PHASE TRANSITIONS IN FERROMAGNETIC MONOLAYERS?

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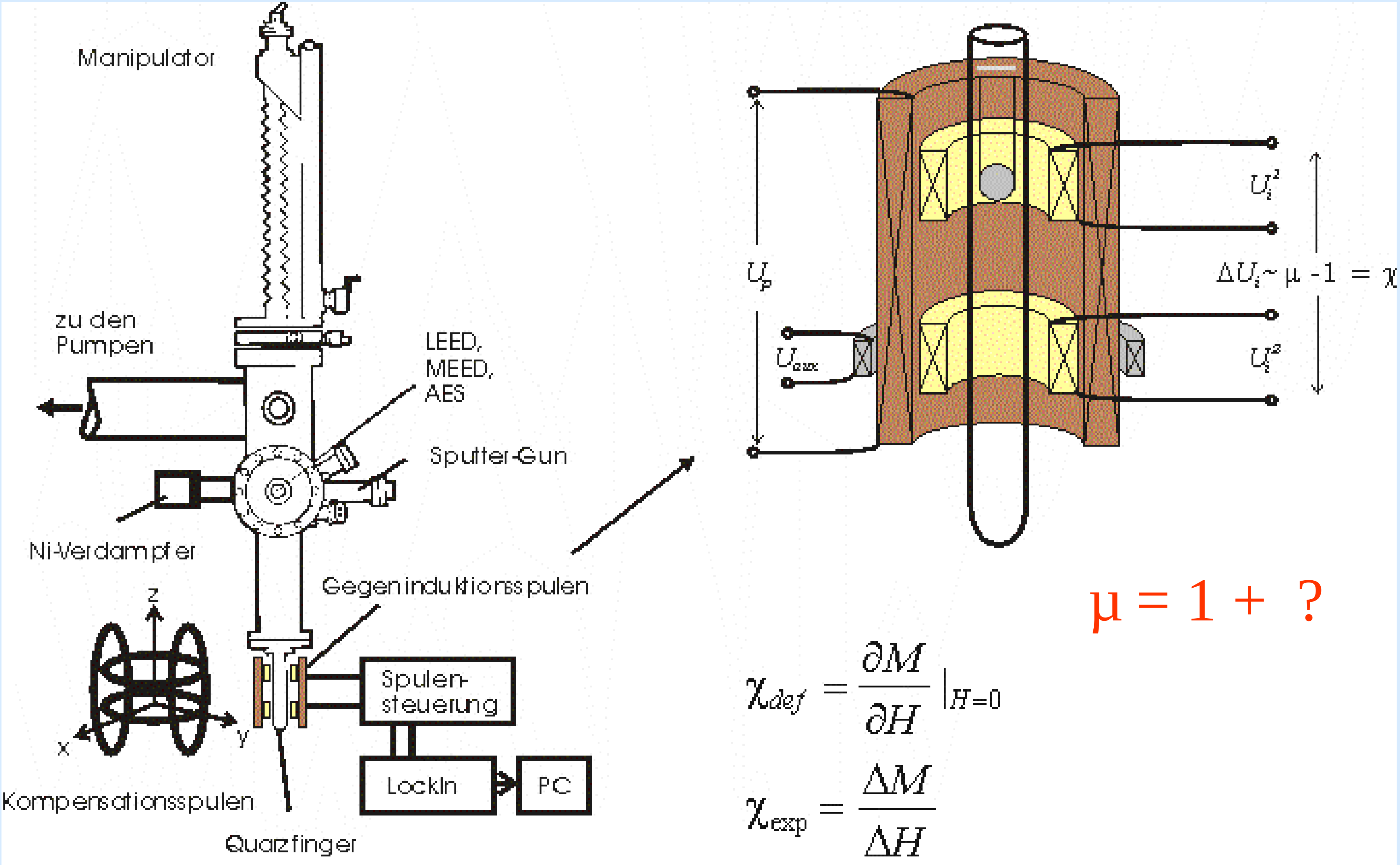
Lecture 2

4. Curie - Weiss susceptibility, χ_{ac} measured by means of mutual inductance, MOKE, and XMCD.
5. How do we determine T_C and the critical exponents?
6. Non linear χ_{ac}, the interpretation of higher harmonics in χ_{ac}.

Determination of critical observables
as BH wanted

4. Curie - Weiss susceptibility C_{ac} measured by means of mutual inductance, MOKE, and XMCD.

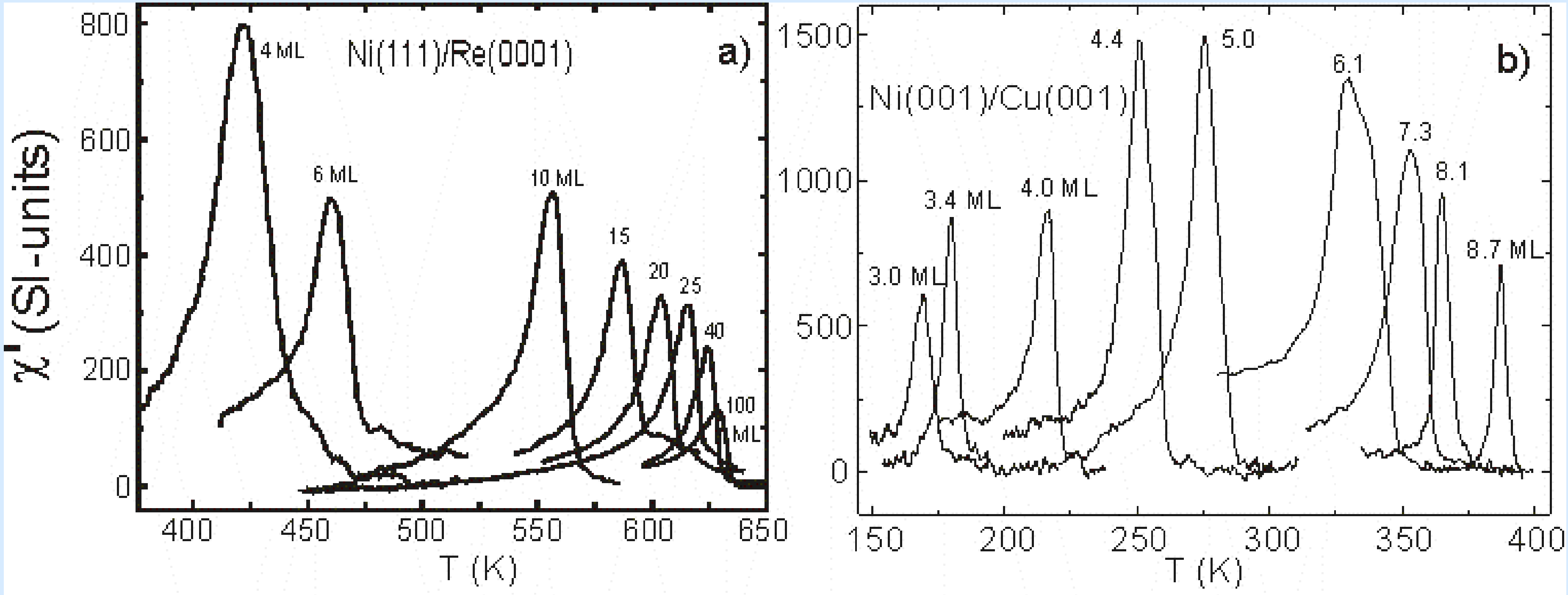


$\mu = 1 + ?$

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

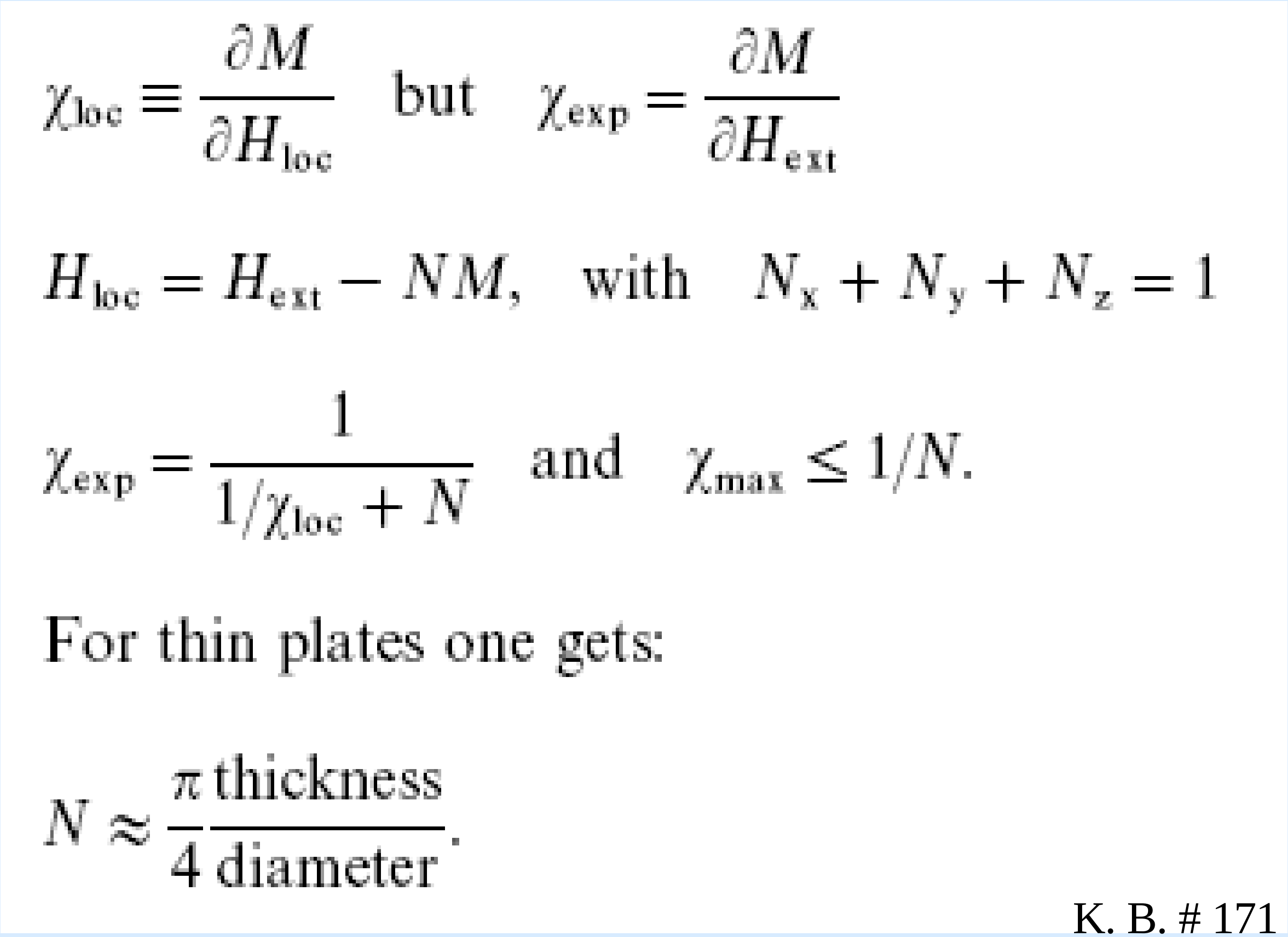
$$\chi_{exp} = \frac{\Delta M}{\Delta H}$$

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)



$$\chi_{\rm loc} \equiv \frac{\partial M}{\partial H_{\rm loc}} \quad \text{but} \quad \chi_{\rm exp} = \frac{\partial M}{\partial H_{\rm ext}}$$

$$H_{\rm loc} = H_{\rm ext} - NM, \quad \text{with} \quad N_x + N_y + N_z = 1$$

$$\chi_{\rm exp} = \frac{1}{1/\chi_{\rm loc} + N} \quad \text{and} \quad \chi_{\rm max} \leq 1/N.$$

For thin plates one gets:

