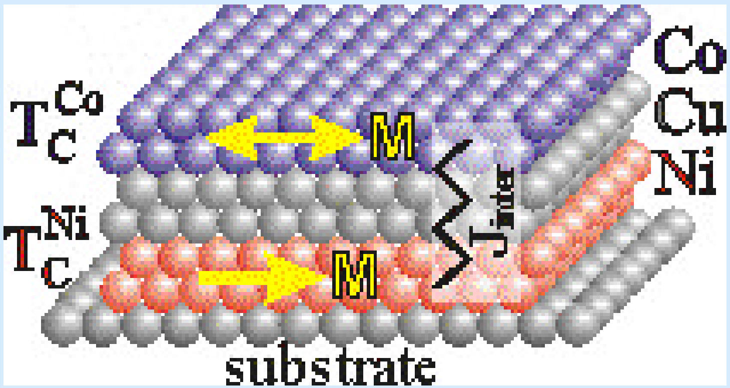
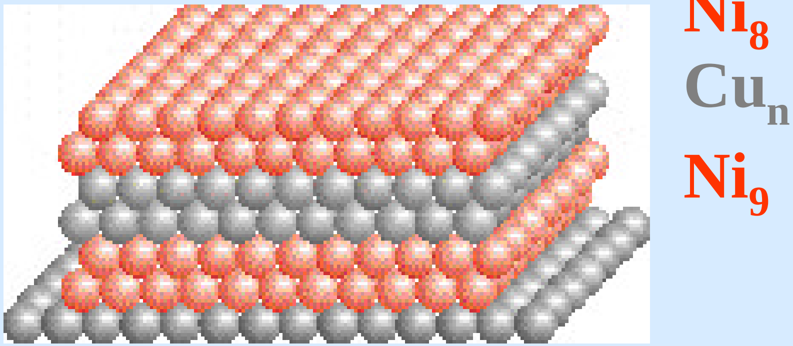
Lectue 4 Trilayers a prototype of multilayers

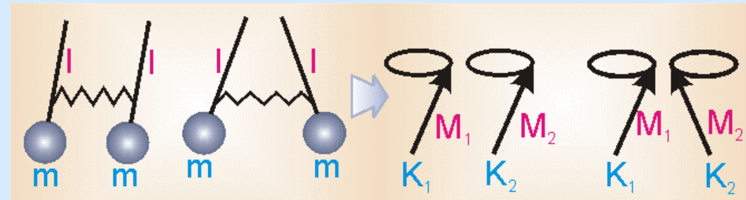




Important parameters: K – anisotropy, ΔE_{band} for FM1 and FM2

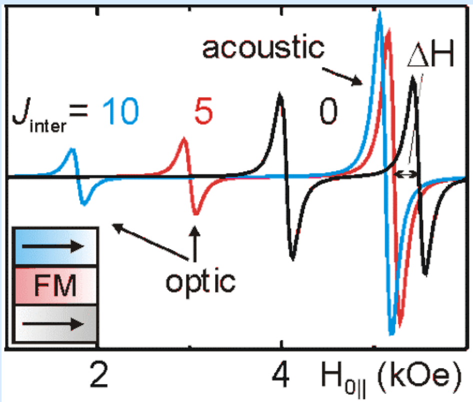
interlayer exchange coupling IEC, J_{inter}

4a Optical and acoustic modes in the spin wave spectrum

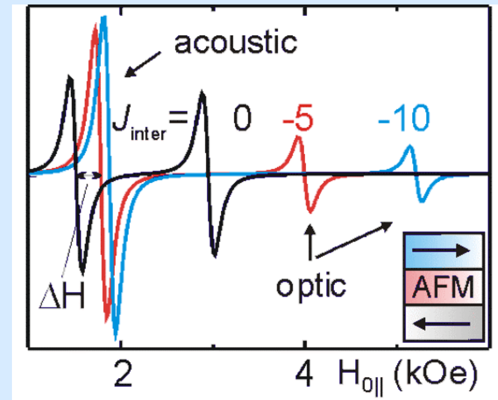


Landau-Lifshitz-Gilbert-Equation

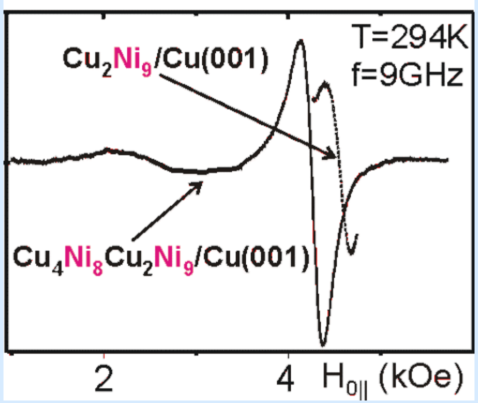
$$\frac{1}{\gamma}\frac{\partial M}{\partial t} = -M\times H_{eff}(J_{inter},K) + \frac{G}{\gamma M_S^2}\left(M\times\frac{\partial M}{\partial t}\right)$$



