Lecture 6: Spin Dynamics

All kinds of resonance spectroscopies deliver (at least) 3 informations:

1. **The resonance position**
2. **The width of the resonance (and its shape)**
3. **The area under the resonance**

From Para- and Ferromagnetic Resonance (EPR, FMR) we get:

1. **The anisotropy field (K/M, 4pM), g-tensor =>** lecture 2
2. **Relaxation rate =>** this lecture
3. **Magnetization**

Local moment ESR in superconductors

SOVIET PHYSICS – SOLID STATE VOL. 14, NO. 1 JULY, 1972

OBSERVATION OF ELECTRON SPIN RESONANCE IN A TYPE-II SUPERCONDUCTOR

T. S. Al'tshuler, I. A. Garifullin, and É. G. Kharakhash'yan

Kazan' Physicotechnical Institute, Academy of Sciences of the USSR
Translated from Fizika Tverdogo Tela, Vol. 14, No. 1, pp. 263–264, January, 1972
Original article submitted July 26, 1971

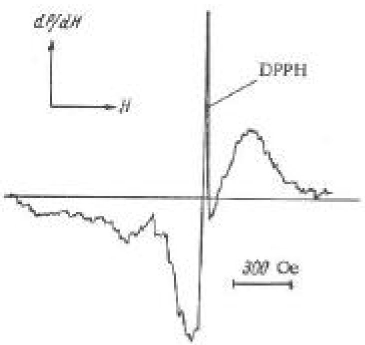


Fig. 1. ESR spectrum of a sample of $La_{2.99}Gd_{0.01}In$ recorded together with the signal of diphenyl picryl hydrazyl at 9320 MHz at 4.2°K.

LECTRON RESONANCE WITH LOCALIZED MAGNETIC MOMENTS OF Er in SUPERCONDUCTING La

N. E. Alekseevskii, I. A. Garufullin, B. I. Kochelaev, and E. G. Kharakhash'yan
Kazan' Physico-technical Institute, USSR Academy of Sciences
Submitted 1 August 1973
ZhETF Pis. Red. 18, NO. 5, 323 – 326 (5 September 1973)

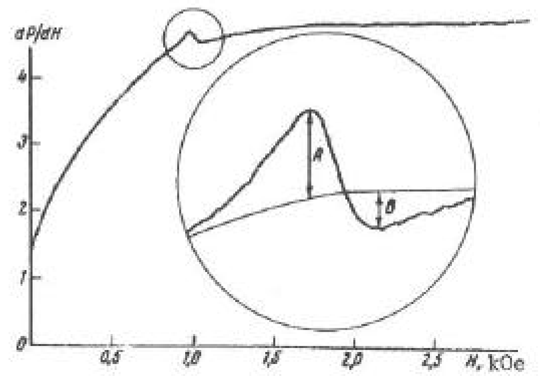


Fig. 1. Plot of EPR signal (dP/dH in relative units) for a sample of La + 1.5 at.% Er at T = 2.5°K and ν = 9369.4 MHz.

Solid State Communications **12**, 977 (1973)

LOCAL MOMENT SPIN RESONANCE IN A SUPERCONDUCTOR

U. Engel, K. Baberschke, G. Koopmann and S. Hüfner

IV, Physikalisches Institut, Freie Universität, Berlin, Germany

and

M. Wilhelm

Forschungslaboratorium der Siemens AG, Erlangen, Germany

(*Received* 14 *February* 1973 *by B. Mühlschlegel*)

The ESR of Gd in $CeRu_2$ and $LaRu_2$ has been observed in the normal and superconducting state. The temperature dependence of the linewidth in the superconducting state follows a trend expected from NMR measurements in superconductors.

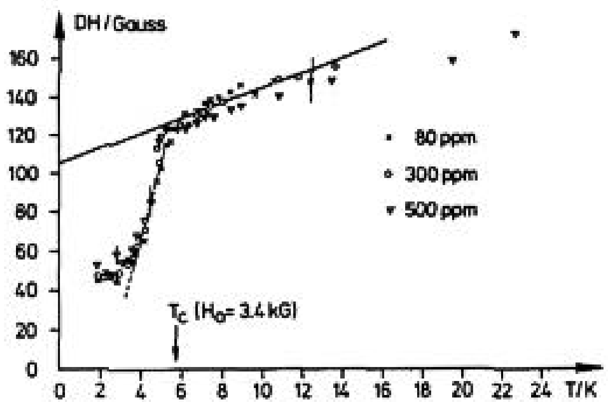


FIG. 1. Temperature dependence of the linewidth *DH* (*for a definition see reference 1*) *in Gd:CeRu*$_2$ *at X*-band frequencies; concentrations are given in the figure.