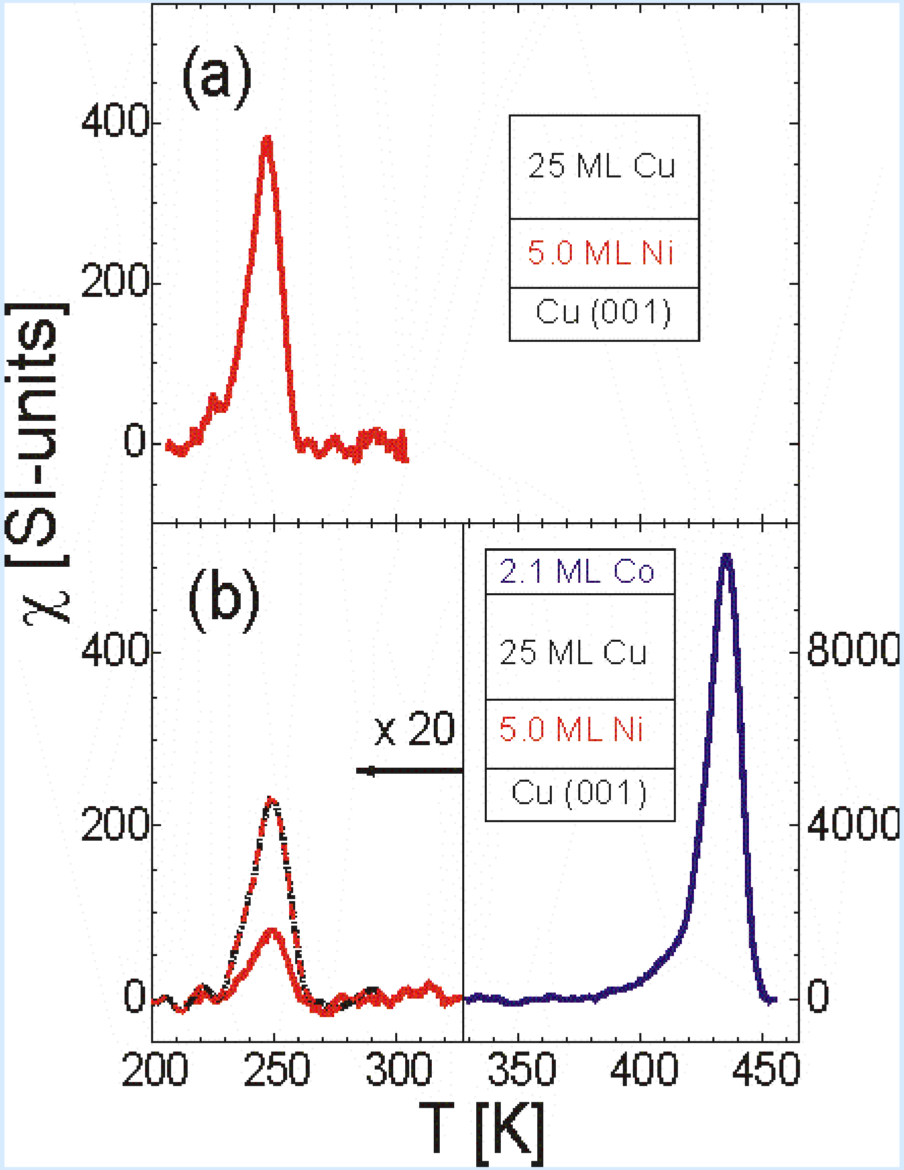
$$N \approx \frac{\pi}{4}\frac{\text{thickness}}{\text{diameter}}.$$

K. B. # 171

In many papers χ is given in arb. units, why ? Use SI-units!

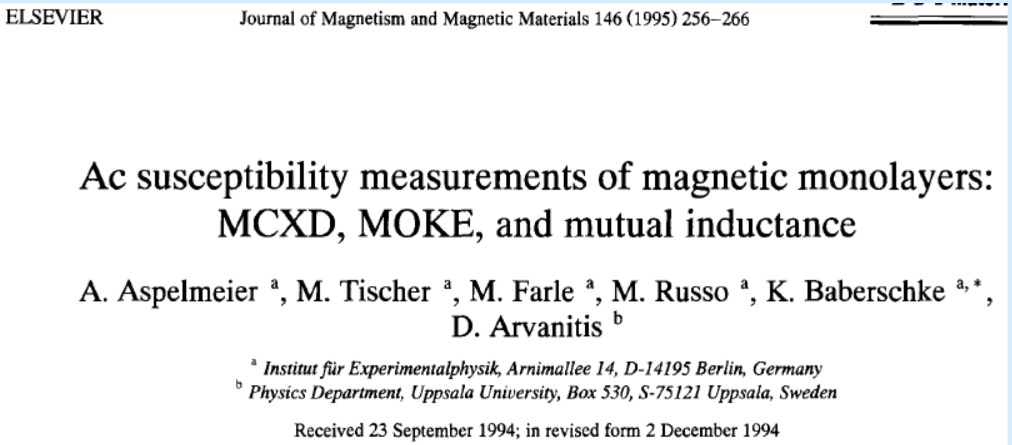
N gives nice information. $N_{\text{in-plane}}$ may be $10^{-3} – 10^{-5}$, but > 0

2 peaks in the ac-susceptibility



see lecture 1

ac MOKE and ac XMCD



ELSEVIER Journal of Magnetism and Magnetic Materials 146 (1995) 256–266

Ac susceptibility measurements of magnetic monolayers: MCXD, MOKE, and mutual inductance

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JMMM, **146**, 256 (1995)

2.1. Ac MCXD

The typical setup for the ac MCXD experiments developed by our group is shown in Fig. 1. Circularly polarized light from the SX700 beamlines at

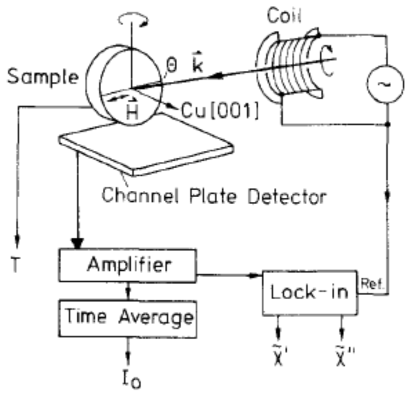


Fig. 1. Schematic view of the ac MCXD setup. Circularly polarized light is incident at $\theta \approx 7°$. The four signals $\tilde\chi'$, $\tilde\chi''$, I_0, and T are recorded simultaneously.

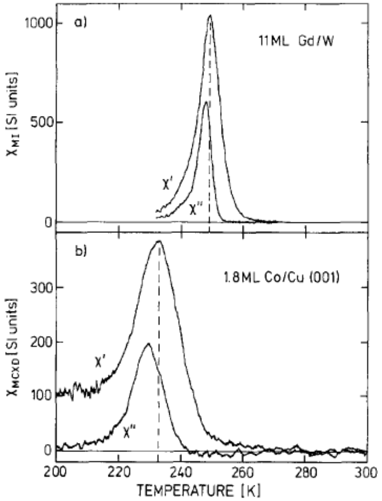


Fig. 2. Calibrated χ' and χ'' as a function of temperature in the vicinity of T_C. A large constant background has been subtracted from the χ'_{MCXD} of the Co film and also from χ'_{MI} of the Gd film. χ''_{MI} was corrected for the temperature-dependent hyperbolic background due to eddy currents of the substrate.

example, the angular dependence and the saturation effect is discussed in Refs. [28,29].

The experimental $\tilde\chi$ is related to the real χ in SI units [26] via

$$(\chi', \chi'') = (\tilde\chi', \tilde\chi'') \cdot \frac{2\sqrt{2}\,B(d)}{I_0 N^{\mathrm{sat}}_{\mathrm{MCXD}}} \cdot \frac{4\pi M_{\mathrm{sat}}}{\hat{H}}, \qquad (1)$$

JMMM, **135**, L1 (1994)

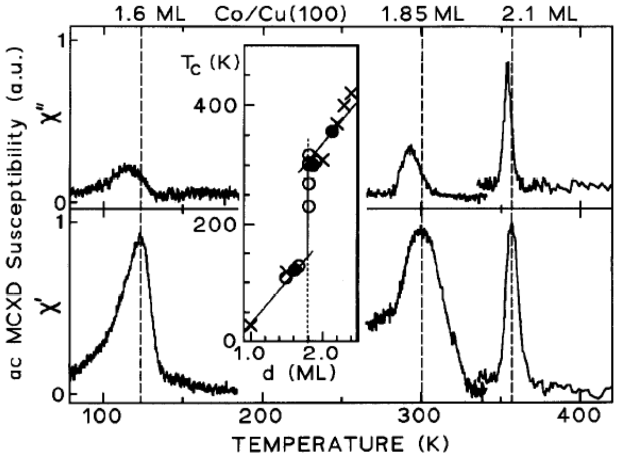


Fig. 3. Same as Fig. 2 for 3 thicknesses. The dashed lines indicate T_c. In the inset $T_c(d)$ is plotted, this work (○, ● shown in Fig. 3) and previous results (×) [12,13]. The full lines are guides to the eye.

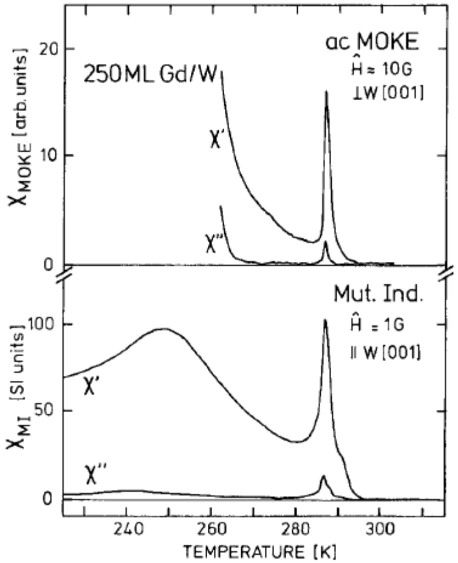
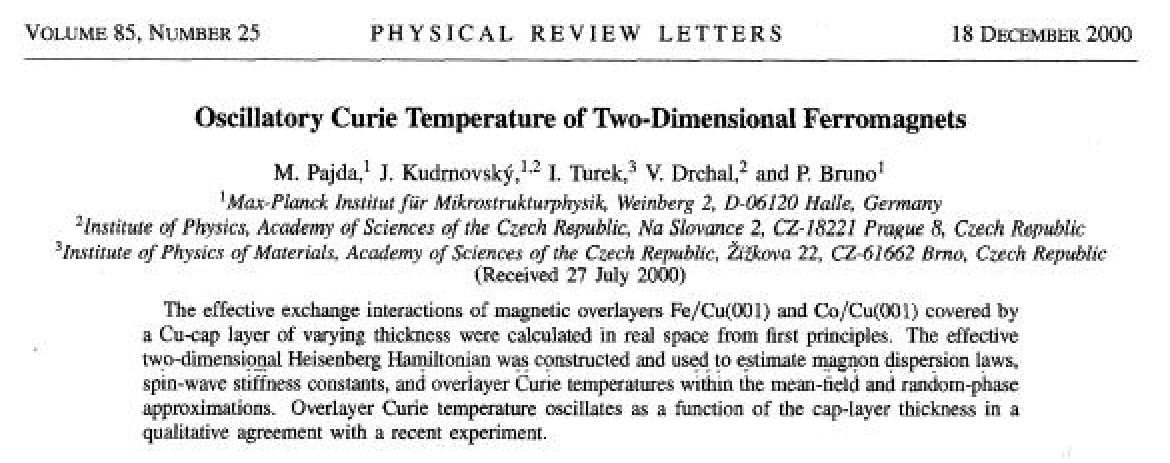


Fig. 5. $\chi(T)$ of 250 ML Gd/W(110) measured by ac MI (lower) and ac MOKE (upper curves). The field was applied in the film plane parallel and perpendicular to a W[001] direction as indicated. The scaling of the ac MOKE signal is arbitrary. However, the origin of the ordinate axis is the true experimental zero. Note the difference in the applied field amplitudes. The Gd film had been annealed to 800 K.

Oscillatory Curie Temperature in Ultrathin Ferromagnets: Experimental Evidence



VOLUME 85, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 2000

Oscillatory Curie Temperature of Two-Dimensional Ferromagnets

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(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.