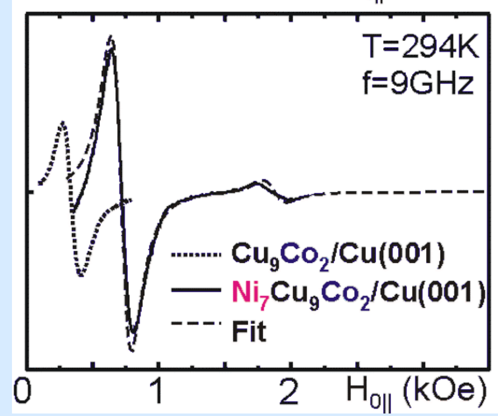
theory



FMR

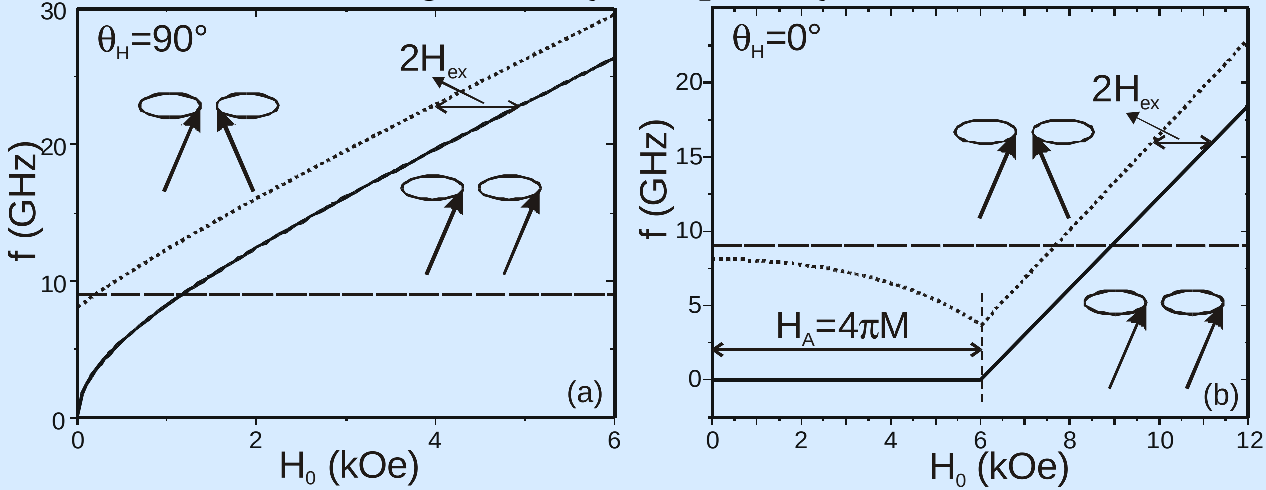


in-situ
UHV-experiment

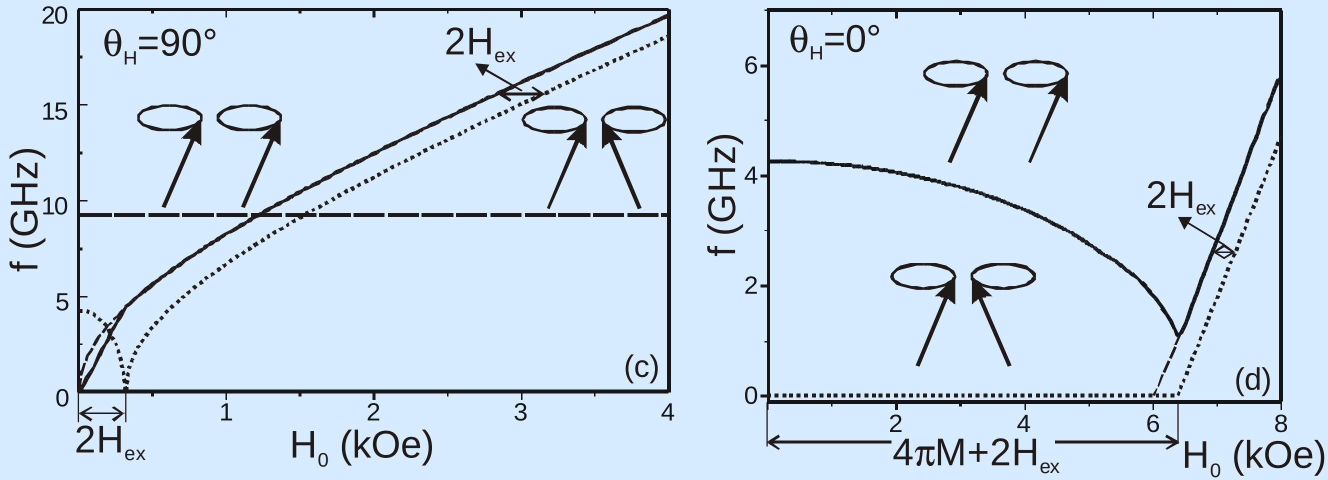


J. Lindner, K. B. Topical Rev., J. Phys. Condens. Matter **15**, R193-R232 (2003)

Ferromagnetically coupled system



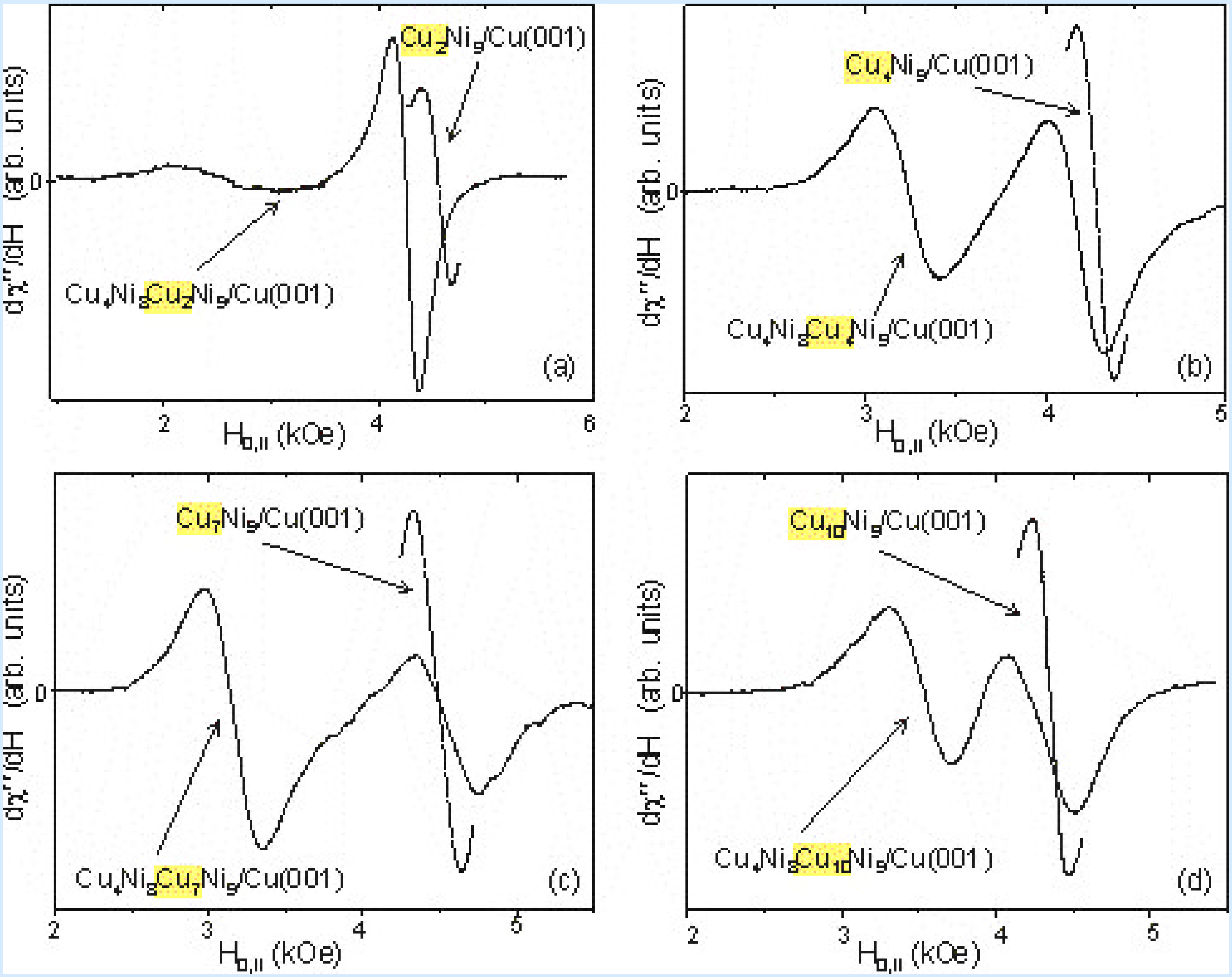
Antiferromagnetically coupled system



