“Lectures on magnetism”
at the Fudan University, Shanghai
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Introduction

These lectures will cover the recent development of magnetic nanostructures, which are of tremendous interest, be it for technological applications or for the fundamental understanding of magnetism. Magnetism in the past has mostly been discussed as a macroscopic function of the free energy. Today’s magnetic cluster and films of nanometer scale combined with UHV technique offer a new point of view to discuss magnetism in a microscopic atomistic picture.

1. **Introduction**
   a) Orbital and spin magnetic moments
   b) Which experimental technique measures what?
2. **Magnetic Anisotropy Energy (MAE)**
   a) Ferromagnetic resonance (UHV-FMR)
   b) *ab initio* calculations
3. **ac – Susceptibility ?’, ?’’ in UHV**
   a) T_C, critical phenomena
   b) Oscillatory Curie temperatures
   c) Higher harmonics ?(n?)
4. **Trilayers a prototype of multilayers**
   a) Optical and acoustic modes in the spin wave spectrum
   b) Interlayer exchange coupling (IEC)
5. **X-ray magnetic circular dichroism (XMCD)**
   a) Element specific XMCD, induced magnetism
   b) Sum rules and advanced theory
   c) Importance of strong spin–spin correlations in 2D-magnets
6. **Spin Dynamics**
   a) Magnon-magnon scattering and Gilbert damping
   b) Spin pumping

Acknowledgement

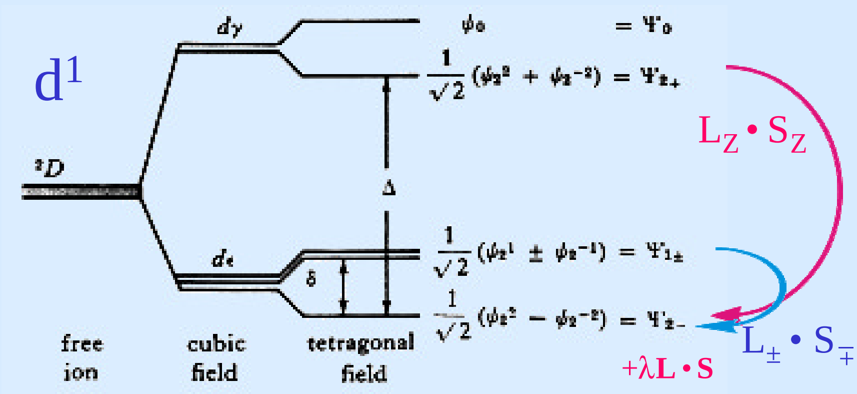
Synchrotron (BESSY, ESRF):
H. Wende, C. Sorg, N. Ponpandian, (M. Bernien, A. Scherz, F. Wilhelm), Luo Jun (AvH fellow)

Lab. Experiments (FMR, SQUID, C_{ac}, STM):
K. Lenz, (T.Tolinski, J. Lindner, E. Kosubek, C. Rüdt, R. Nünthel, P. Poulopoulos, A. Ney)

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

Þ **http://www.physik.fu-berlin.de/~bab**

1a Orbital and spin magnetic moments



Splitting of the ²D term by a tetragonally distorted cubic field.

The orbital moment is quenched in cubic symmetry

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

but not for tetragonal symmetry

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

Orbital magnetism in second order perturbation theory

$$\mathcal{H}' = \mu_B \mathbf{H \cdot L} + \lambda \mathbf{L \cdot S}$$

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

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

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

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

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

$< o|\mu_B \mathbf{H \cdot L}|n > < n|\lambda \mathbf{L \cdot S}|o >$ $\qquad$ $< o|\lambda \mathbf{L \cdot S}|n > < n|\lambda \mathbf{L \cdot S}|o >$

In the principal axis system of a crystal with axial symmetry, the $\underline{\mathbf{\Lambda}}$ 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

$$g_\parallel - g_\perp = g_e \lambda (\Lambda_\perp - \Lambda_\parallel)$$

anisotropic $\mu_L \leftrightarrow$ MAE

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

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

Bruno ('89)

Direct Observation of Orbital Magnetism in Cubic Solids

W.D. Brewer, A. Scherz, C. Sorg, H. Wende, K. Baberschke,
P. Bencok, S. Frota-Pessôa

Phys. Rev. Letters 93, 077205 (2004)

Standard exercise in solid state physics:

cubic symmetry $\Rightarrow \langle L_z \rangle = 0$

Is the orbital moment of 3d impurities in noble metal hosts completely quenched?

- XMCD investigations of Cr, Mn, Fe, Co in Au
- *ab initio* calculations of orbital moment

Motivation

atoms → metals

large μ_L
(Hund's rules)

3d impurities
in noble metal
hosts:

⇓

1970's: indirect evidence for
surviving orbital moments
(HF measurements)