VOLUME 30, NUMBER 10 PHYSICAL REVIEW LETTERS 5 MARCH 1973

Magnetic Resonance of a Localized Magnetic Moment in the Superconducting State: $LaRu_2$:Gd†*

C. Rettori,‡ D. Davidov,§ P. Chaikin, and R. Orbach

Department of Physics, University of California, Los Angeles, California 90024

(Received 15 January 1973)

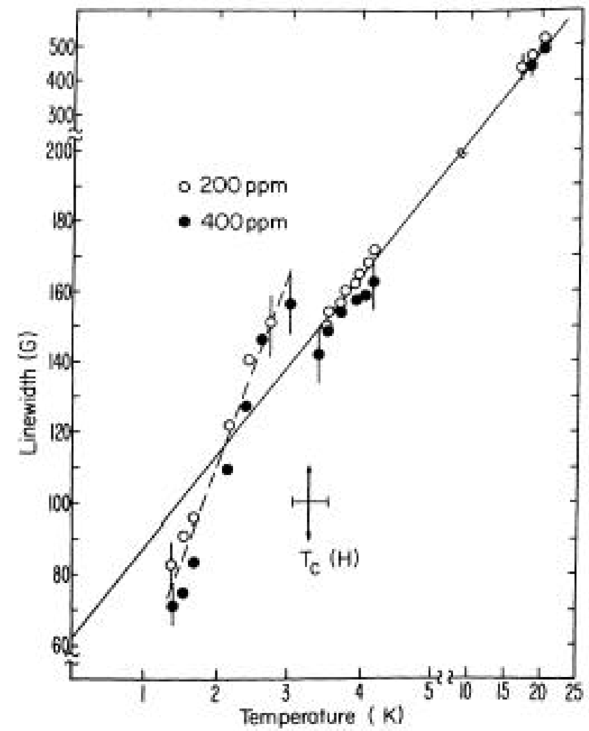
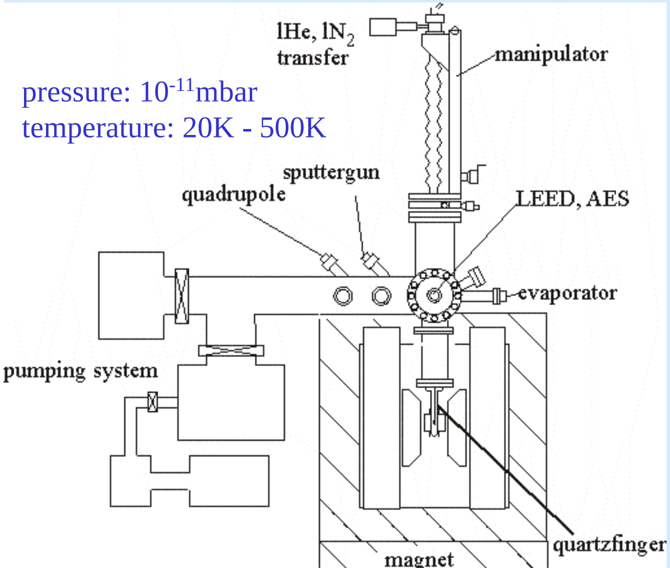


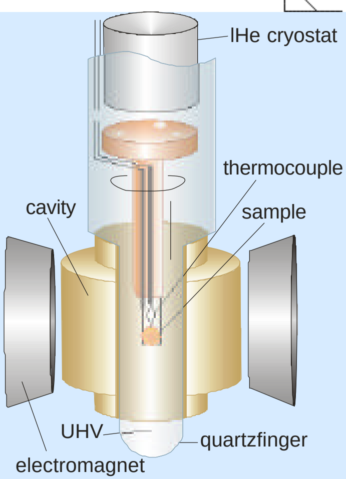
FIG. 1. Linewidth as a function of temperature for two $LaRu_2$:Gd samples. The 200-ppm sample was measured in the form of a powder; 400-ppm, in the form of a ball. The value of $T_c(H)$ is shown. Solid line, fit to our data in the normal state; dashed line, in the superconducting state.