in-situ UHV-FMR measures FM **and** AFM

and determines J_{inter} **in absolute units**, e.g. μeV/atom

in-situ UHV-FMR



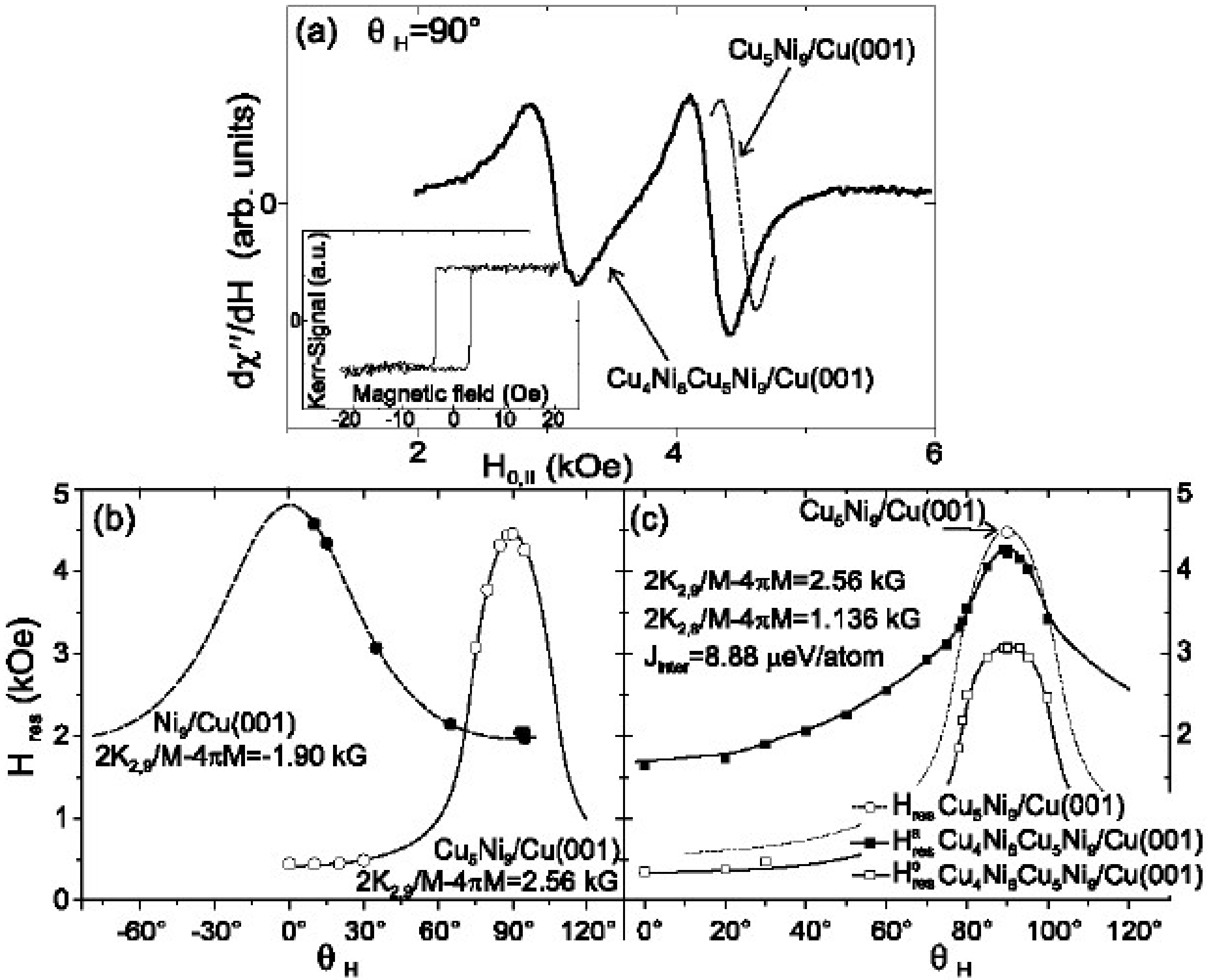
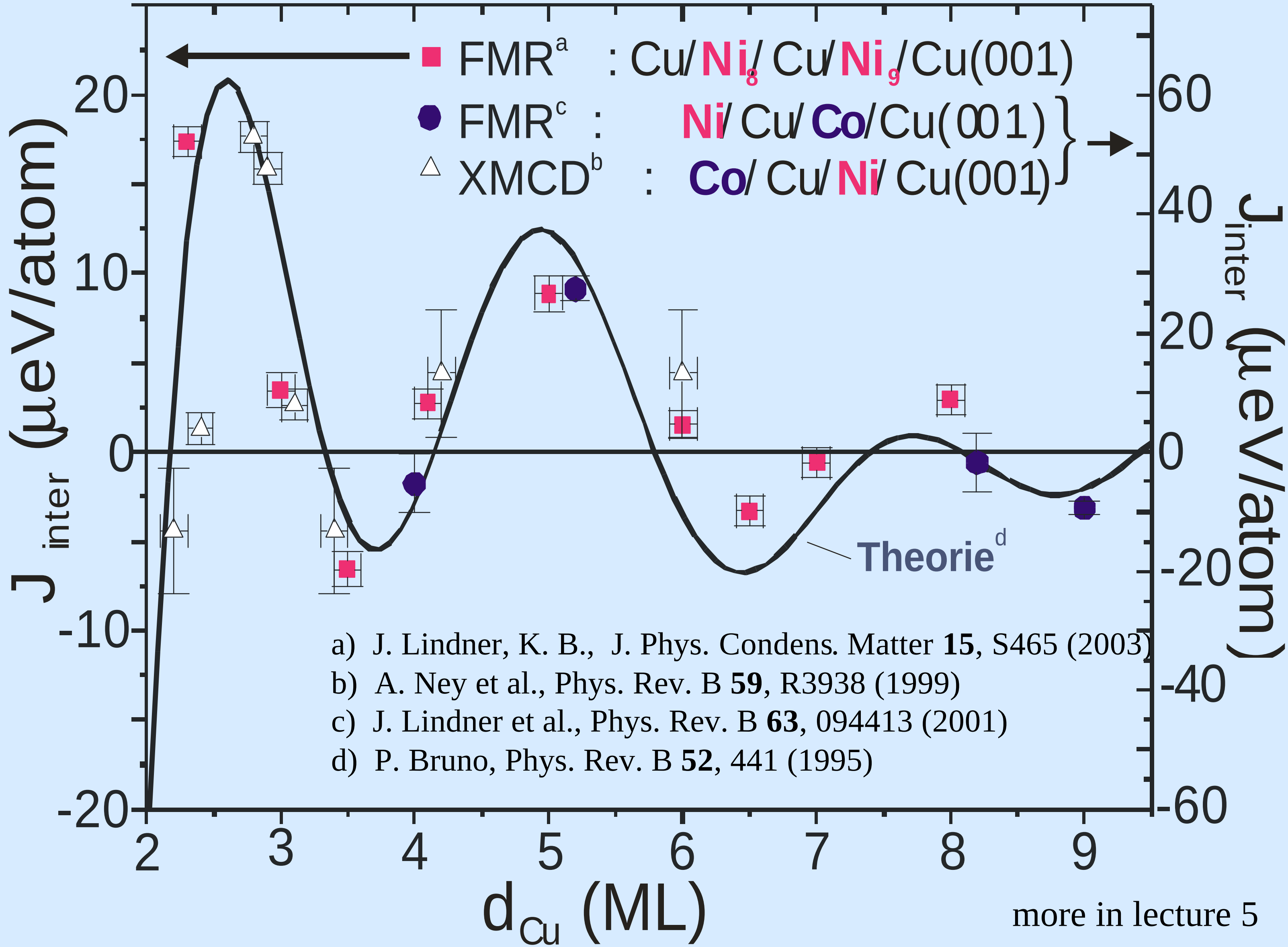
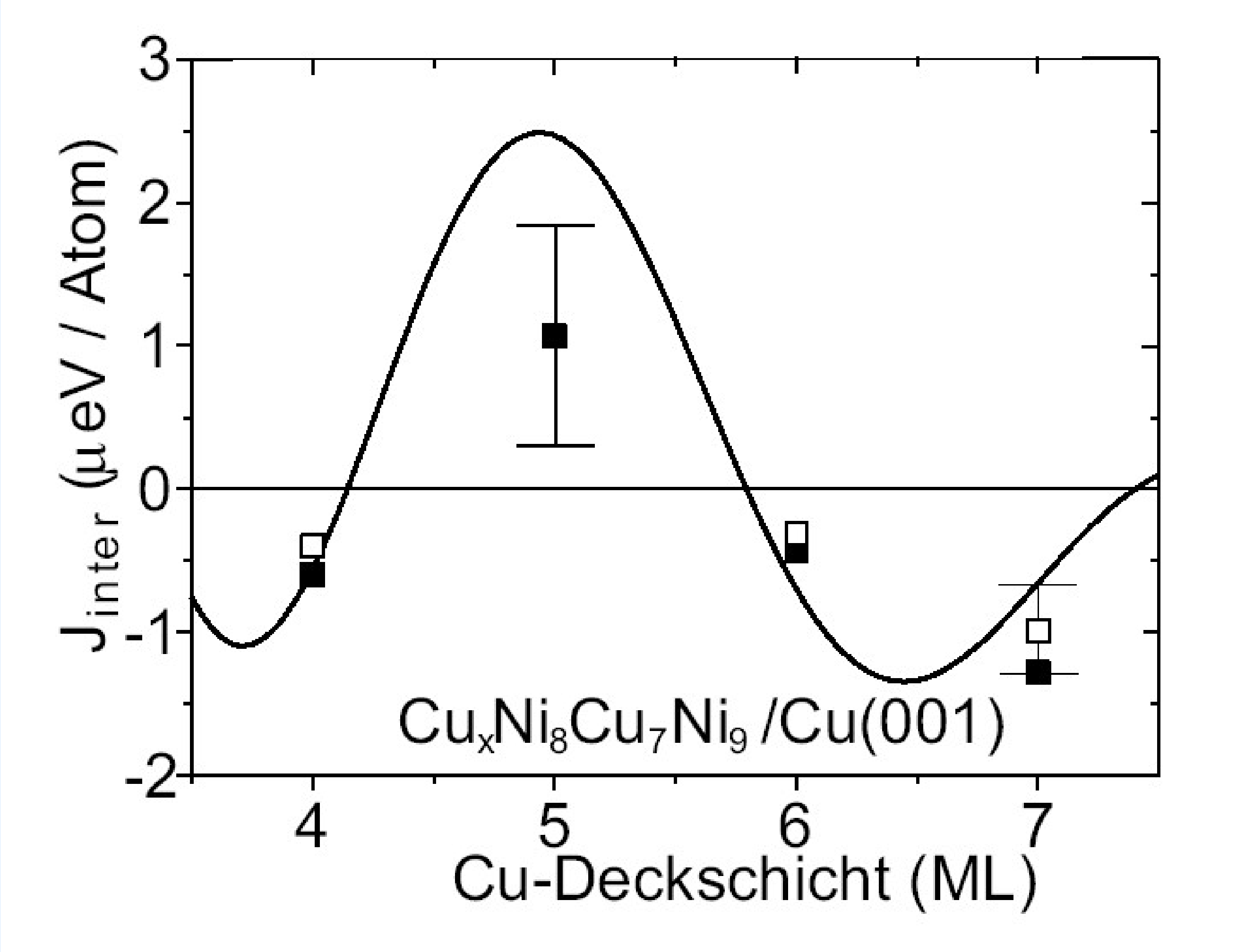


Figure 2. (a) FMR spectra for Cu_5Ni_9/Cu(001) before (dashed curve) and after depositing the topmost Cu_4Ni_8 layers. (b) Angular dependence for Cu_5Ni_9/Cu(001) with (solid curve) and without (dashed curve) a Cu cap layer. (c) Angular dependence measured for optical (open squares) and acoustical (solid squares) modes in the $Cu_4Ni_8Cu_5Ni_9$/Cu(001) trilayer. The dashed curve is the same dependence shown in (b) for the Cu-capped bottom film only.