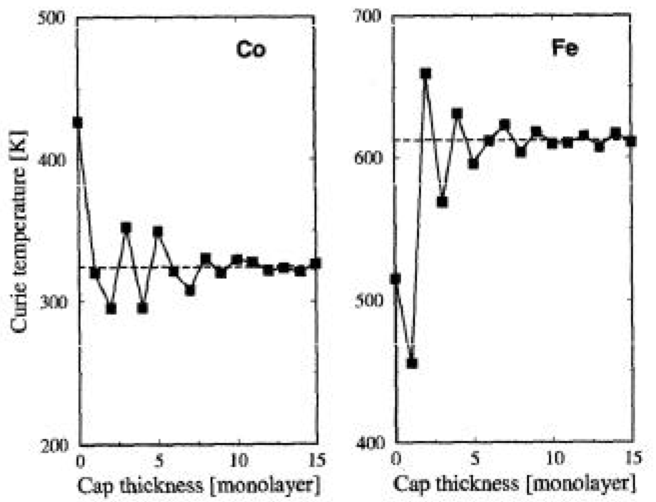
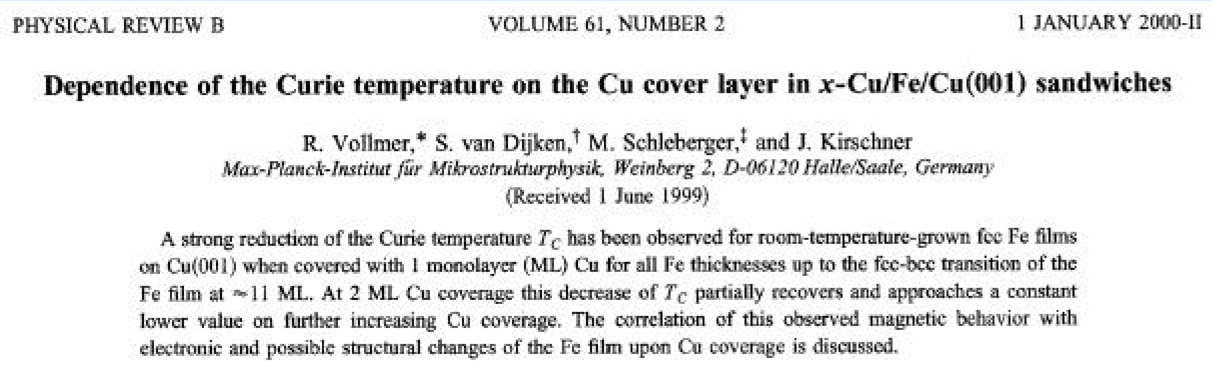


FIG. 3. T_C^{RPA} of Co (left) and Fe (right) overlayers on a fcc-Cu(001) substrate covered by a cap layer of varying thickness. The dashed lines represent the embedded layer limit (infinite cap thickness) while the limit of zero cap thickness corresponds to the uncovered overlayer.



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

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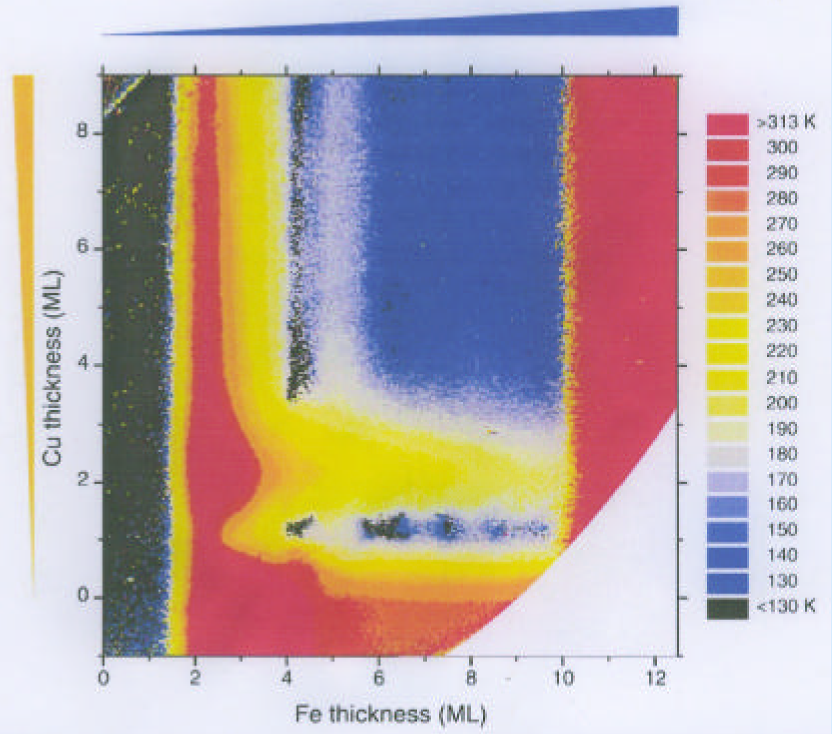
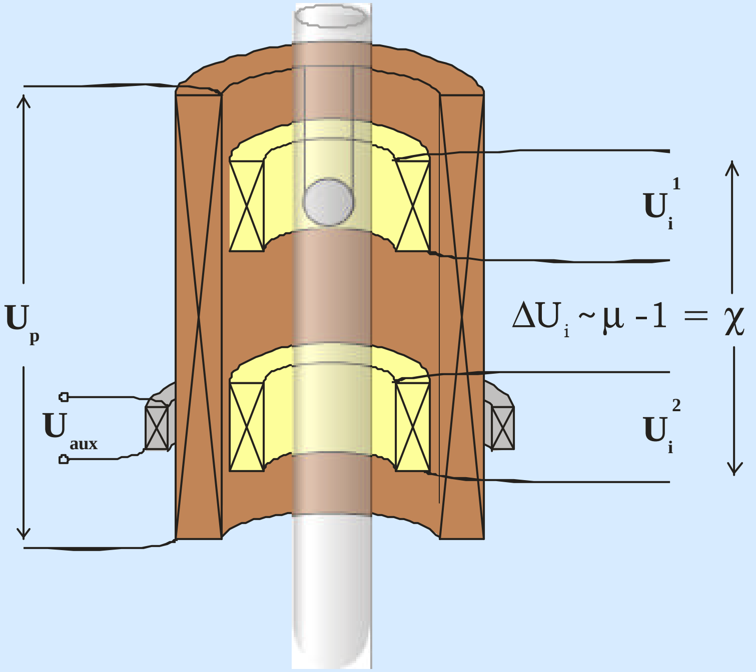
(Received 1 June 1999)

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.