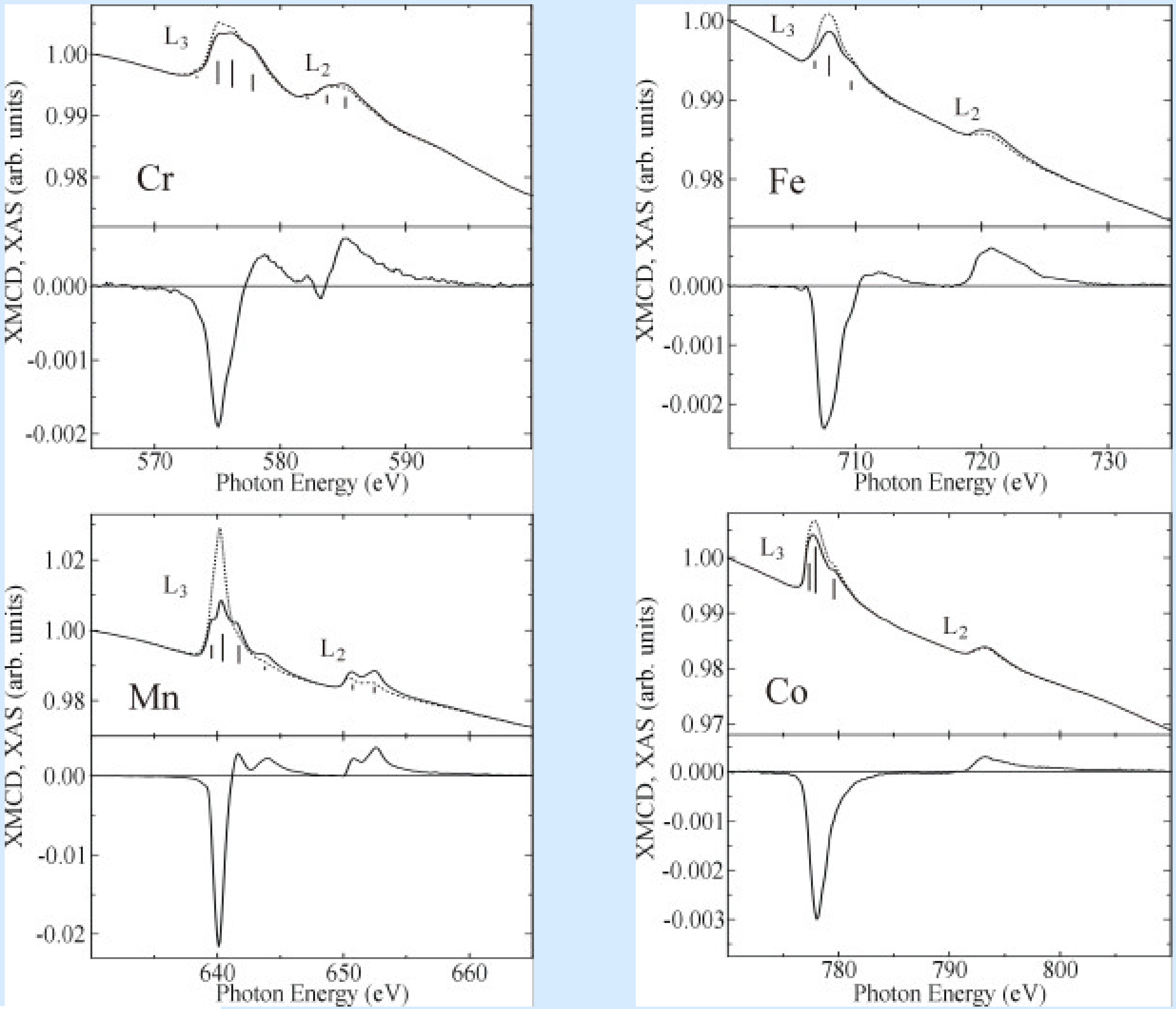
⇓

here: first direct evidence
(electronic structure) by
X-ray absorption spectroscopy
(XMCD)

μ_L mostly quenched
(Fe, Co, Ni:
μ_L/μ_S~5-10%)

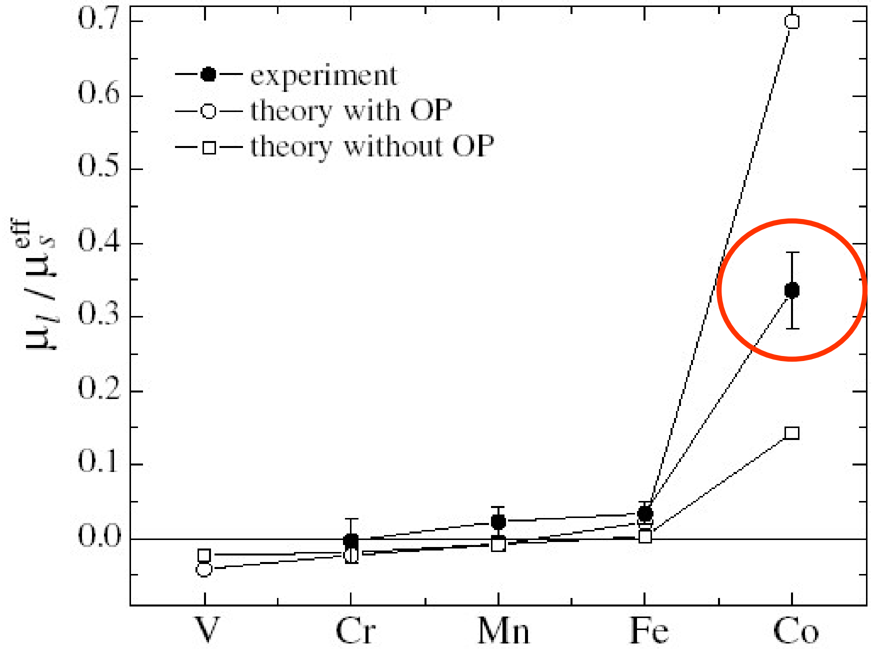
impurity concentration in Au host: 1.0 at. %

ESRF ID8:
7 T, 7-18 K



$$\frac{\mu_l}{\mu_s^{\text{eff}}} = \frac{2}{3}\,\frac{1+R}{1-2R}.$$

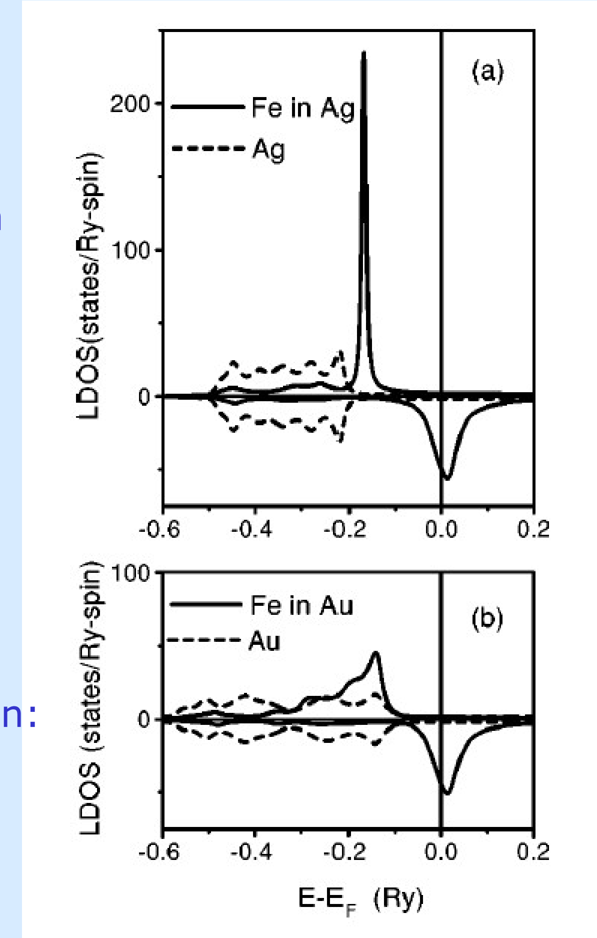
- Brewer et al., ESRF Highlights 2004, p 96