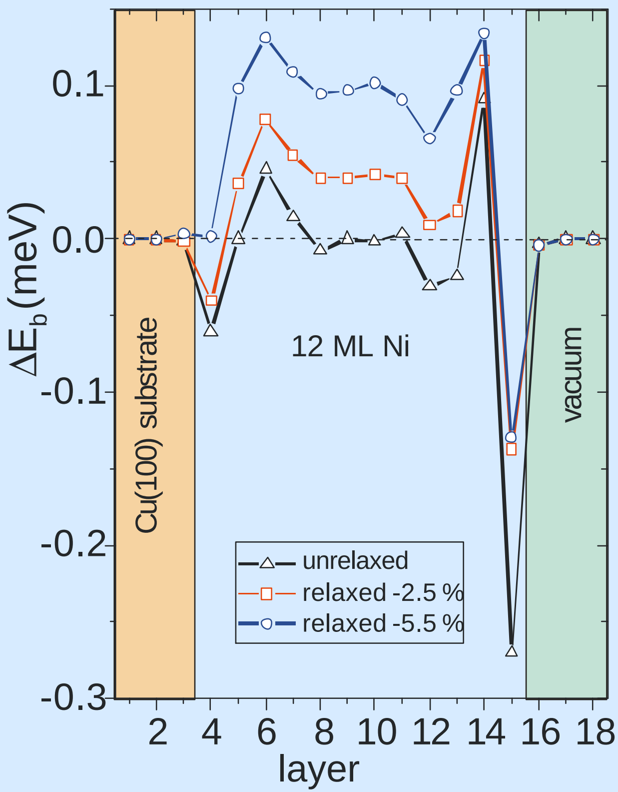
a) J. Lindner, K. B., J. Phys. Condens. Matter **15**, S465 (2003)
b) A. Ney et al., Phys. Rev. B **59**, R3938 (1999)
c) J. Lindner et al., Phys. Rev. B **63**, 094413 (2001)
d) P. Bruno, Phys. Rev. B **52**, 441 (1995)

more in lecture 5


3
2
1
0
-1
-2
J_{inter} (μeV / Atom)
$Cu_xNi_8Cu_7Ni_9$ /Cu(001)
4
5
6
7
Cu-Deckschicht (ML)

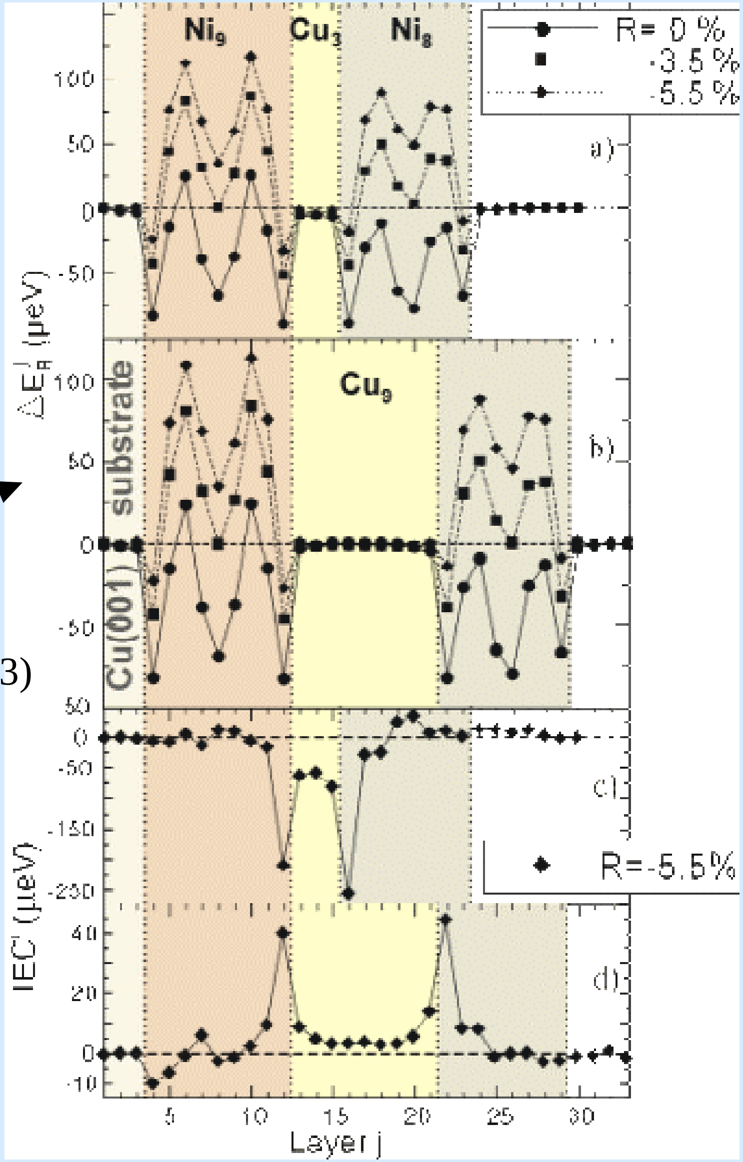
SP-KKR calculation for rigit fcc and relaxed fct structures

layer resolved $\Delta E_b = \Sigma K_i$ at T=0



C. Uiberacker et al., PRL **82**, 1289 (1999)

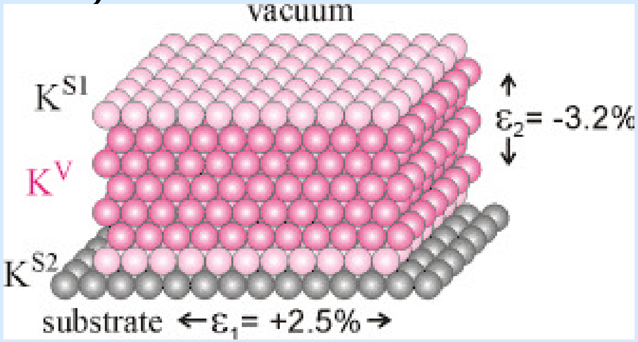
R. Hammerling et al., PRB **68**, 092406 (2003)



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.