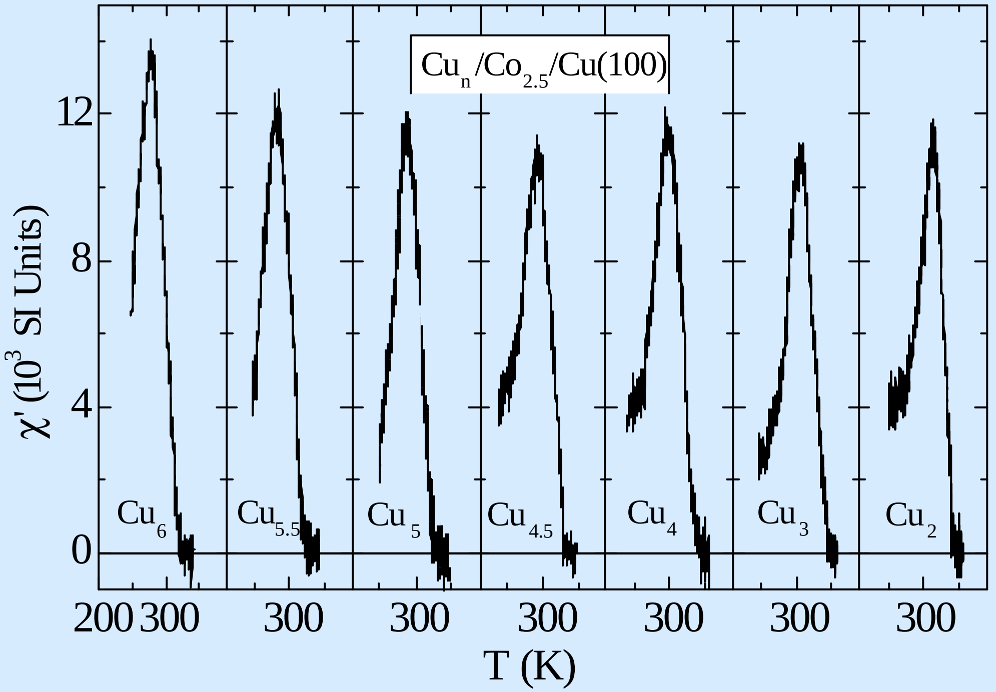
ac Susceptibility of $Cu_n/Co/Cu(100)$

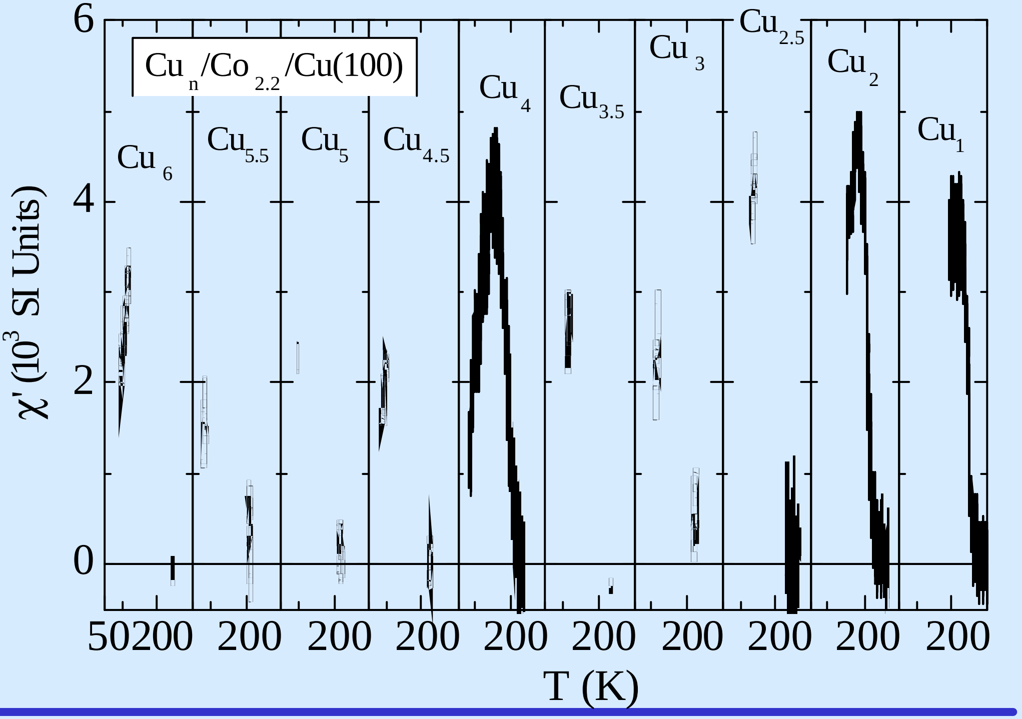


$$c_{def} = \frac{\partial M}{\partial \hat{H}}\Big|_{H=0}$$

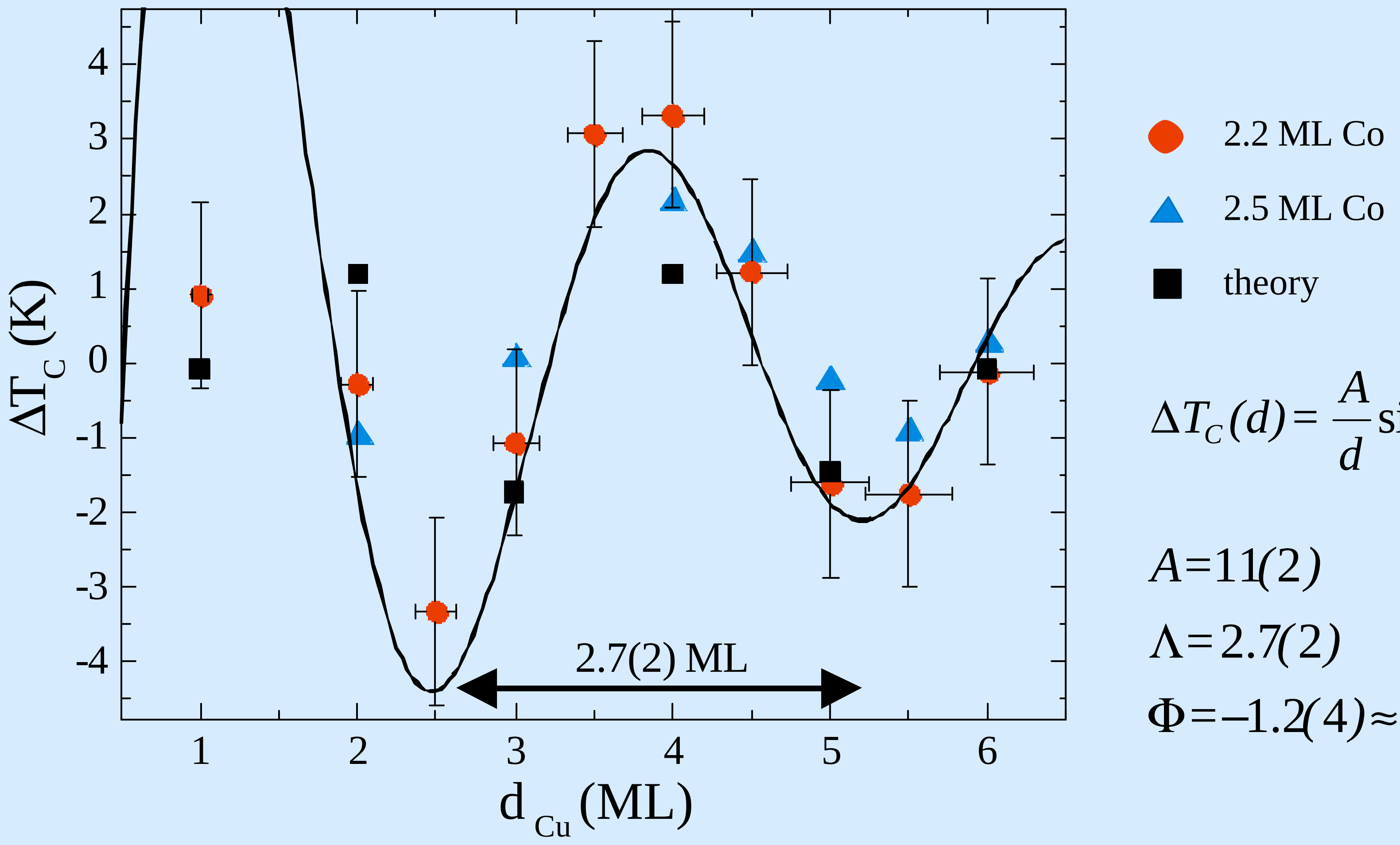
$p = 4\times10^{-11}$ mbar
$17\ \mathrm{mOe} < H_{ac} < 1.6$ Oe
$\omega_0 = 213$ Hz
compensation < 10 mOe

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





Oscillatory T_C: Experimental Evidence



$$\Delta T_C(d) = \frac{A}{d}\sin\left(\frac{2\pi}{\Lambda}d + \Phi\right)$$

$$A = 11(2)$$

$$\Lambda = 2.7(2)$$

$$\Phi = -1.2(4) \approx -\pi/2$$

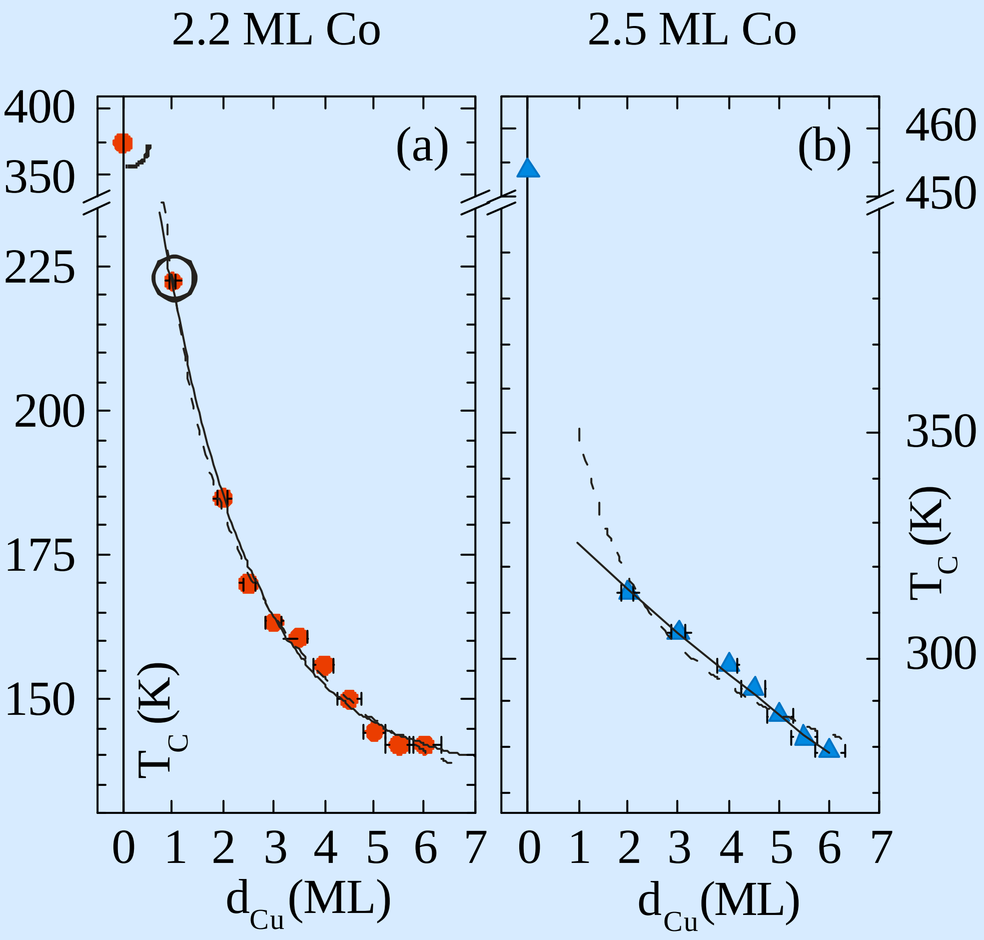
C. Rüdt, A. Scherz and K. B., *J. Magn. Magn. Mater*. **285**, 95 (2004)

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))



Plausibility of oscillatory amplitude of T_C

Ferromagnetic Trilayers

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

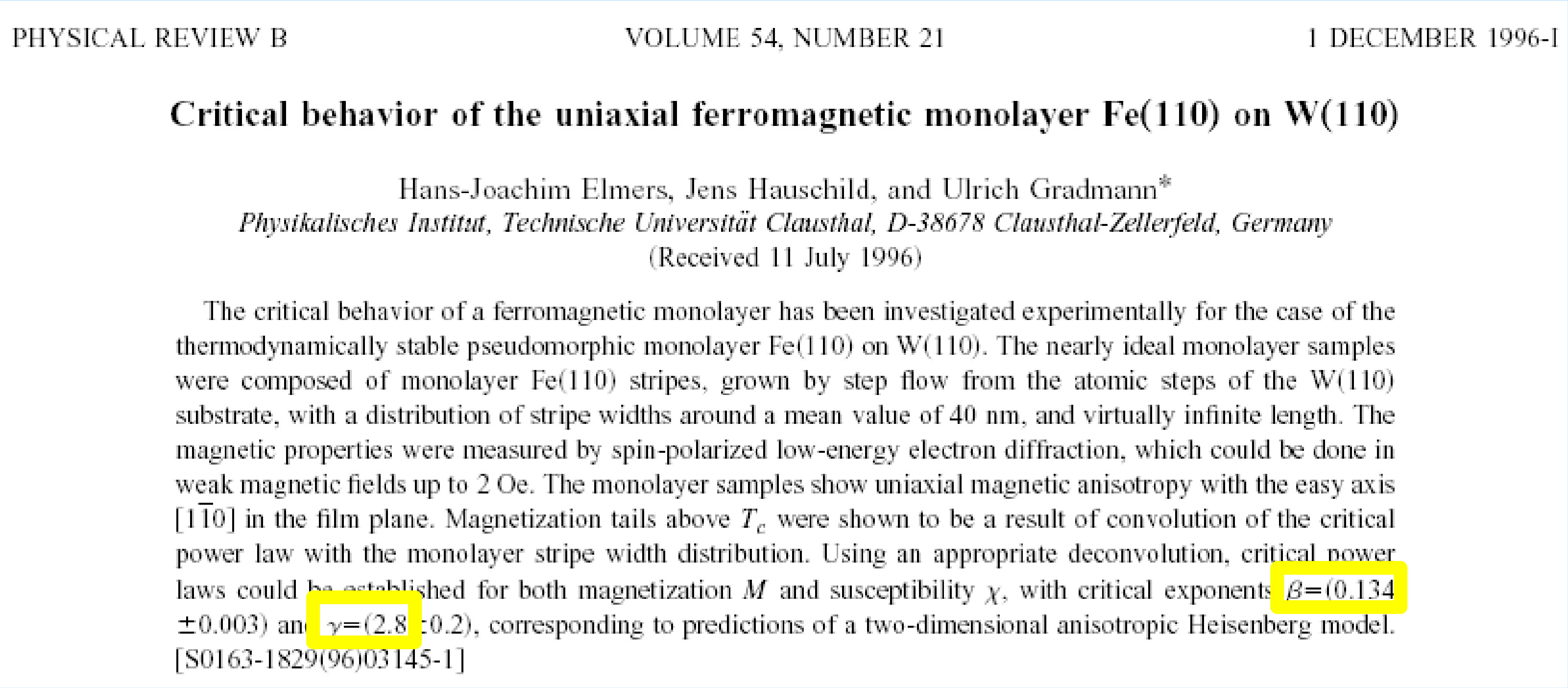
(FMR) $J_{cap} \approx 2\,\mu eV\,/\,atom \Leftrightarrow \Delta T_C^{cap} \approx 4K$ (*ac* susceptibility)