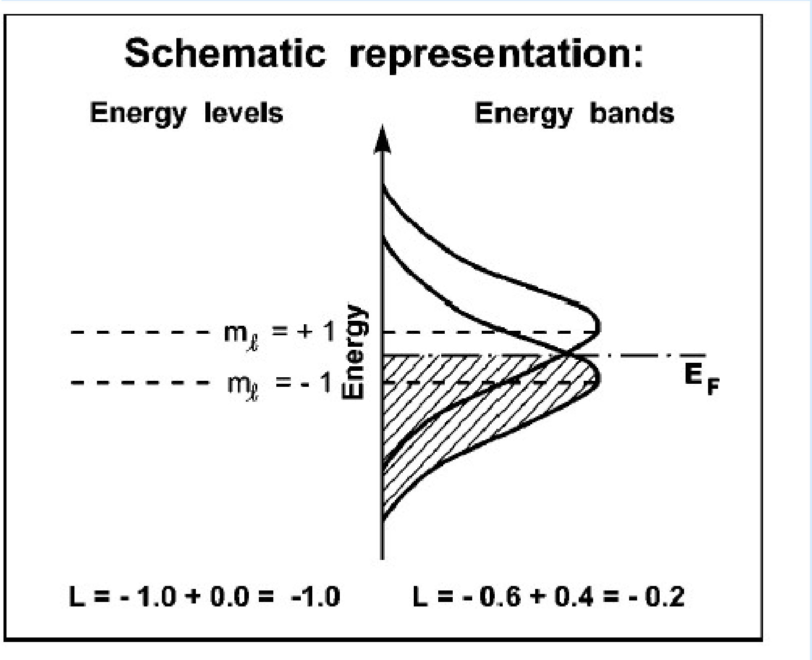


Alloy	R	$T(K)$	μ_l/μ_s^{eff}
*Au*Cr (1.0 at.%)	−1.01	18.7	−0.003(30)
*Au*Mn (1.0 at.%)	−0.90	6.8	+0.023(20)
*Cu*Mn (1.0 at.%)	−0.94	6.8	+0.013(20)
*Au*Fe (0.8 at.%)	−0.86	7.2	+0.034(15)
*Au*Co (1.5 at.%)	−0.247	6.8	+0.336(52)

dramatic increase of orbital moment for Co impurity (~4 times larger than Co bulk)

Fe in Ag:
weak hybridization
μ_L survives





Fe in Au:
strong hybridization:
μ_L quenched

subtle effect of hybridization and band-filling

S. Frota-Pessôa, PRB **69** (2004) 104401

Conclusion

- first direct experimental evidence for orbital moments in cubic symmetry
- text book arguments: weak Spin-Orbit coupling, distinct separation of t_{2g} and e_g, no intermixing
- comparison to *ab initio* calculations: delicate balance hybridization between local impurity and host and the filling of the 3d states of the impurity

⇒ future works on Kondo systems, e.g. with STM, may include surviving orbital moment

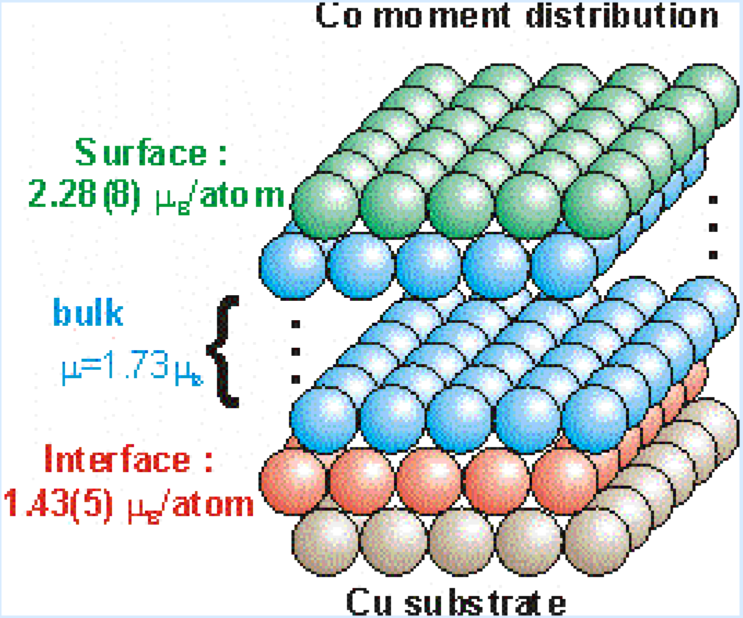
⇒ description beyond pure spin magnetism (e.g. Kondo-like Hamiltonian $JS \cdot \sigma$)

Orbital- and spin- magnetic moments at surfaces and interfaces of ferromagnetic nanostructures