FMR in ferromagnetic nanostructure

In situ UHV-FMR set up

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





VOLUME 58, NUMBER 5 PHYSICAL REVIEW LETTERS 2 FEBRUARY 1987

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

M. Farle and K. Baberschke

Institut für Atom- und Festkörperphysik, Freie Universität Berlin, D-1000 Berlin 33, Federal Republic of Germany
(Received 18 September 1986)

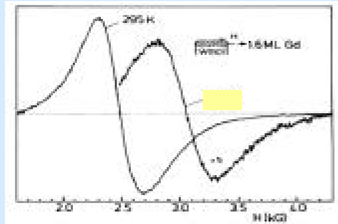


Fig. 4. ESR spectra for the new 1.6 ML sample (not cited in [2, 3]). Note the significant change in intensity and resonance field from 16 to 39 K above T_c

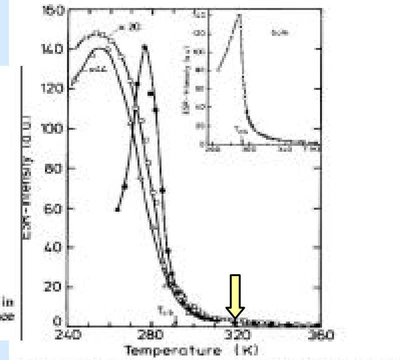
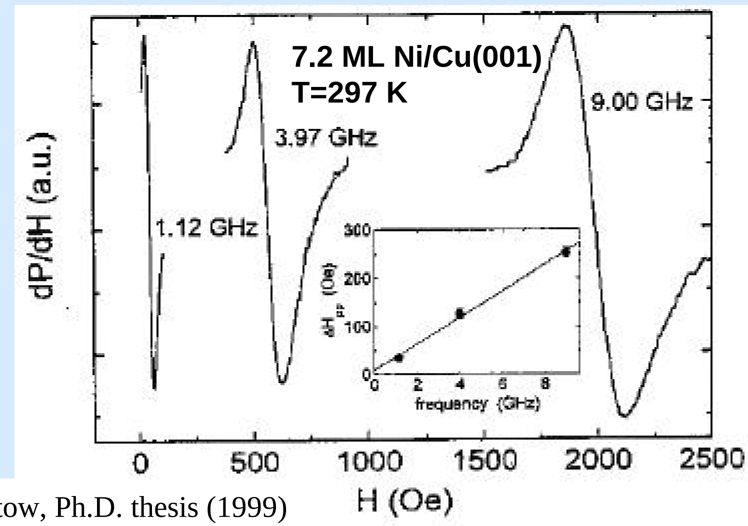


Fig. 5. Area of the ESR signal as a function of temperature for 80 Å (●), the new 1.6 ML (□), and the 0.8 ML (△). The insert shows the same data for a 18 μm thick Gd foil (bulk). Solid lines are guides to the eye. The 1.6 and 0.8 ML have a vertical gain factor of 20 and 44 with respect to 80 Å. The insert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

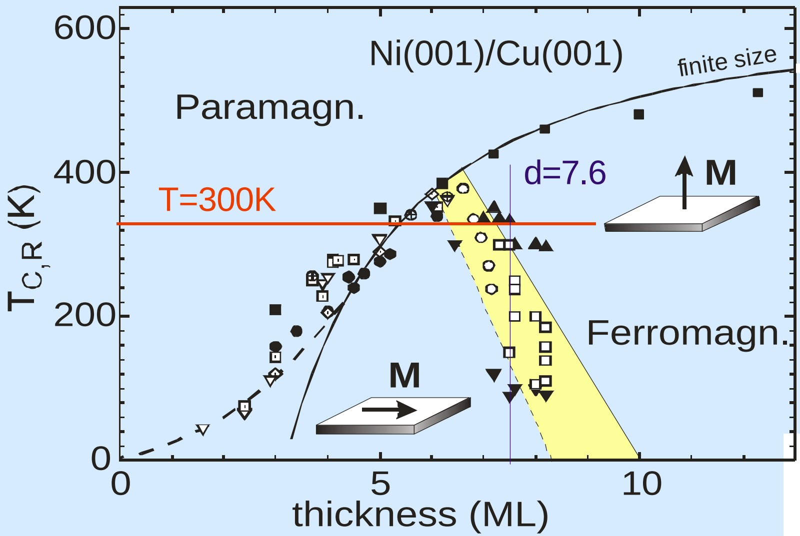
M. Zomak et al.,
Surf. Sci. **178**, 618 (1986)