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

5. How do we determine T_C and the critical exponents?

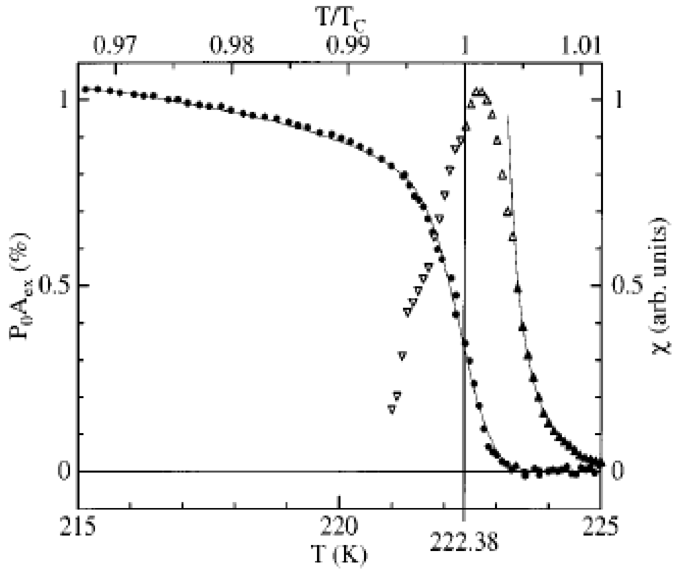


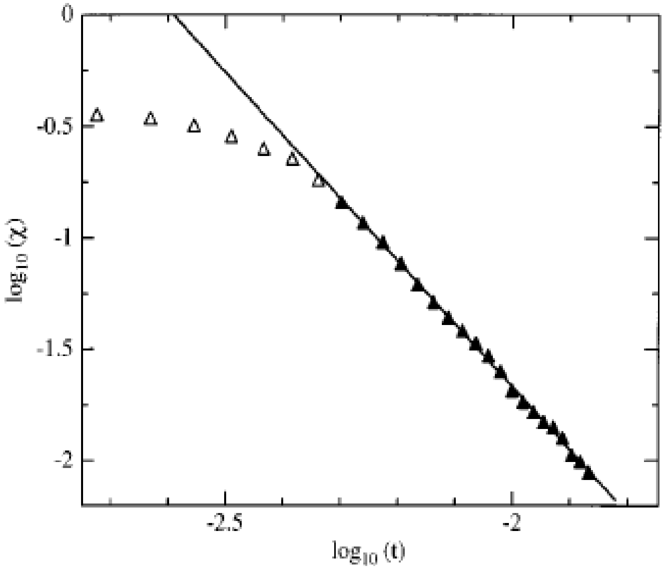
PHYSICAL REVIEW B VOLUME 54, NUMBER 21 1 DECEMBER 1996-I

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

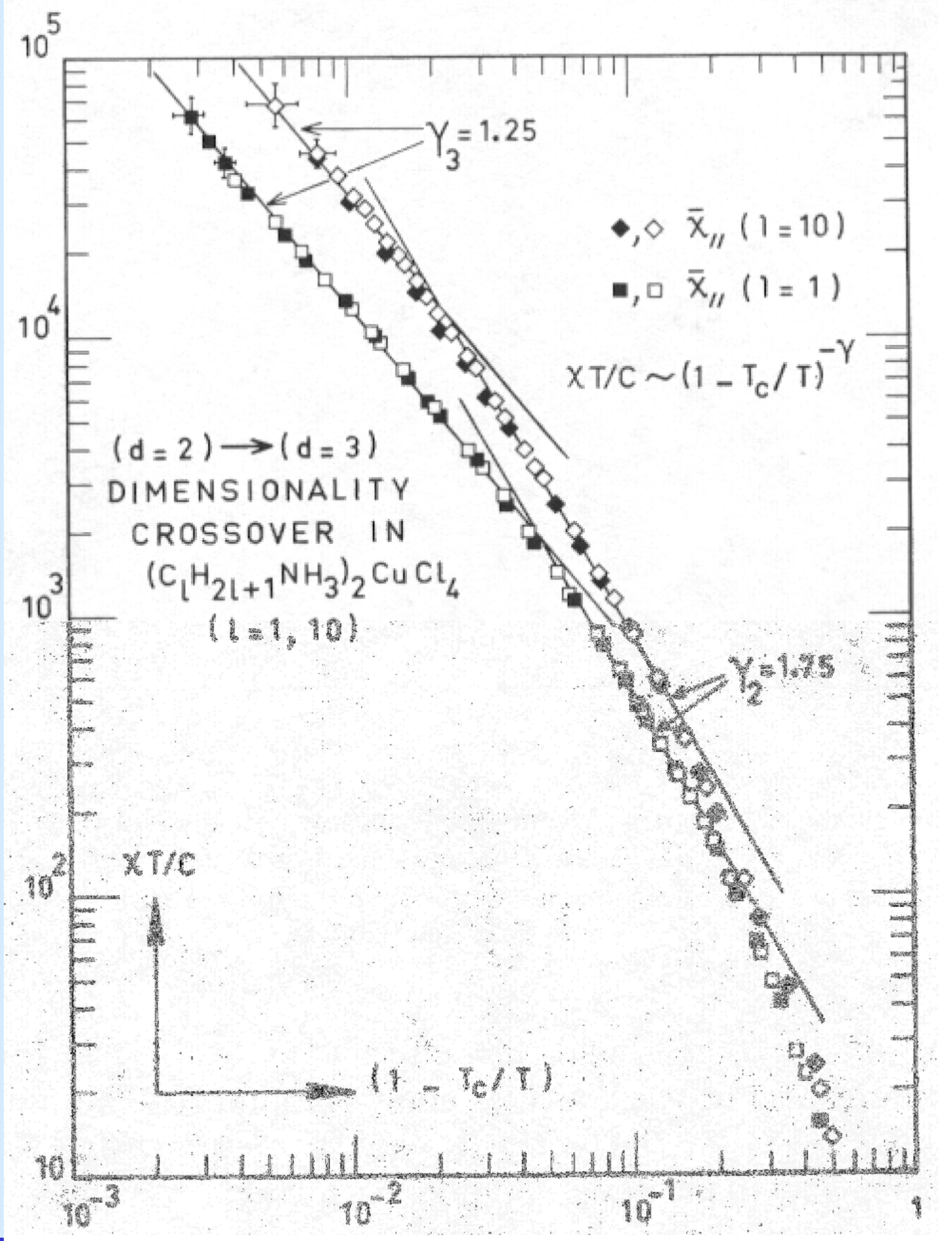
Hans-Joachim Elmers, Jens Hauschild, and Ulrich Gradmann*
Physikalisches Institut, Technische Universität Clausthal, D-38678 Clausthal-Zellerfeld, Germany
(Received 11 July 1996)

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]





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)

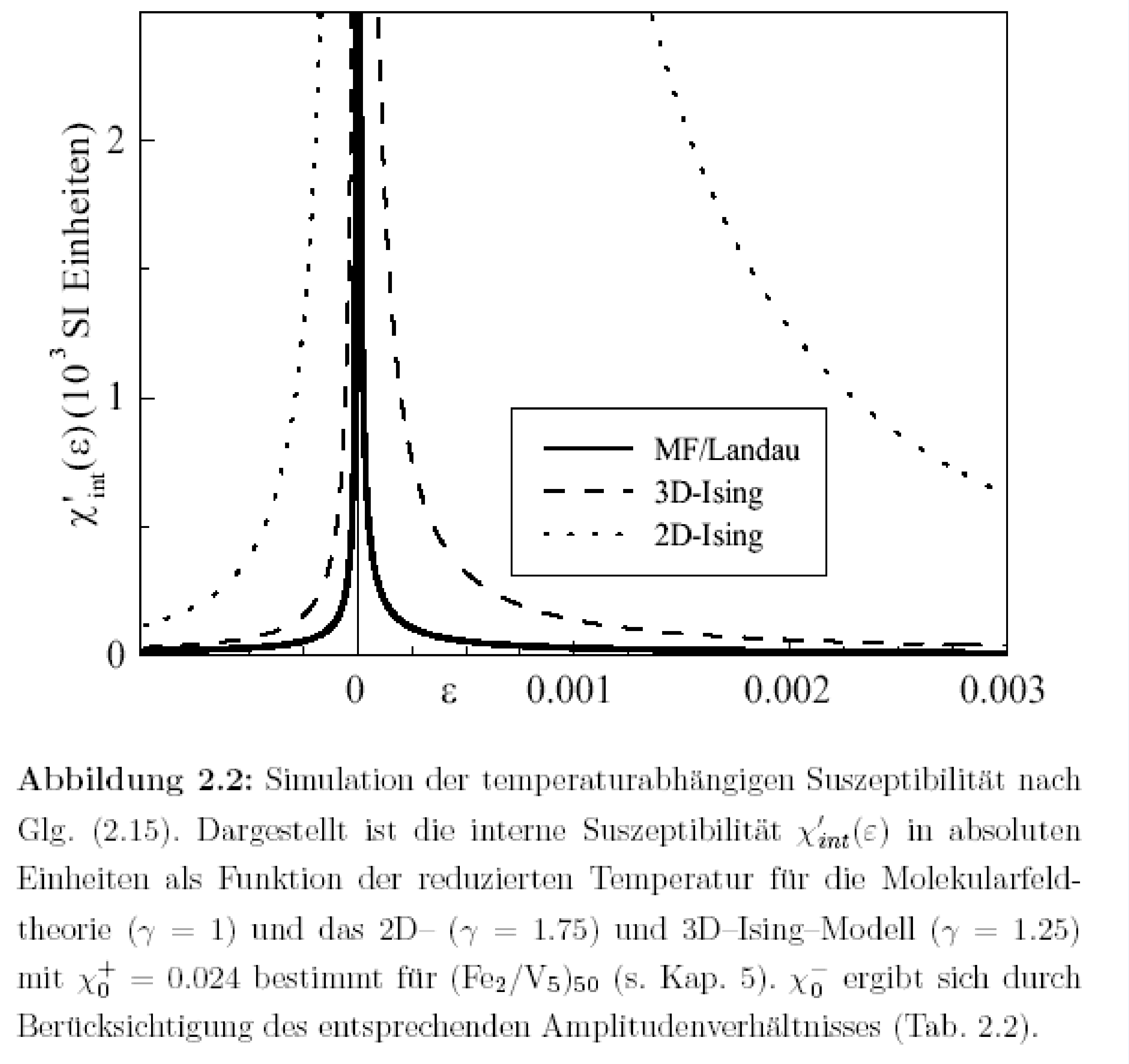
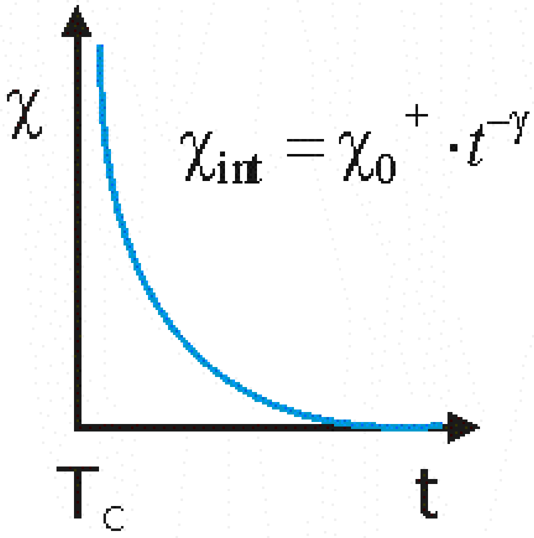


Abbildung 2.2: Simulation der temperaturabhängigen Suszeptibilität nach Glg. (2.15). Dargestellt ist die interne Suszeptibilität $\chi'_{int}(\varepsilon)$ in absoluten Einheiten als Funktion der reduzierten Temperatur für die Molekularfeldtheorie ($\gamma = 1$) und das 2D– ($\gamma = 1.75$) und 3D–Ising–Modell ($\gamma = 1.25$) 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).

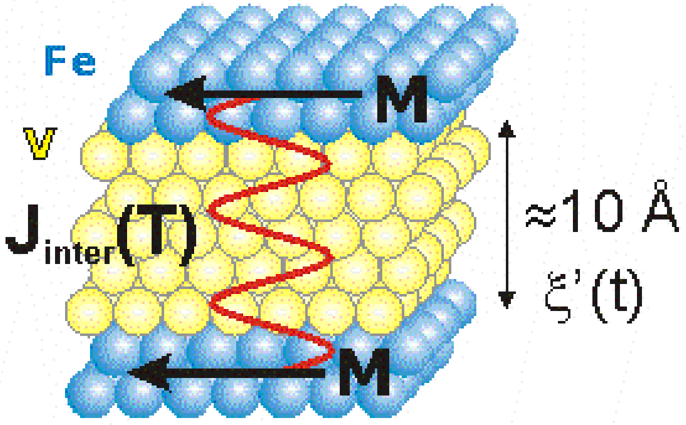
Susceptibility and critical exponent γ



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

γ = 2D / 3D ?