1. $\mu_L + \mu_S$ in UHV - SQUID

2. μ_L , μ_S in UHV - XMCD

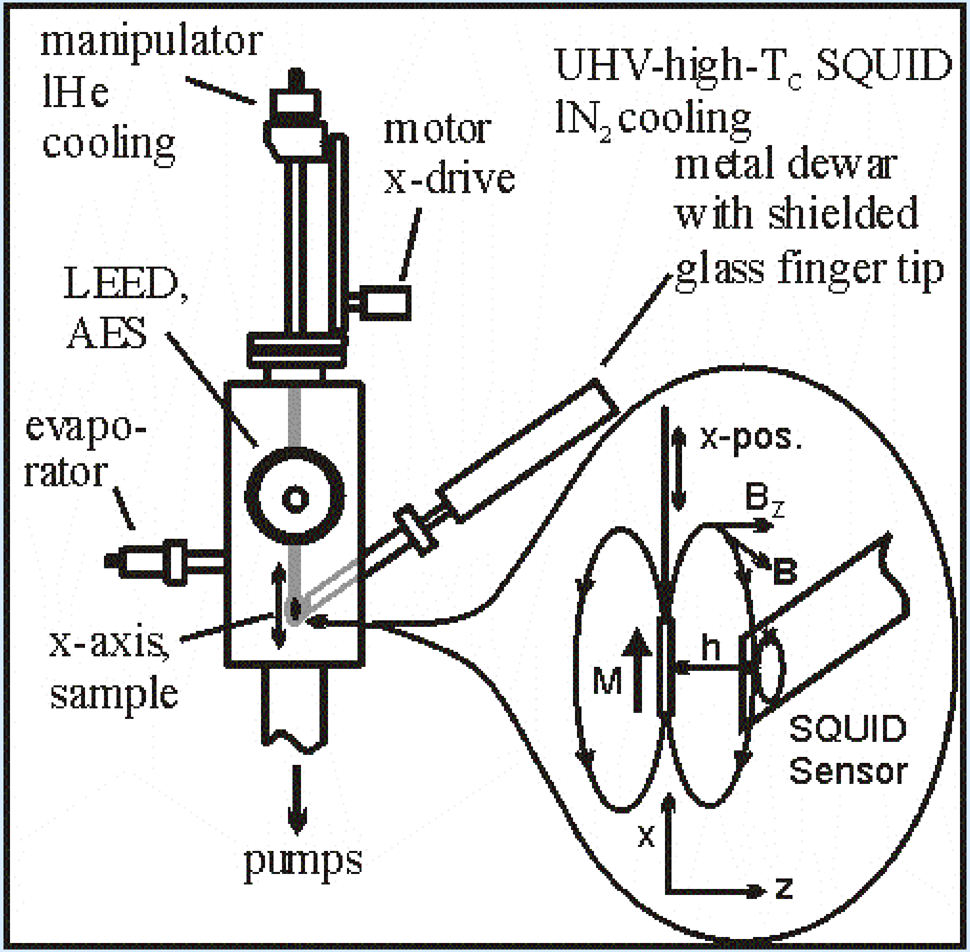
3. μ_L / μ_S in UHV - EPR / FMR



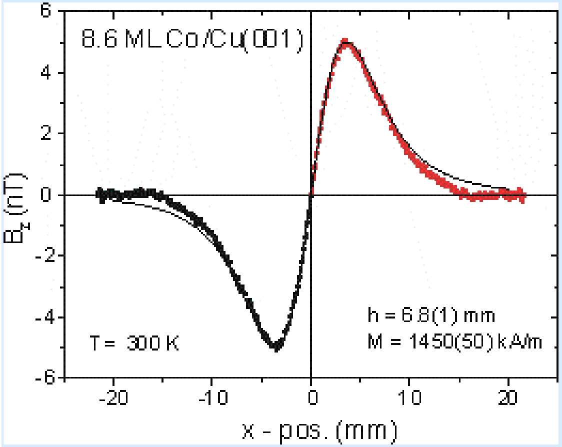
Design of the

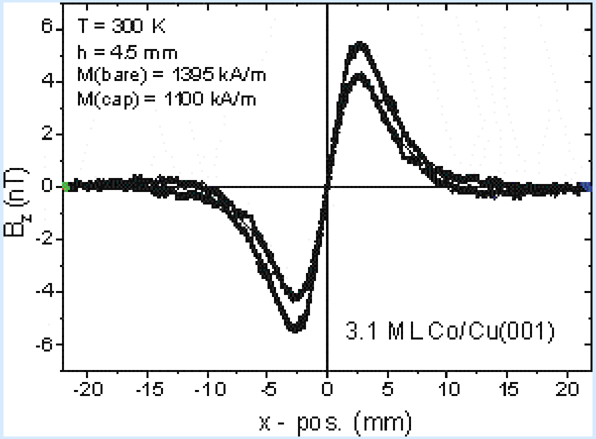
UHV-SQUID

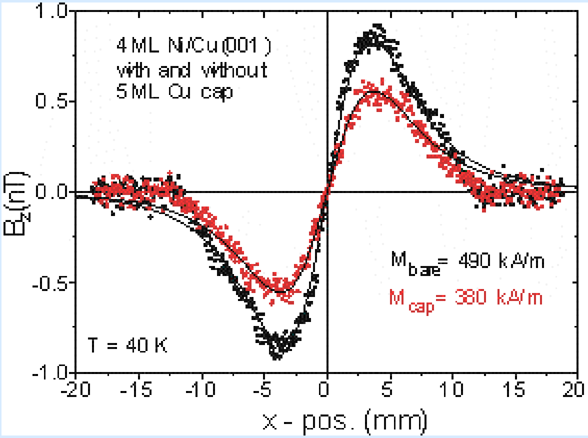
magnetometer



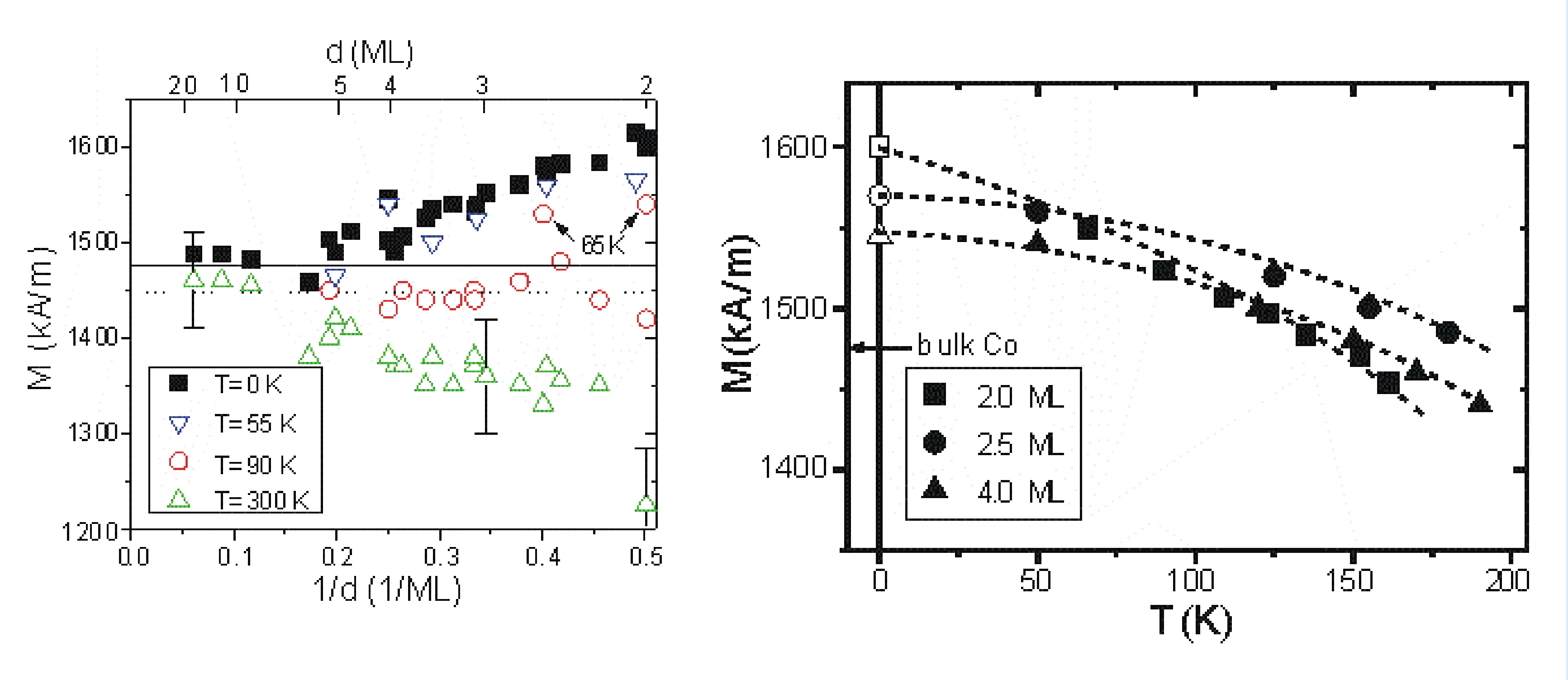
Sensitivity







The effect of temperature

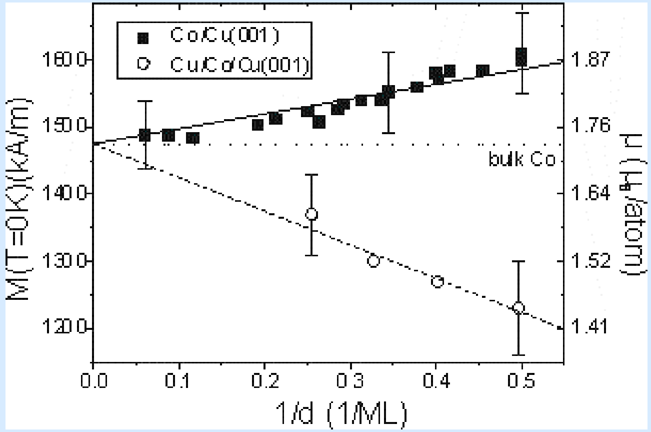


The magnetization of Co/Cu(001) vs the inverse

film thickness at different temperatures.