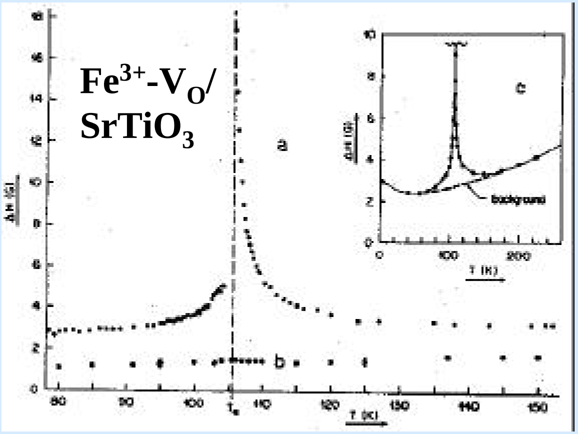
J. Lindner, K.B.
J. Phys.: Cond. Matt **15**, R193 (2003)



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

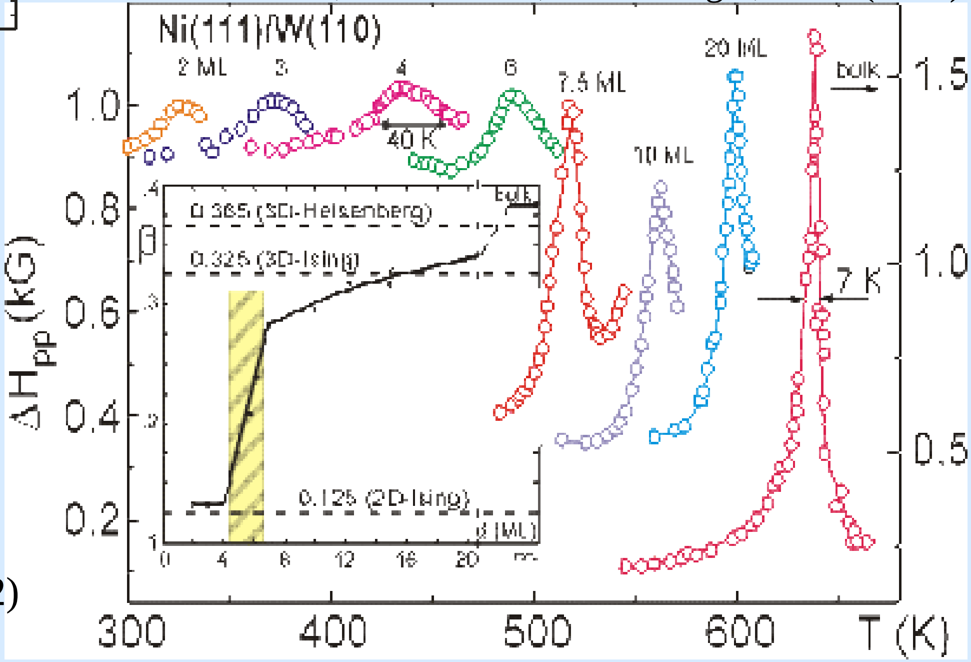
For thin films the Curie temperature can be manipulated





Th.v. Waldkirch, K.A. Müller, W. Berlinger, PRB (1973)

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



Yi Li, K. B., PRL **68**, 1208 (1992)

Thermodynamics of thin ferromagnetic films in …

R.P. Erickson & D.L. Mills PRB **44**, 11825 (91)

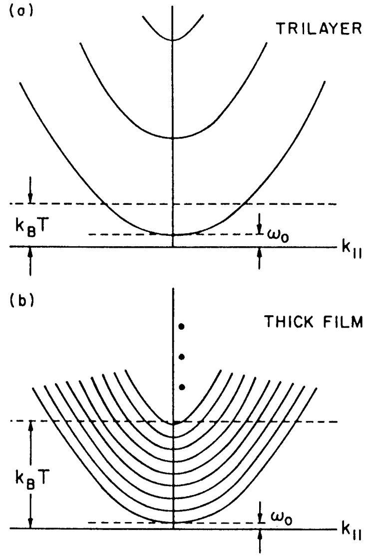


FIG. 4. Depicted are (a) the spin-wave normal modes of a trilayer, sketched at room temperature, and (b) the spin-wave "minibands" in a thick layer.