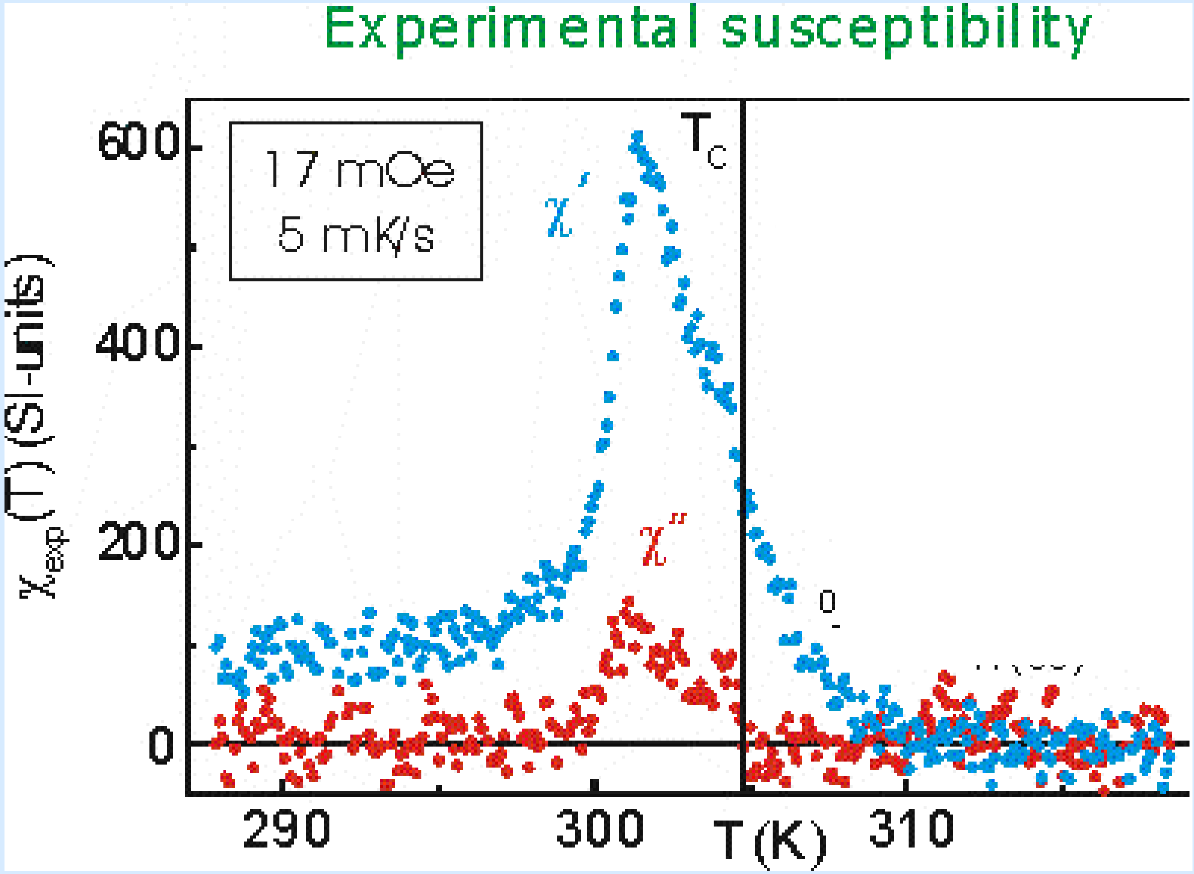
$$\frac{\chi_1}{\chi_2} = \left(\frac{\xi_1}{\xi_2}\right)^{\gamma/\nu}$$

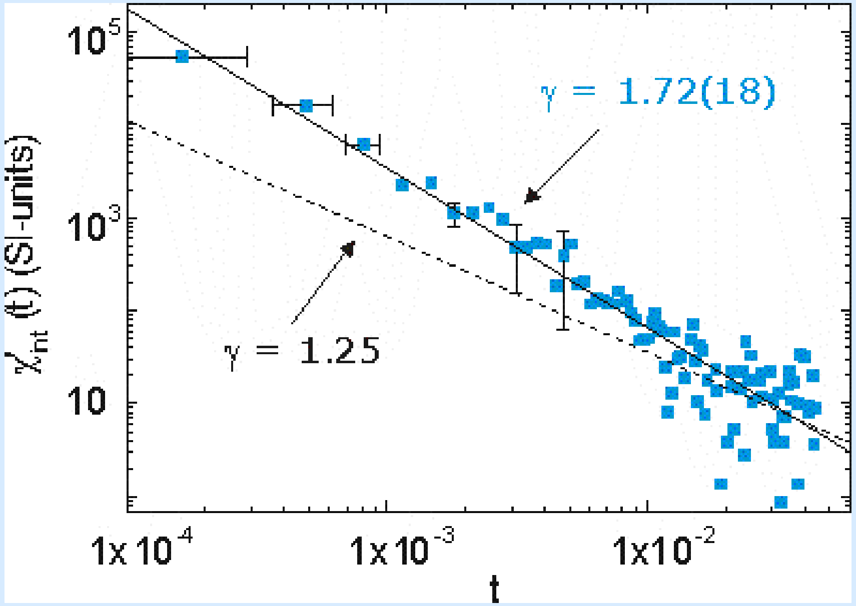


Earlier works

- 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*

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





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

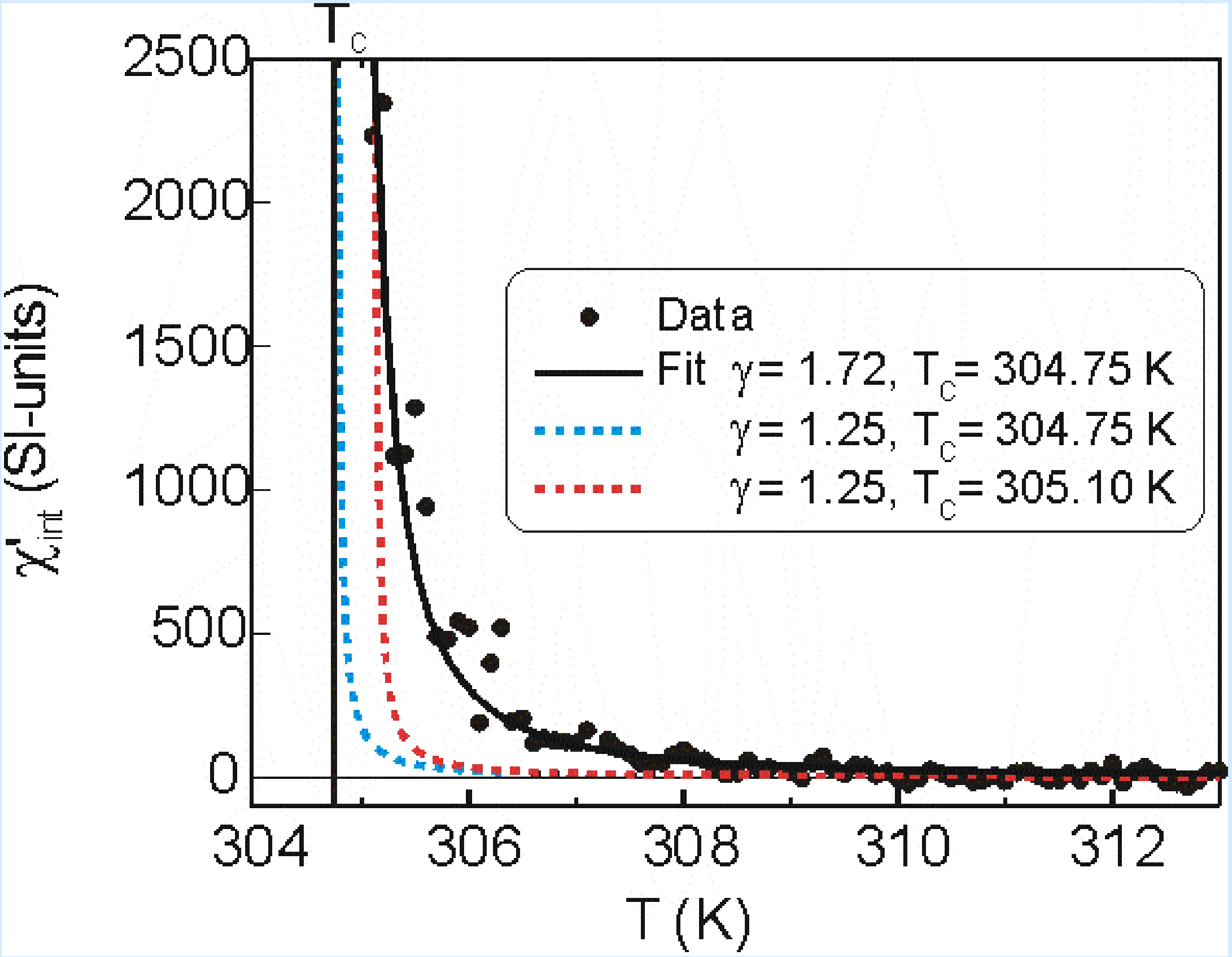
T_c=304.75(5) K , $t = \frac{T - T_c}{T_c}$

$\longrightarrow$

N≈ thickness / diameter ≈10^{-3}

$$c_{int}(t) = c_0^{+} \cdot t^{-g}$$

Forced manipulation of T_C and γ



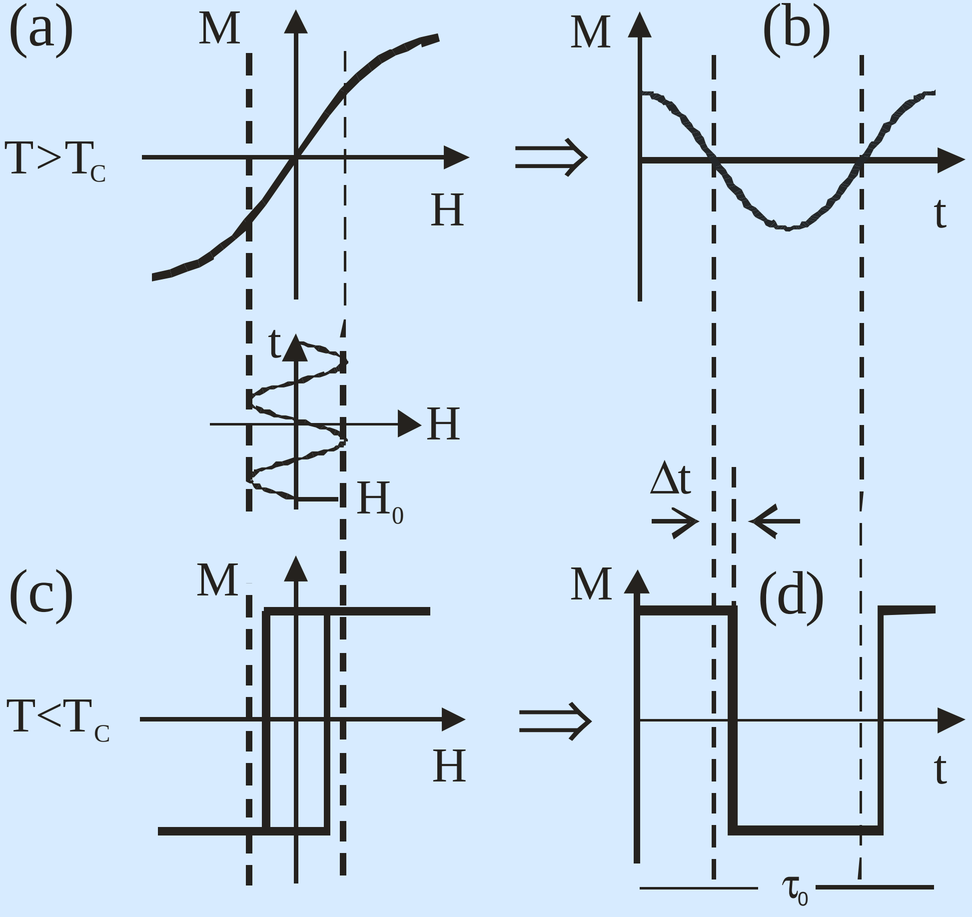
$50\ K < T < 650\ K$
$\Delta T = 3\text{-}5\ mK/s$
$\Delta T/T_C \sim 10^{-4}$

PRB **65**, 220404 (2002)

Summary: Usually T_C and ? or ß are fitted together in a log-log plot. This is very dangerous, small changes of ~ 0.4 K can change the exponent dramatically.
Exponents need to be fitted to χ_{int} (after correction for N) NOT to χ_{exp}.