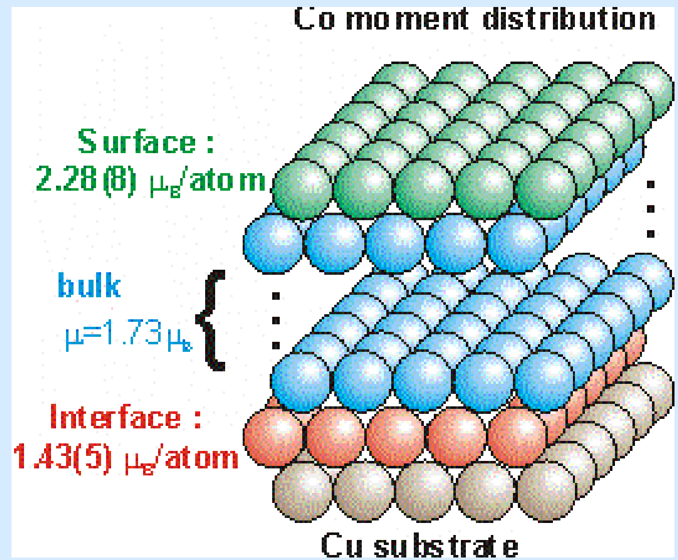
The bulk values for 4K (full line) and 300K

(dashed line) are indicated.



$$m_{tot} = m_{vol} + \frac{m_{surf} + m_{inter} - 2}{d}$$ (linear with 1/d)

Co moment distribution

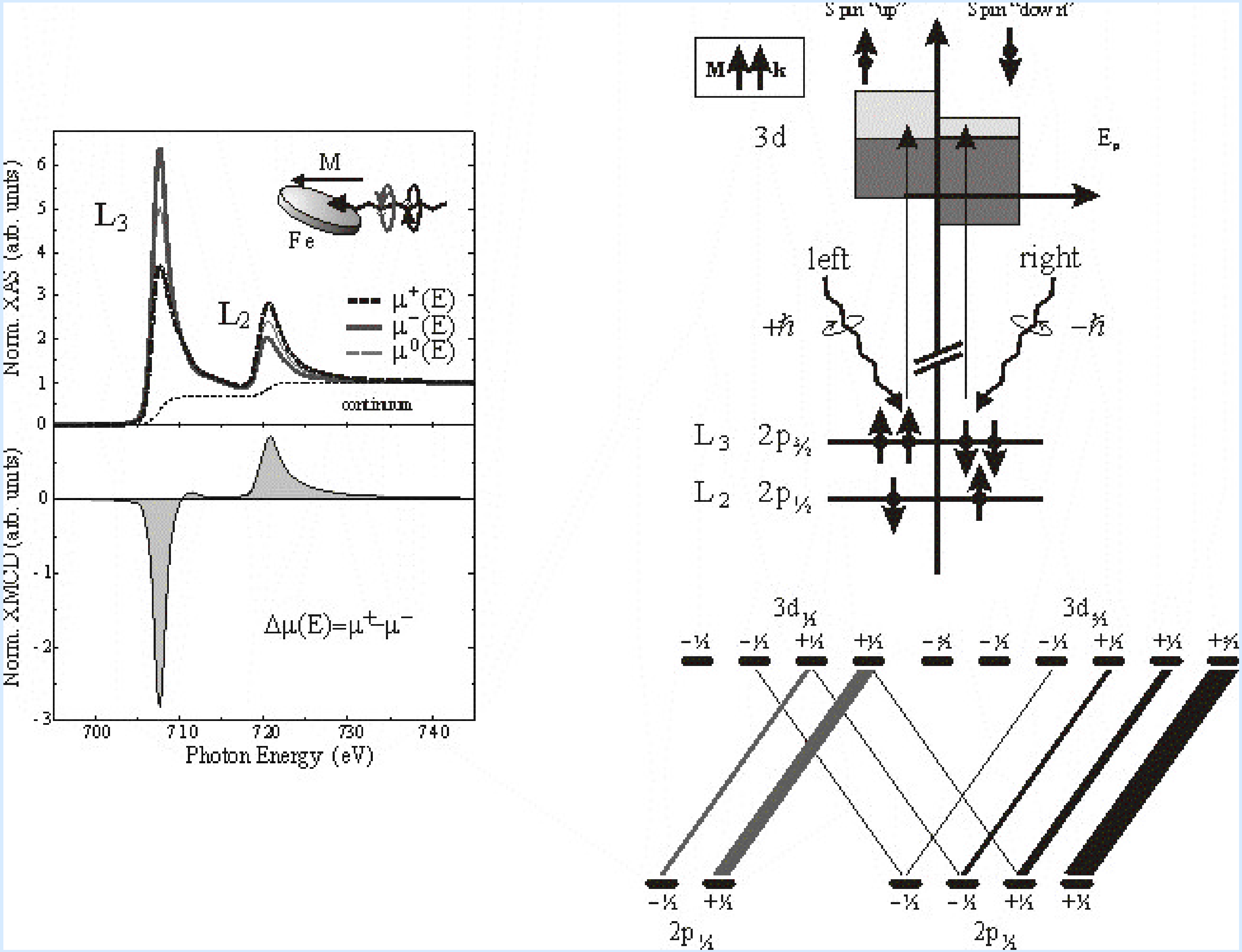


Theory:
Hjortstam et al., PRB 53, 9204 (1996)

Pentcheva et al., PRB 61, 2211 (2000)