Spin wave branches = $\omega_0 + \frac{1}{2} D\{k_{II}^2 + [\frac{\pi}{Nd}]^2\}$

"A criterion for a crossover from quasi 2D to 3D is…"

$$N_C = \sqrt{\frac{\hbar D}{kT}} \cdot \frac{\pi}{d}$$

D: stiffness const.

Ni: $\hbar D \approx 4{\cdot}10^{-1}$ eVÅ^2 ; d= 2.03Å

T = 300 ~ 500 K $\Rightarrow$ $N_C \approx 6 - 5$ layers

STAN4

6a Magnon-magnon scattering and Gilbert damping

1834 IEEE TRANSACTIONS ON MAGNETICS, VOL. 34, NO. 4, JULY 1998

THEORY OF THE MAGNETIC DAMPING CONSTANT

Harry Suhl
Department of Physics, and Center for Magnetic Recording Research, Mail Code 0319,
University of California-San Diego, La Jolla, CA 92093-0319.

Abstract—The aim of this paper is to express the effects of basic dissipative mechanisms involved in the dynamics of the magnetization field in terms of the one most commonly observed quantity: the spatial average of that field. The mechanisms may be roughly divided into direct relaxation to the lattice, and indirect relaxation via excitation of many magnetic modes. Two illustrative examples of these categories are treated; direct relaxation via magnetostriction into a lattice of known elastic constant, and relaxation into synchronous spin waves brought about by imperfections. Finally, a somewhat speculative account is presented of time constants to be expected in magnetization reversal.

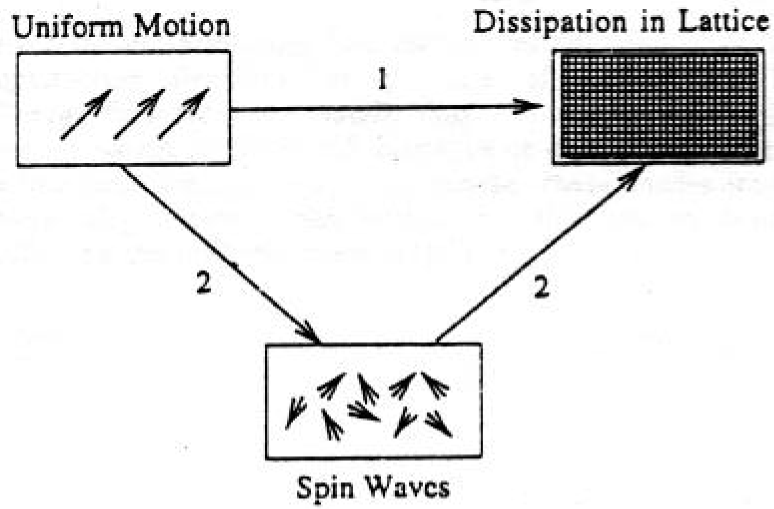
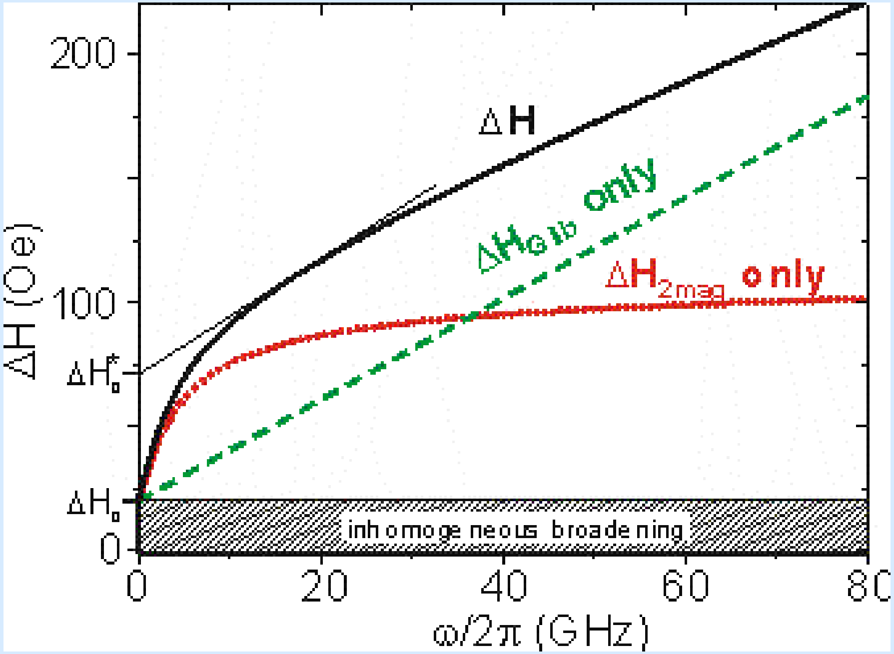