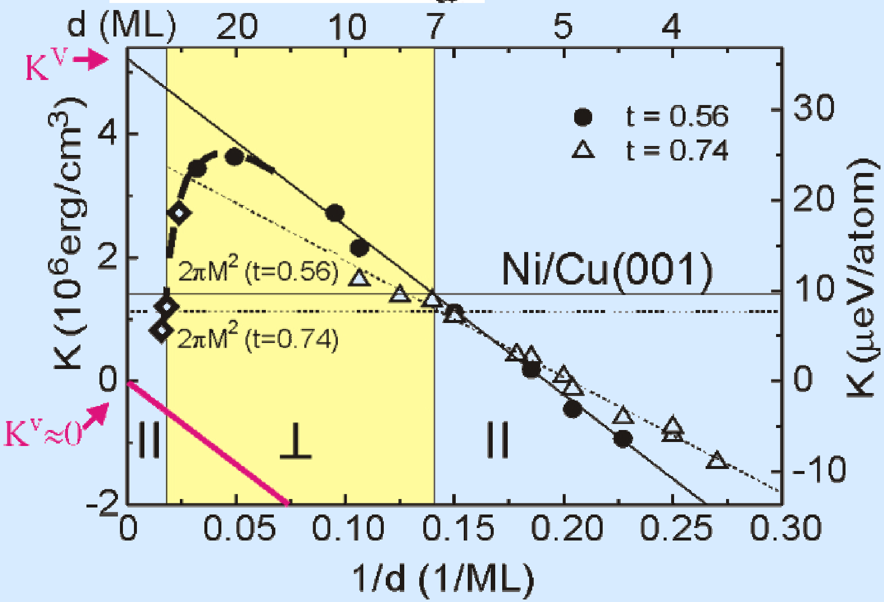
Full trilayer grows in fct structure

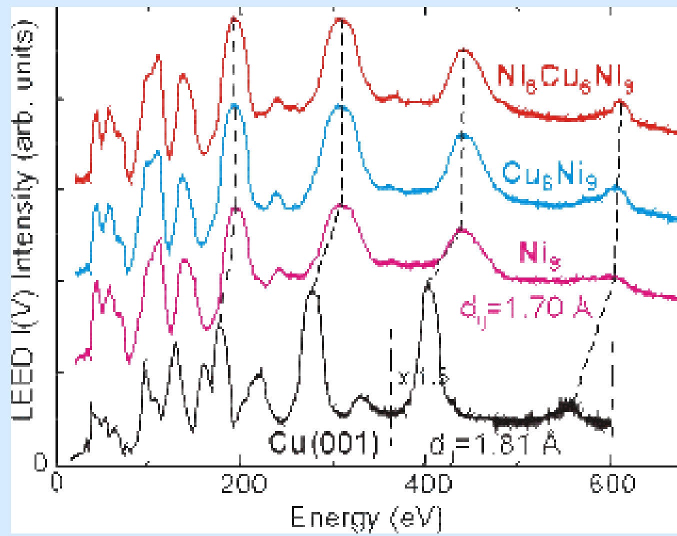
“volume”, “surface” and “interface” MAE



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

t=T/T$_C$(d)





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

4b Interlayer exchange coupling (IEC)

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 macroscopic 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} ® á J ñ

Conclusion: **IEC µ J_{inter}**
but necessarily not identical

Temperature dependence of J_{inter} Û D free energy

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

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

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

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

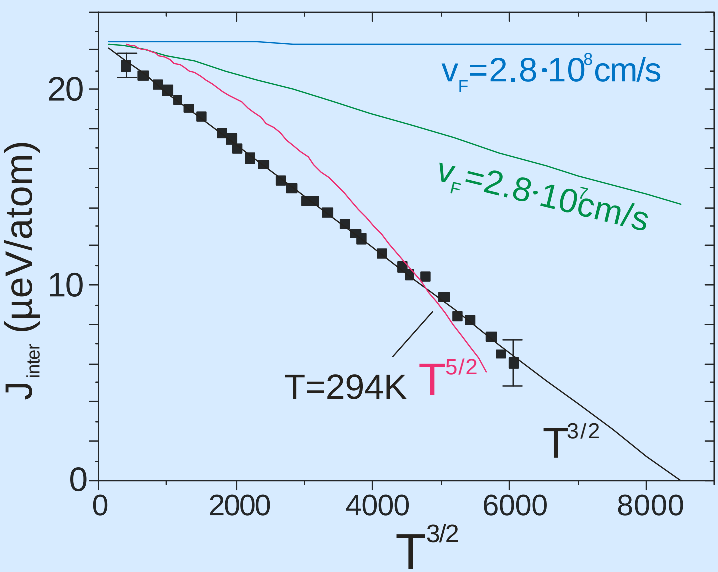
$Ni_7Cu_9Co_2$/Cu(001)

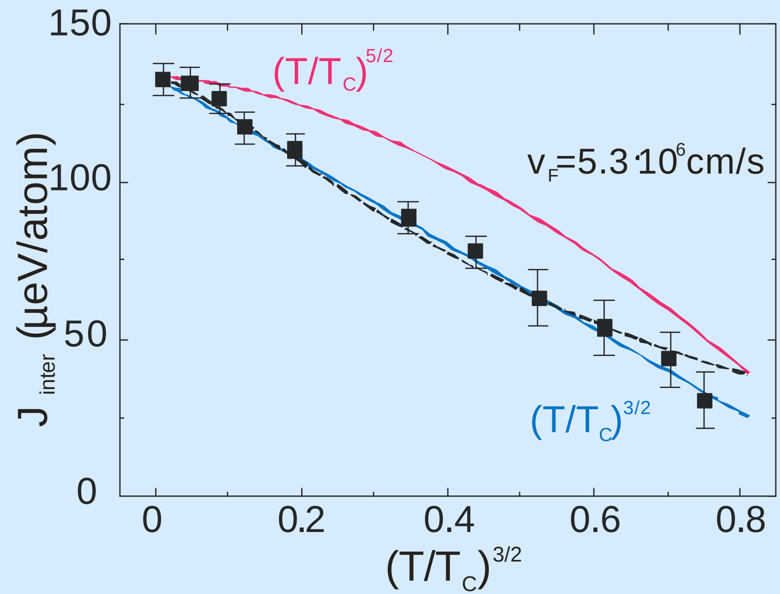
T=55K - 332K

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

$(Fe_2V_5)_{50}$

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





VOLUME 73, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JULY 1994

Using Ferromagnetic Resonance as a Sensitive Method to Study Temperature Dependence of Interlayer Exchange Coupling