6. Non linear ?$_{ac}$, the interpretation of higher harmonics in ?$_{ac}$.

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



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

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

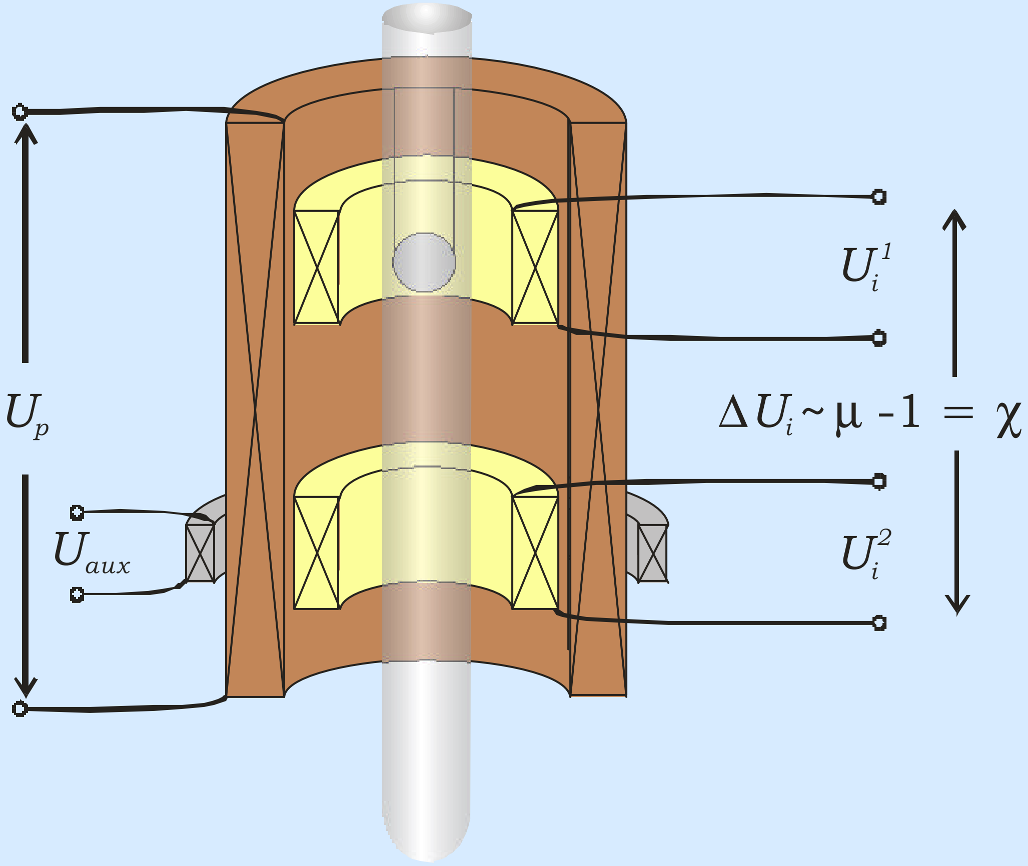
Sketch of the field-, temperature-, and time-dependent magnetization M(H,T,t) subject to an oscillating magnetic field H(t). (a) and (b) represent the paramagnetic case for T>T$_C$, whereas (c) and (d) show the ferromagnetic response for T<T$_C$. The phase-shift Δt between the oscillating magnetic field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

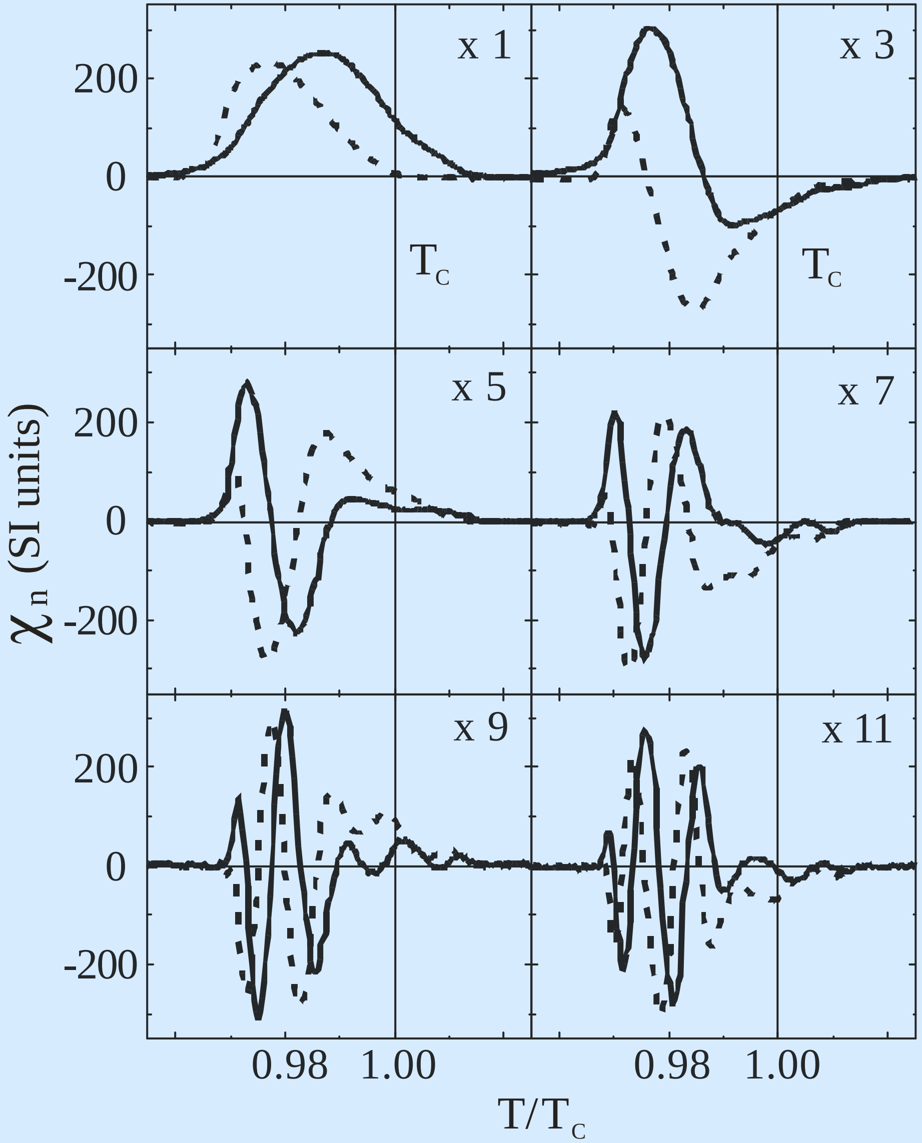
Measurement of higher harmonics

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

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

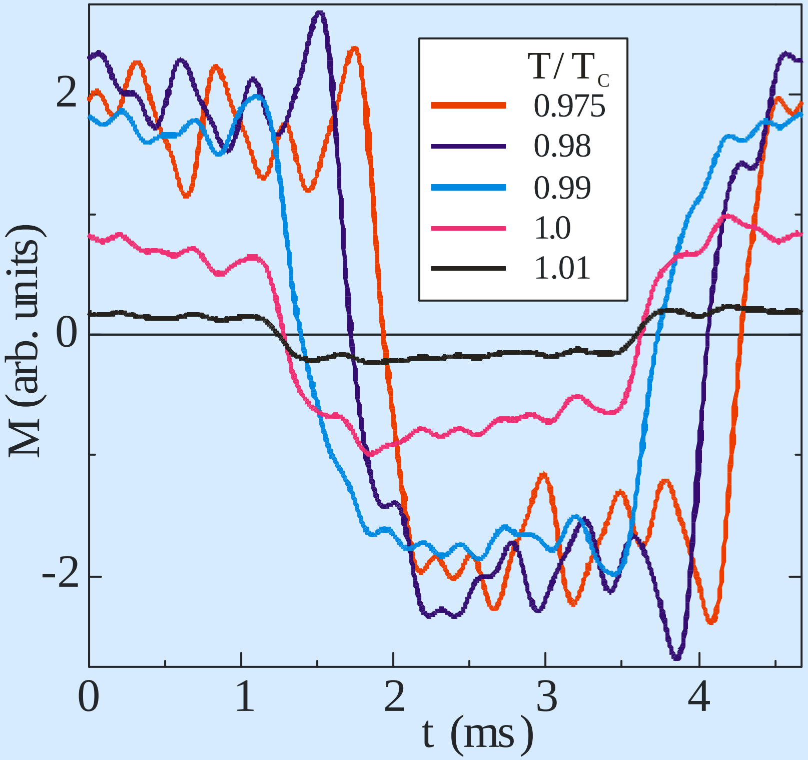
- $\chi(T,H,\omega)$
- quasistatic 213 Hz
- 10 mOe < H_0 < 1.6 Oe



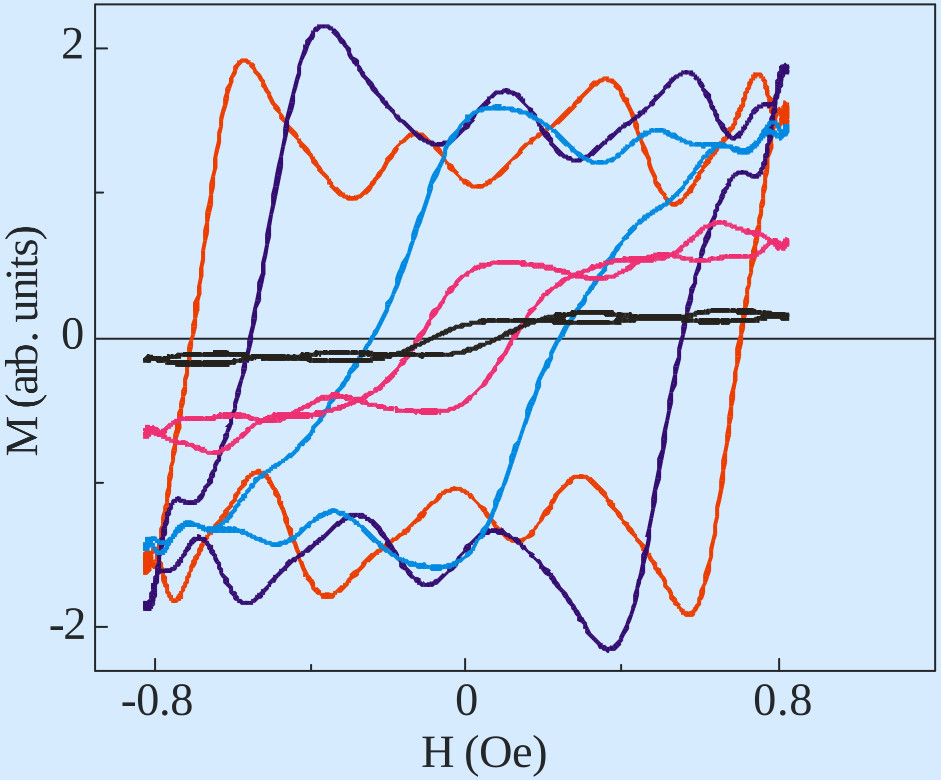


Hysteresis close to T_C

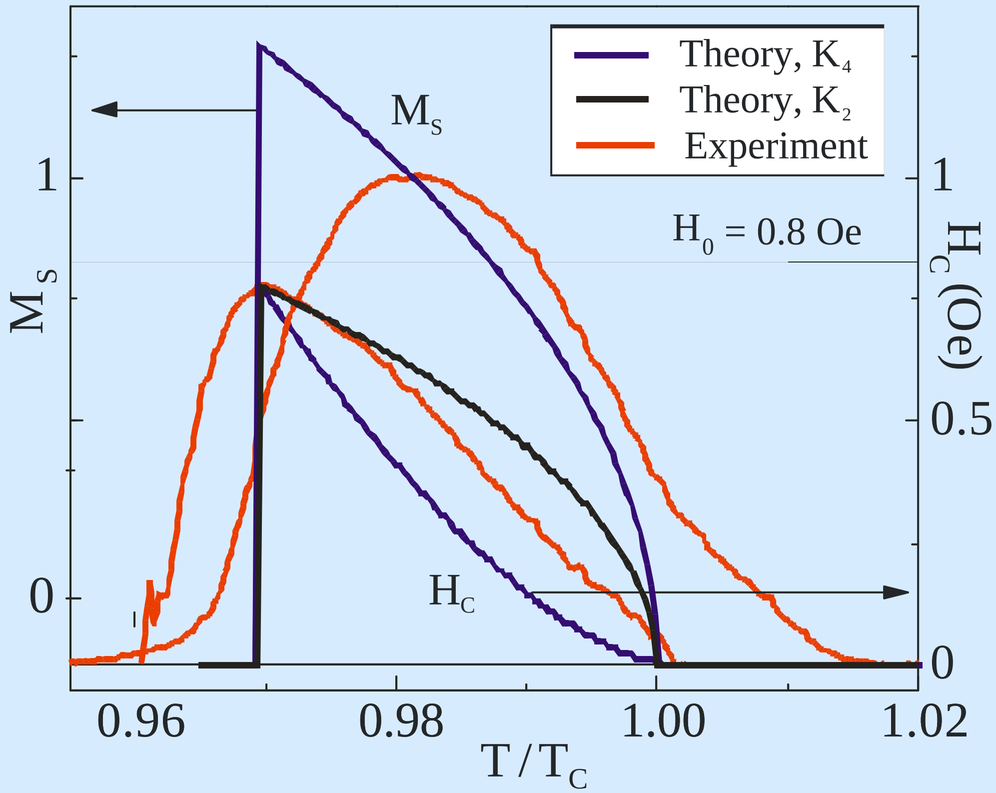
$$M(T,t)= H_0 \sum_{-\infty}^{\infty}\chi_n(T,\omega_0)\, \exp(-in\omega_0 t)$$



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.