Figure 1. Two paths for degradation of uniform motion: 1) Direct relaxation to the lattice; 2) Decay into non-uniform motions, which in turn decay to the lattice.

Landau-Lifshitz-Gilbert equation

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

viscous damping, energy dissipation



- **Gilbert damping contribution:**
  linear in frequency

$$\Delta H_{\mathrm{Gilbert}}(w) = \frac{2}{\sqrt{3}}\frac{G}{g^2 M_S} w$$

$$a = \frac{G}{g M_S}$$

- **Two-magnon scattering:**
  degenerate states created by dipole-dipole interaction due to surface defects
  non-linear frequency dependence

$$\Delta H_{2-\mathrm{magnon}}(w) = \Gamma \arcsin\sqrt{\frac{\sqrt{w^2+(w_0/2)^2}-w_0/2}{\sqrt{w^2+(w_0/2)^2}+w_0/2}}$$

*R. Arias et al., PRB **60**, 7395 (1999)*

$\omega_0 = \gamma M_{eff}$

FMR Linewidth - Damping

Landau-Lifshitz-Gilbert-Equation

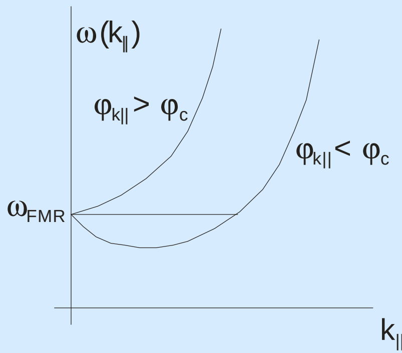
$$\frac{1}{\gamma}\frac{\partial M}{\partial t} = -(M\times H_{eff}) + \frac{G}{\gamma M_S^2}\left(M\times\frac{\partial M}{\partial t}\right)$$

Gilbert-damping ~ω

$$\Delta H^{Gil}(\omega) = \frac{G}{\gamma^2 M_S}\,\omega$$

2-magnon-scattering

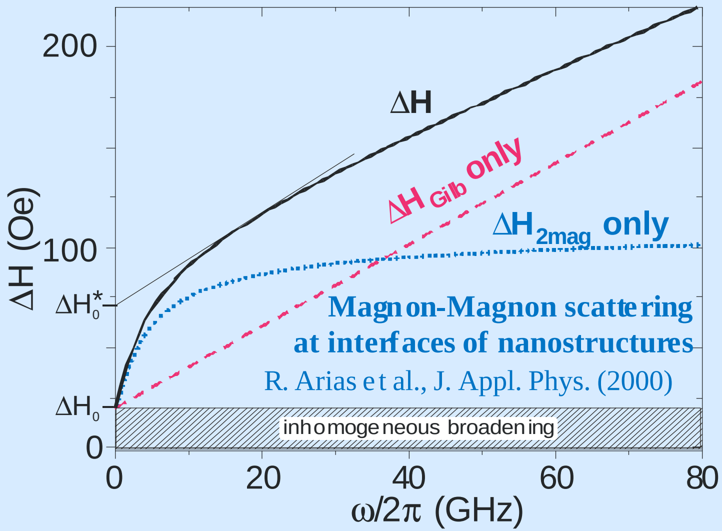
R. Arias, and D.L. Mills, *Phys. Rev. B* **60**, *7395 (1999);*
D.L. Mills and S.M. Rezende in
'Spin Dynamics in Confined Magnetic Structures',
edt. by B. Hillebrands and K. Ounadjela, Springer Verlag