A. Ney et al. Europhys. Lett. 54, 820 (2001)

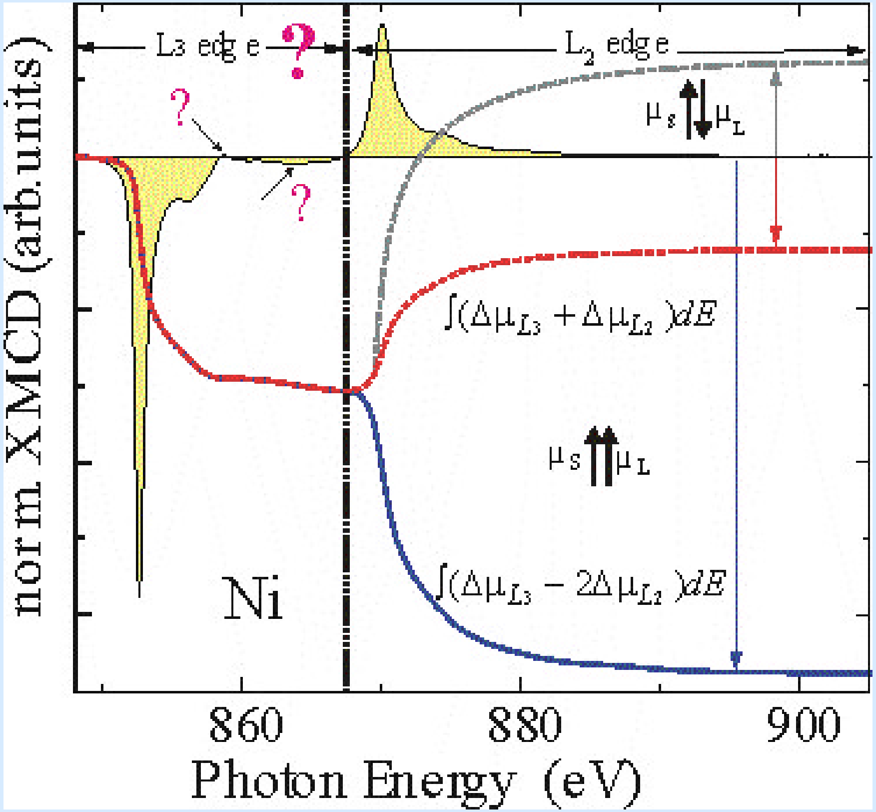
X-ray Magnetic Circular Dichroism



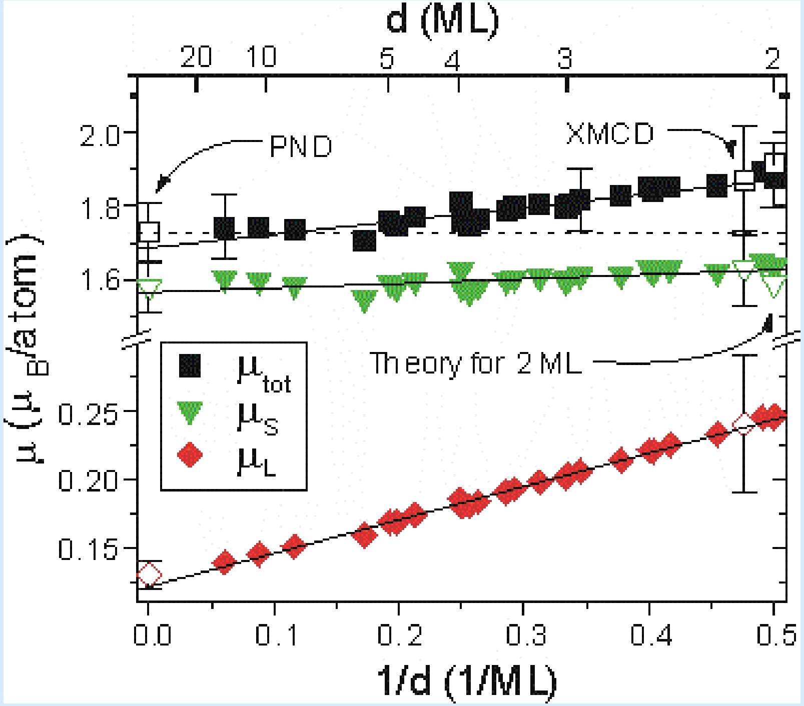
Orbital and spin magnetic moments deduced from XMCD

$$\int(\Delta\mu_{L3} - 2\cdot\Delta\mu_{L2})dE = \frac{N}{3N_h^d}\left(2\langle S_z\rangle^d + 7\langle T_z\rangle^d\right)$$

$$\int(\Delta\mu_{L3} + \Delta\mu_{L2})dE = \frac{N}{2N_h^d}\langle L_z\rangle^d$$



Deconvolution into spin (μ_S) and orbital (μ_L) moments



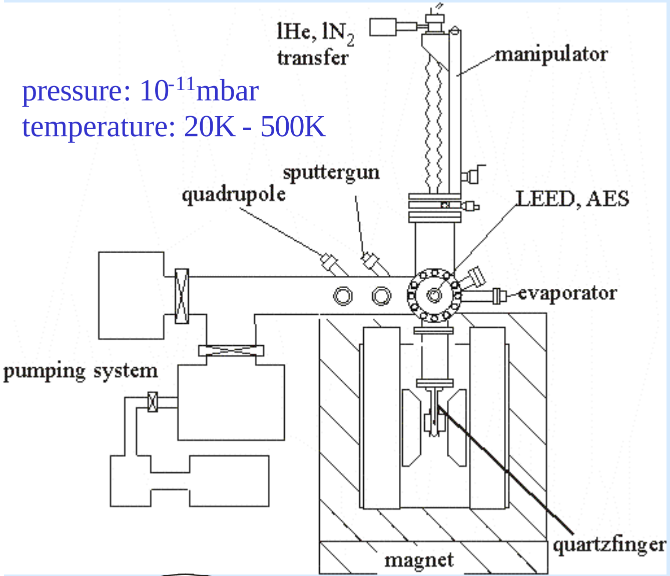
The total magnetic moment (squares) of Co/Cu(001) vs the inverse film thickness and its separation into spin (down triangle) and orbital (diamonds) contribution. The bulk value is indicated (dashed line). For comparison experimental results using PND and XMCD are given by the open symbols.

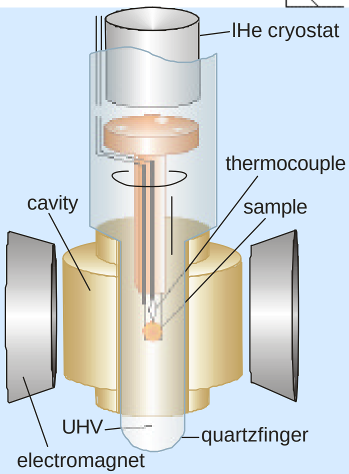
http://www.dissertation.de/PDF/an452.pdf

FMR in ferromagnetic nanostructure

In situ UHV-FMR set up

pressure: 10^{-11}mbar
temperature: 20K - 500K





M. Zomak et al.,
Surf. Sci. **178**, 618 (1986)

J. Lindner, K.B.
J. Phys.: Cond. Matt **15**, R193 (2003)

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Ferromagnetic Order and the Critical Exponent γ for a Gd Monolayer: An Electron-Spin-Resonance Study

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(Received 18 September 1986)