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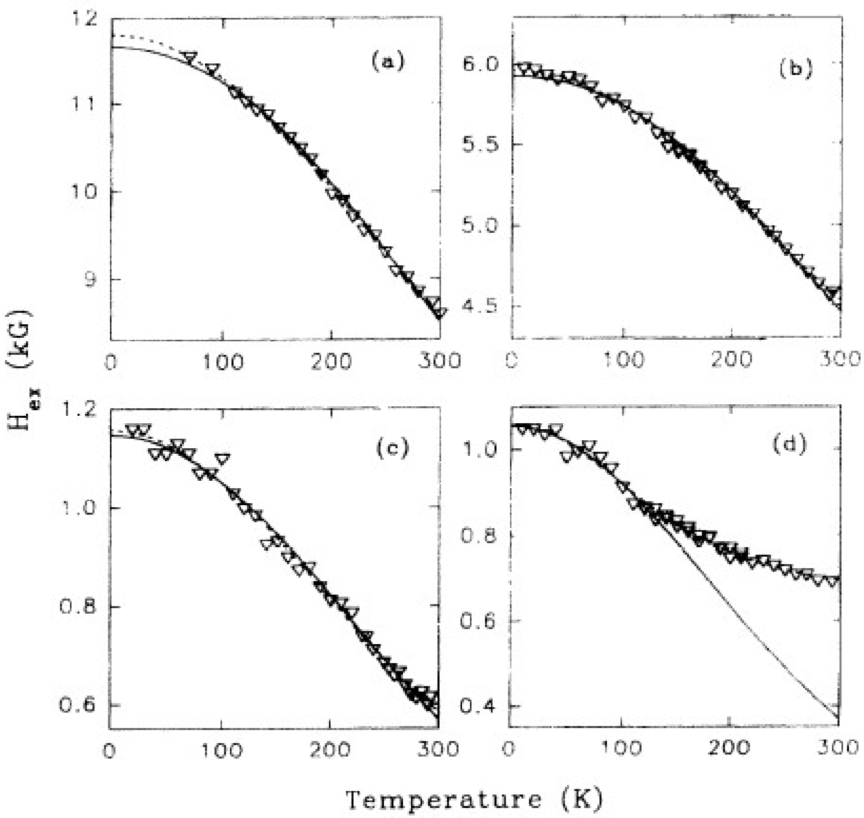


FIG. 4. The exchange field H_{ex} as a function of temperature for various Co(32 Å)/Ru(t_{Ru})/Co(32 Å) structures with t_{Ru} = 9 Å (a), 10 Å (b), 20 Å (c), and 24 Å (d), respectively. The solid lines are best fits using $H_{ex} = H_{ex}^0 (T/T_0)/\sinh(T/T_0)$ (theoretical model) and the broken lines are best fits using $H_{ex} = H_{ex}^0 (T/T_0)/\sinh(T/T_0) + H_{ex}^{\infty}$ (modified theoretical model) with the parameters listed in Table I.

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

S. Schwieger and W. Nolting PRB **69**, 224413 (2004)

(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 ϕ_σ 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_σ[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

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

contributes to the temperature dependence of the IEC.

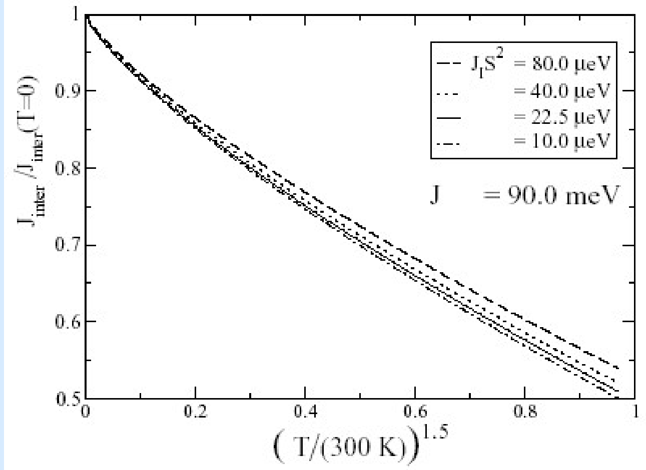


FIG. 3: Temperature dependent factor of $J_{\rm inter}$ plotted against temperature for different zero temperature couplings $J_I S^2$