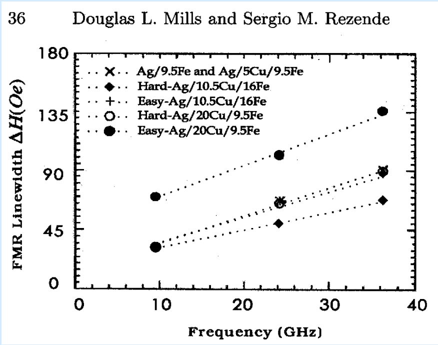


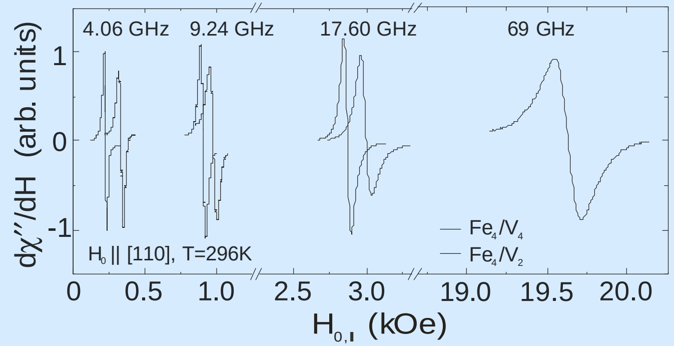
$$\Delta H^{2Mag}(\omega) = \Gamma \arcsin\sqrt{\frac{[\omega^2+(\omega_0/2)^2]^{1/2} - \omega_0/2}{[\omega^2+(\omega_0/2)^2]^{1/2} + \omega_0/2}}$$

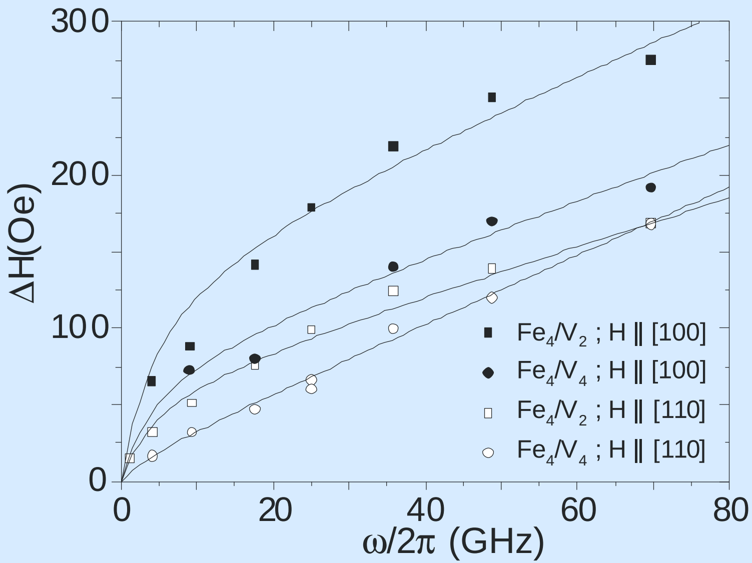
$\omega_0 = \gamma(2K_{2\perp} - 4\pi M_S)$, $\gamma=(\mu_B/h)g$
$K_{2\perp}$ - uniaxial anisotropy constant
M_S - saturation magnetization