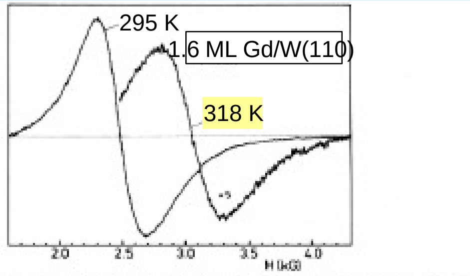


Fig. 4. ESR spectra for the new 1.6 ML sample (not cited in [2, 3]). Note the significant change in intensity and resonance field from 16 to 39 K above T_c

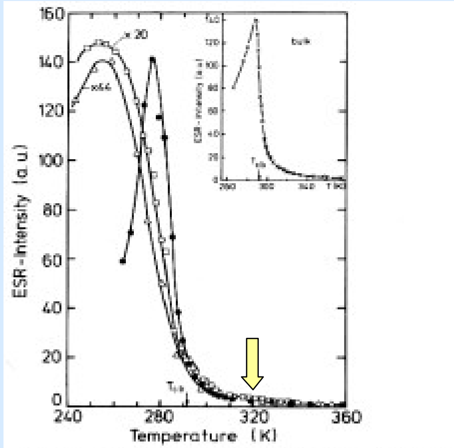
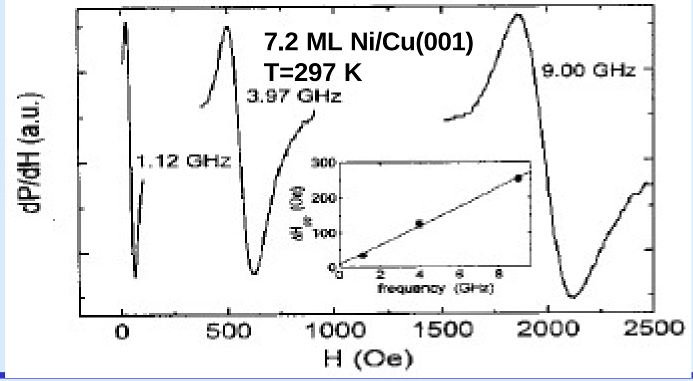


Fig. 5. Area of the ESR signal as a function of temperature for 80 Å (●), the new 1.6 ML (□), and the 0.8 ML (△). The insert shows the same data for a 18 µm thick Gd foil (bulk). Solid lines are guides to the eye. The 1.6 and 0.8 ML have a vertical gain factor of 20 and 44 with respect to 80 Å. The insert is not to scale

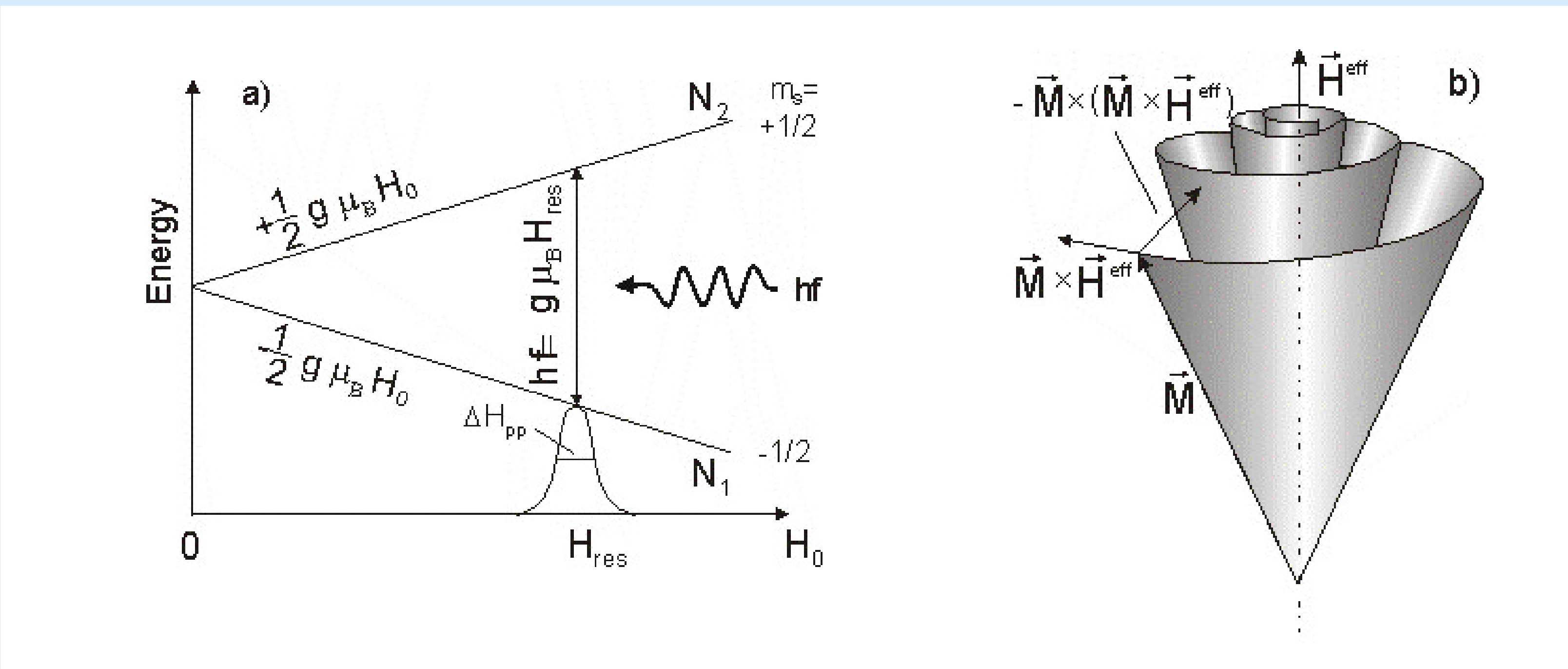


W. Platow, Ph.D. thesis (1999)

Magnetic resonance (ESR, FMR)