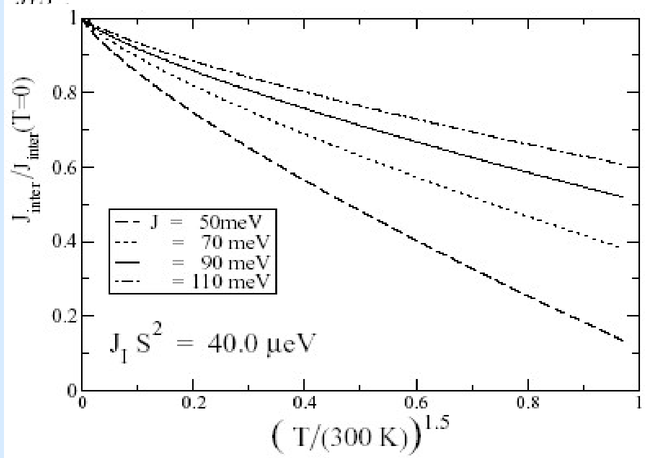
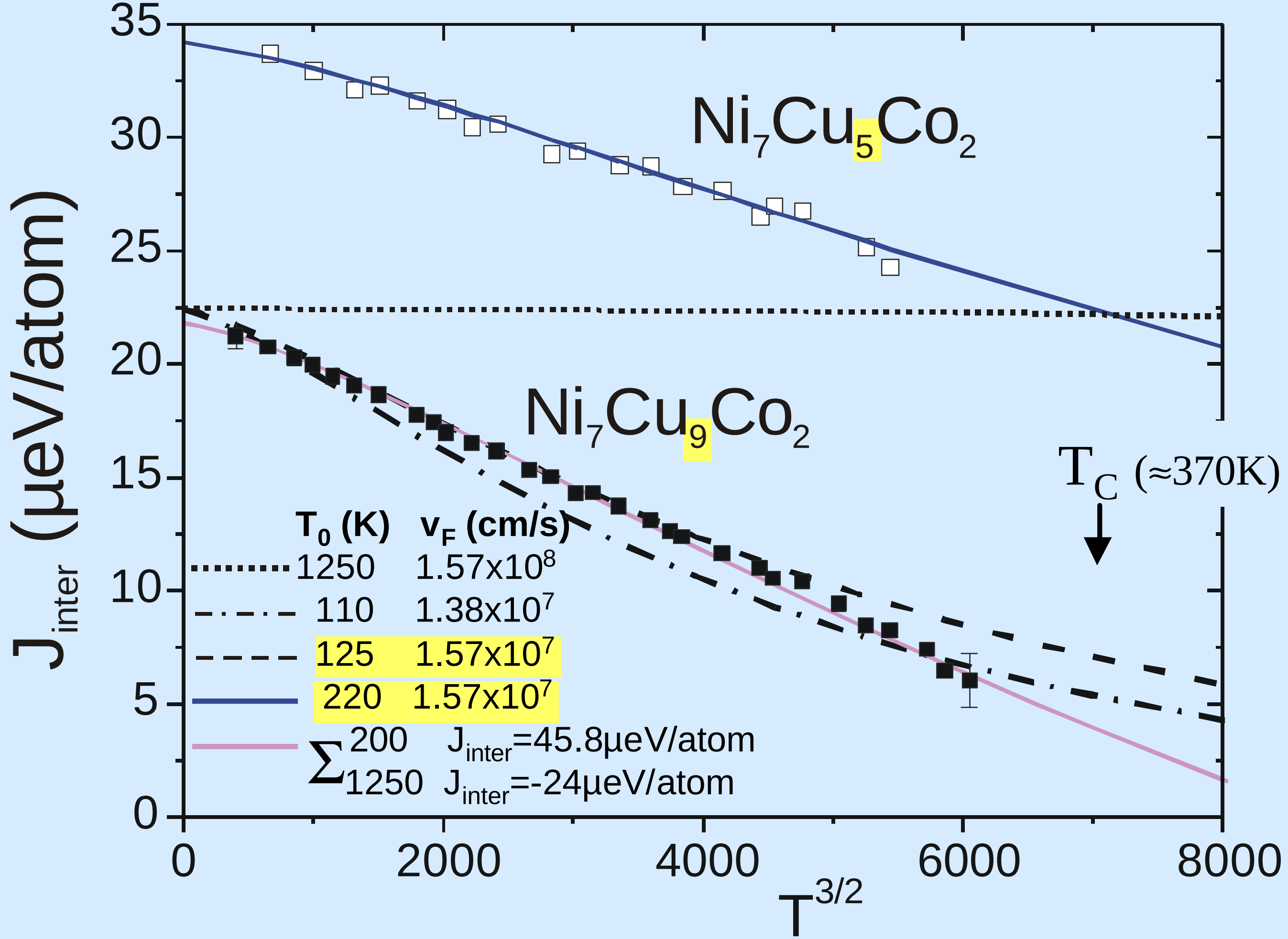


FIG. 4: Temperature dependent factor of $J_{\rm inter}$ plotted against temperature for different intra-layer couplings J

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



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

K. Lenz et al. unpublished

PHYSICAL REVIEW B **71**, 174441 (2005)

Temperature dependence of interlayer exchange coupling: Spin waves versus spacer effects

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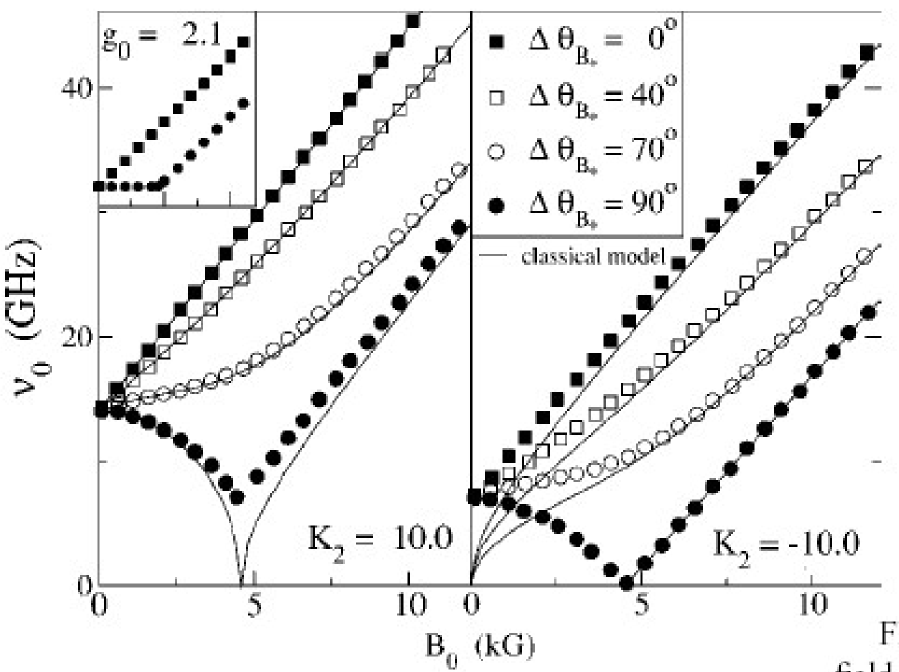

FIG. 1. The resonance frequency as a function of the external field at $T=0$ for different angles between the easy direction and the external field $\Delta\theta_{B_0}$ (symbols). Left panel: positive lattice anisotropy $K_2=10\mu_B$ kG, right panel: negative lattice anisotropy $K_2=-10\mu_B$ kG, inset: dipolar coupling $g_0=2.1\mu_B$ kG. Here and in the following pictures the spin quantum number is set to unity ($S=1$). The results of the classical model are also shown (solid lines).

Summary

1. Trilayer is a prototype to study multilayer coupling
2. UHV-FMR is a useful method to measure *in situ* MAE and IEC in trilayer - step by step
3. Both parameter are measured in absolute energy units (e.g. eV/atom) for the FM and the AFM coupling
4. The IEC energy is a T-dependent quantity, vanishing at T_C. Note when comparing with T=0 calculations
5. The linewidth of optical and acoustical modes will be discussed again in lecture 6