Delta T = 3\text{-}5$ mK/s
$\Delta T/T_C \sim 10^{-4}$





Oscillatory T_C: Experimental Evidence



$$?T_C(d) = \frac{A}{d}\sin\left(\frac{2p}{?}d + F\right)$$

$A = 11(2)$

$? = 2.7(2)$

$F = -1.2(4) \approx -p/2$

C. Rüdt, A. Scherz and K. Baberschke, *J. Magn. Magn. Mater.* **285**, 95 (2004)

Origin of T_C Change: Three Different Mechanisms

I. Change in the magnetic moment of the top layer in Co/Cu(100)® **Large drop of T_C**

μ_{Co} 32 % enhanced at the vacuum interface
μ_{Co} 17 % reduced at the Cu interface
(A. Ney et al., *Europhys. Lett.* **54**, 820 (2001), UHV-SQUID)

T_C μ m² yields:

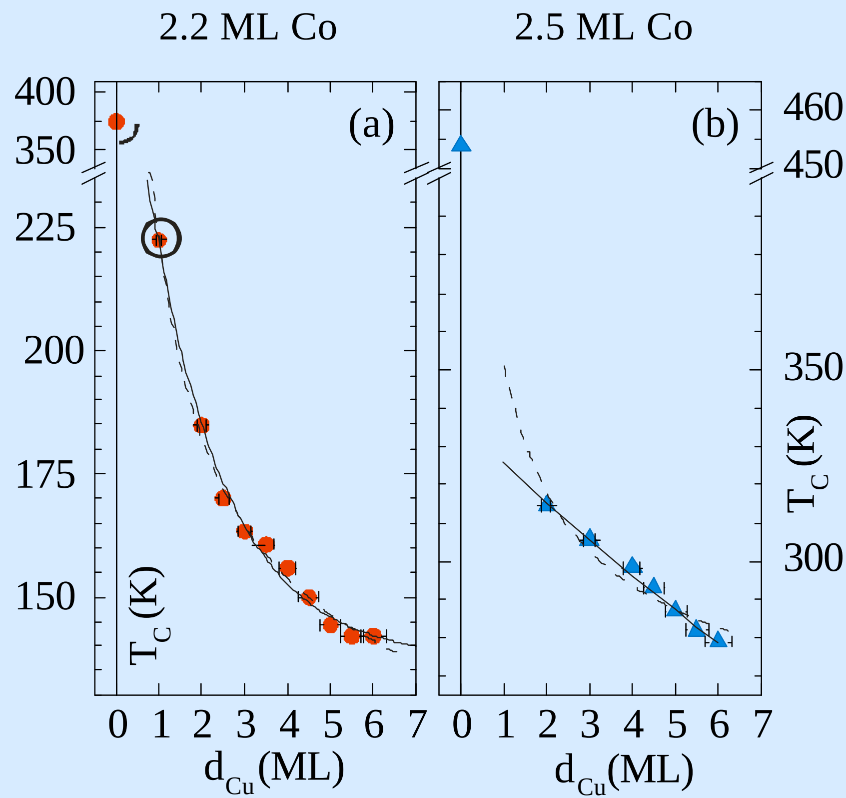
$Co_2/Cu(100)$: T_C=370 K
$Cu_1/Co_2/Cu(100)$: T_C=220 K

II. Modification of electronic band structure at the Cu/Co interface® **Monotonic decrease of T_C**

$Cu_{2\text{-}8}/Co_{20}/Cu(100)$: change of effective mass due to Quantum-Well states
(P. Johnson et al., *Phys. Rev. B* **50**, 8954 (1994), ARUPS)

III. Quantum-Well effects® **Oscillations of T_C**

as theoretically predicted by P. Bruno, MPI Halle
(M. Pajda et al., *Phys. Rev. Lett.* **85**, 5425 (2000))



Summary

Plausibility of oscillatory amplitude of T_C

Ferromagnetic Trilayers

(XMCD) $?T_C \approx 100\,K \Leftrightarrow J_{inter} = 50\,\mu eV\,/\,atom$ (FMR)

(FMR) $J_{cap} \approx 2\,\mu eV\,/\,atom \Leftrightarrow ?T_C^{cap} \approx 4K$ (*ac* susceptibility)

Capped ferromagnetic monolayer Cu/Co/Cu(100)

Dramatic change in T_C due to three different mechanisms

- Change of the magnetic moment at the Cu/Co interface
- Modifications of the electronic bandstructure at the Cu capping layer
- Oscillation of T_C due to the formation of QW-states