Landau-Lifshitz-Gilbert-Equation

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



Determination of g-Tensor components

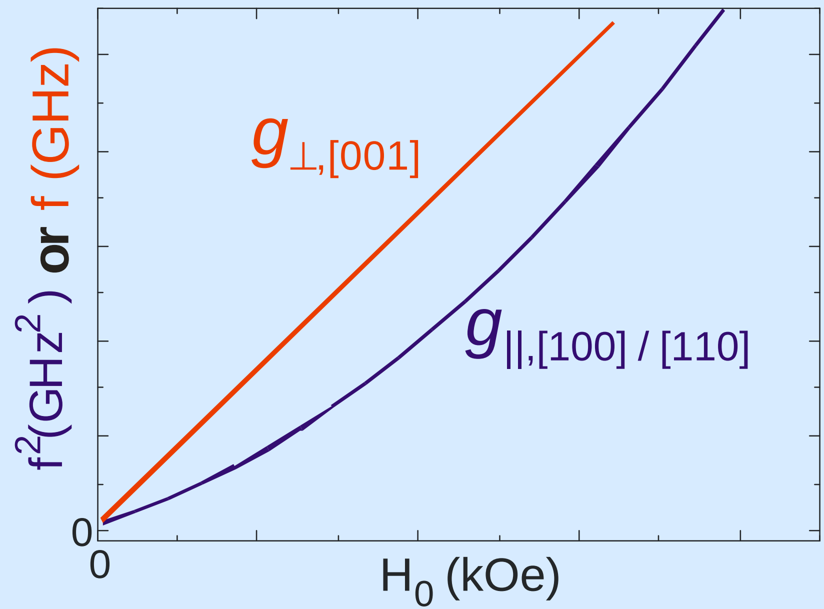
$$\frac{w^2}{g^2_{||,[100]}} = H^2_{0,[100]} + H_{0,[100]}\left(4pM - 2\frac{K_2}{M} + \frac{4K_{4||}}{M}\right) + 2\frac{K_{4||}}{M}\left(4pM - 2\frac{K_2}{M} + \frac{2K_{4||}}{M}\right)$$

$$\frac{w}{g_{\perp,[001]}} = H_{0,\perp} - 4pM + \frac{2(K_2 + K_{4\perp})}{M}$$

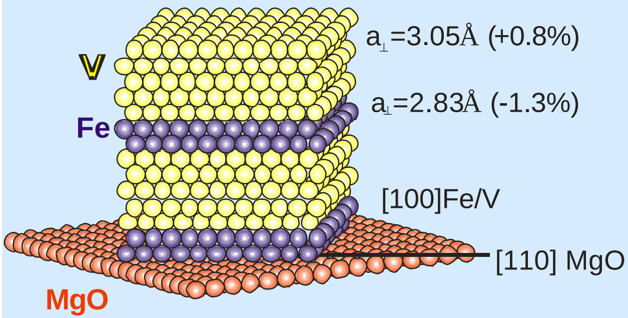
with $\gamma = \frac{g \cdot \mu_B}{\hbar}$

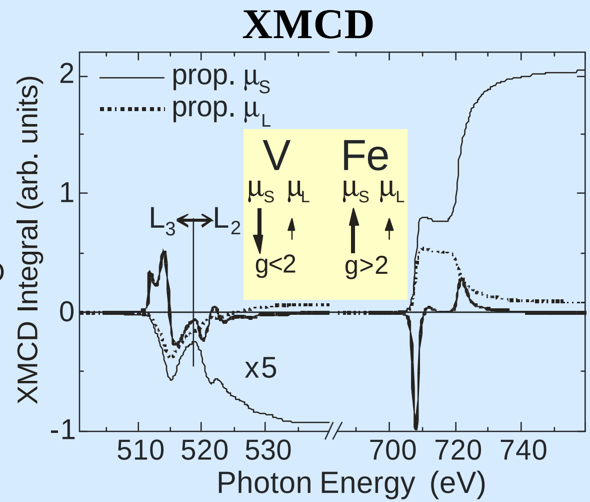
$$\frac{\mu_l}{\mu_s} = \frac{g-2}{2}$$

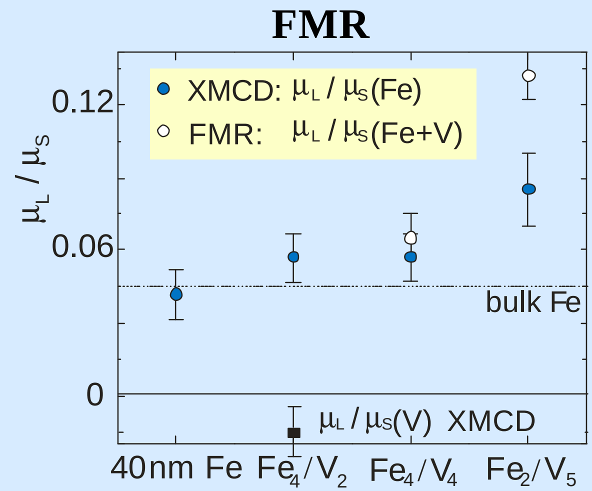
C. Kittel, *J.Phys. Radiat.* ***12****, 291 (1951)*

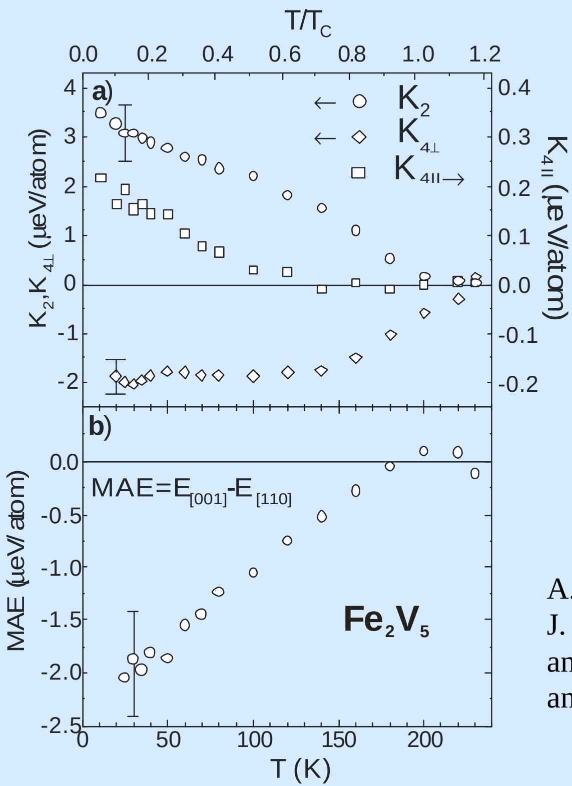


Ferromagnetic resonance on $Fe_n/V_m(001)$ superlattices









$$\frac{\mu_L}{\mu_S} = \frac{g-2}{2}$$ **(Kittel'49)**

In solids g and μ_L are tensors

A.N. Anisimov et al.
J. Phys. C **9**, 10581 (1997)
and PRL **82**, 2390 (1999)
and Europhys. Lett. **49**, 658 (2000)

bcc (001) Fe_2/V_5 superlattice					
$g_{\parallel}$	$g_{\perp}$	μ_L/μ_S	$\mu_L (\mu_B)$	$\mu_S (\mu_B)$	MAE µeV/atom
2.264	2.268	0.133	0.215	1.62	-2.0
bcc Fe-bulk					
2.09	2.09	0.045	0.10	2.13	-1.4

Summary

Distinguish between:

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

per definition:

1) spin moments are isotropic
2) also exchange coupling $\mathbf{J}\ \mathbf{S_1}\cdot\mathbf{S_2}$ is isotropic
3) so called anisotropic exchange is a (hidden) projection of the orbital momentum onto spin space

Quenching of $\langle L_Z \rangle$ is oversimplified argument