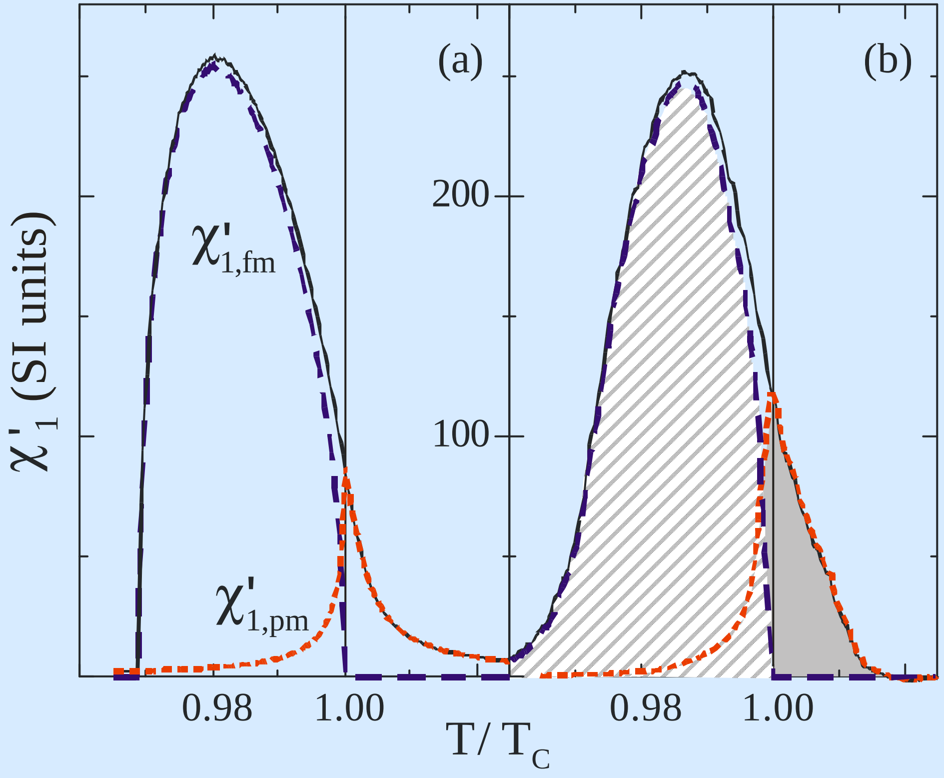
Hysteresis loops M(H) for different reduced temperatures T/T_C.



Theoretically and experimentally $M_S(T)$, normalized to unity (left axis), and $H_C(T)$ (right axis) as a function of T/T_C.

$H_C(T)$ has been calculated for both a uniaxial (K_2) and a quartic (K_4) in-plane anisotropy.

M_S and H_C close to T_C



Separation of
$c¢_1(T)=c¢_{1,fm}(T)+c¢_{1,pm}(T)$
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).

$T_{max} < T_C$

PHYSICAL REVIEW B **71**, 104426 (2005)

Temperature-dependent magnetization and susceptibility of Fe_n/V_7 superlattices

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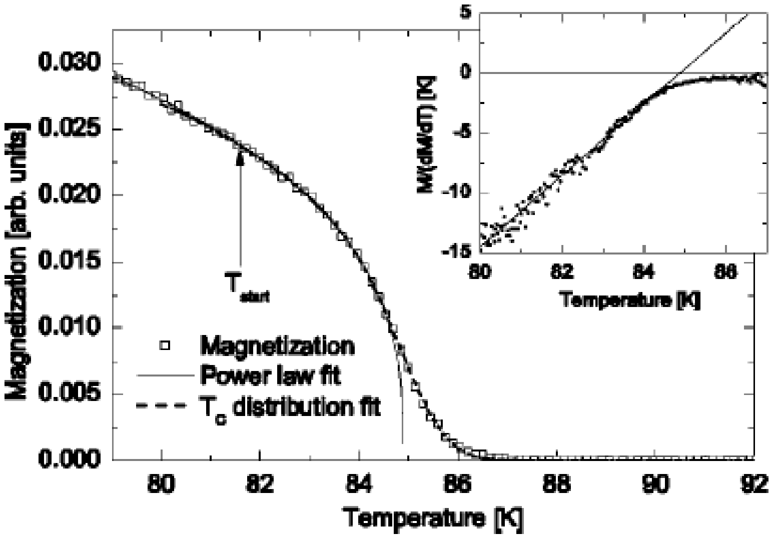

FIG. 2. Magnetization versus temperature for the sample with 2.3 ML of Fe. The full line is a fit using Eq. (1), resulting in $T_C = 84.9 \pm 0.1$ K and $\beta = 0.34 \pm 0.01$. The dashed line is a fit using a distribution of T_C's, yielding $T_C = 84.9 \pm 0.3$ K and $\beta = 0.34 \pm 0.02$. $T_{\mathrm{start}} = 0.95\, T_C$ marks the start of the fitted region. The inset shows $M/(dM/dT)$ vs T, where the straight line is a linear fit with slope $1/\beta$ ($\beta = 0.337 \pm 0.007$) where the x-axis intercept marks T_C ($T_C = 84.9 \pm 1$ K).

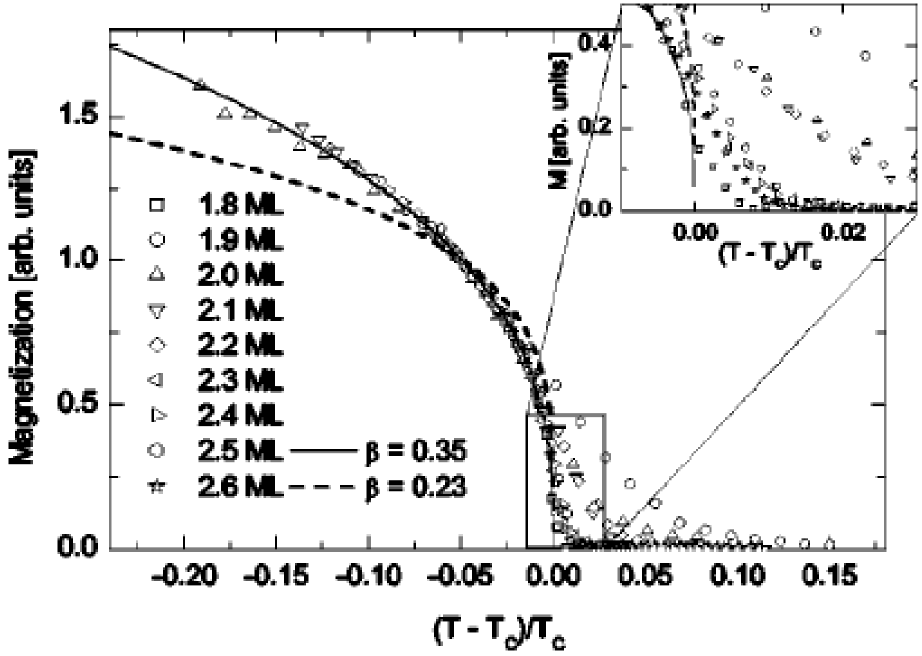

FIG. 3. Normalized M vs reduced temperature for all samples in the series. The magnetization curves are normalized at $t = -0.05$. The full and dashed lines are plots of Eq. (1) with $\beta = 0.35$ and 0.23, i.e., the 3D Heisenberg model and 2D *XY* model, respectively.

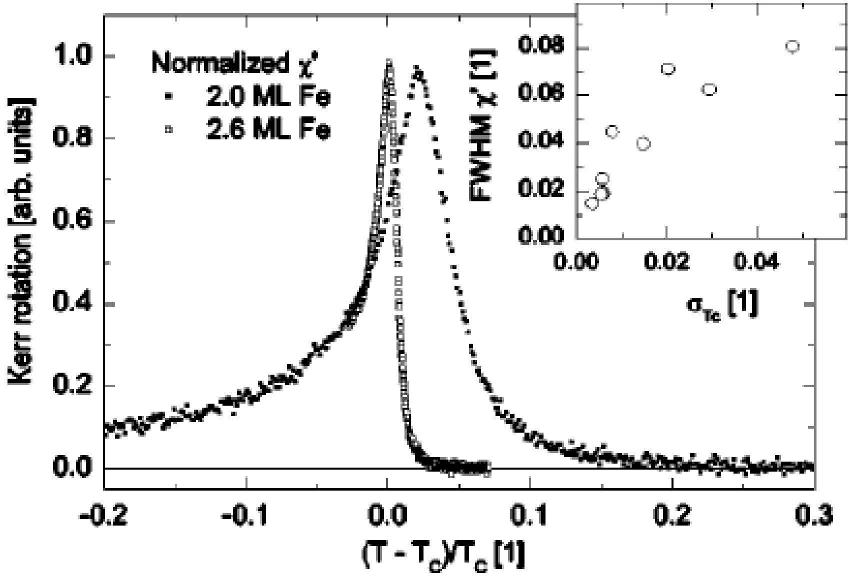

FIG. 5. Normalized susceptibility for two samples with 2.0 and 2.6 ML of Fe, measured using an excitation amplitude of 2.8 μT. The inset shows the relation between the FWHM of $\chi'(T)$ and the standard deviation of the Gaussian T_C distribution (both in reduced temperature).

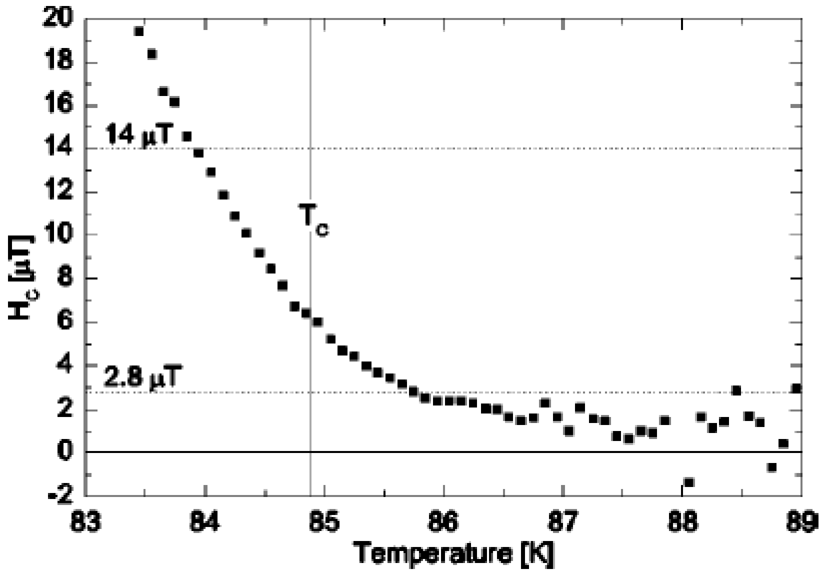

FIG. 7. Coercive field vs temperature for the sample with 2.3 ML of Fe. The horizontal dotted lines mark the values of the applied fields used in our measurements (2.8 and 14 μT, respectively). The vertical line marks T_C as determined from magnetization data.

Summary

•This summer school is dealing with phase transitions in nanomagnetism,
that is to say, the physics close to T_C .
At elevated T the „T = 0 language“ may be inappropriate.
Do not interpret your measurements in a simple MFA.

•Static exchange- and anisotropy-fields, and T=0 DOS are insufficient,
spin wave excitations, spin fluctuations are important for a proper description.

•The ac-susceptibility contains very reach information,
but “a conclusive analysis …is complex” (BH et al.) .
Many mistakes (incompleteness) have been published in the literature.

•Nanomagnetism is clearly important for technological applications,
but it opens also a huge field to study fundamentals,
which may be inaccessible in 3D bulk.