‘Non-Gilbert-Type’ spin-wave damping







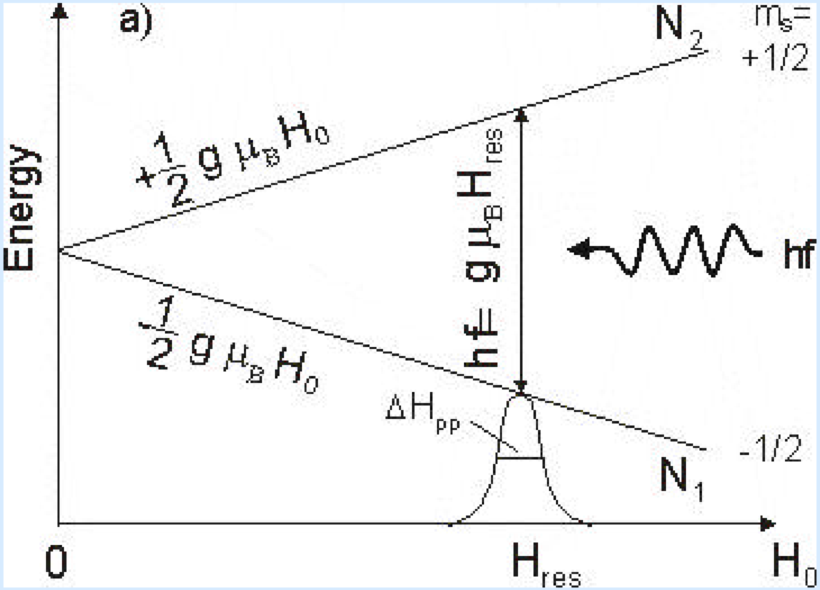


J. Lindner et al. Phys. Rev. B **68**, 060102(R) (2003)

CA 03 / 9

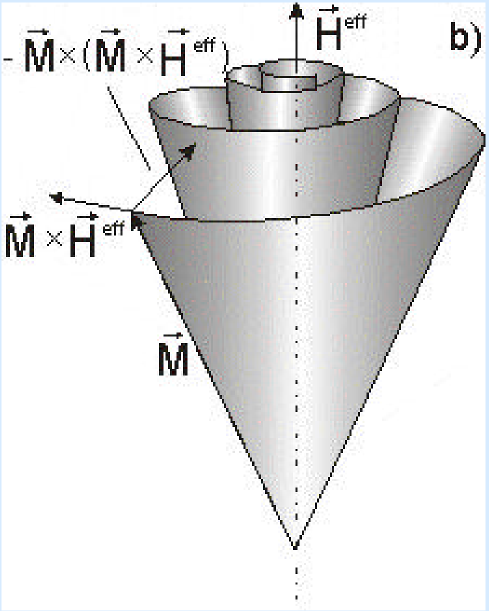
Linewidth in magnetic resonance

ESR



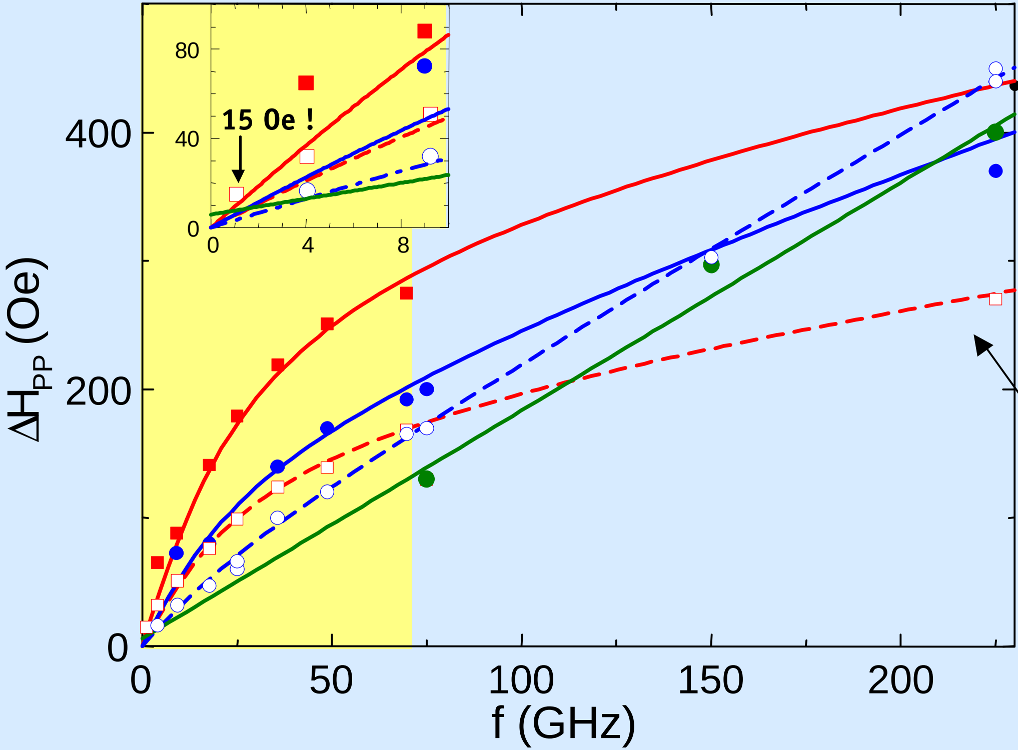
T_1 = long. relaxation, spin-phonon
T_2 = transv. relaxation

FMR



Landau-Lifshitz-Gilbert equation

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



two-magnon scattering observed in Fe/V superlattices – interface defects

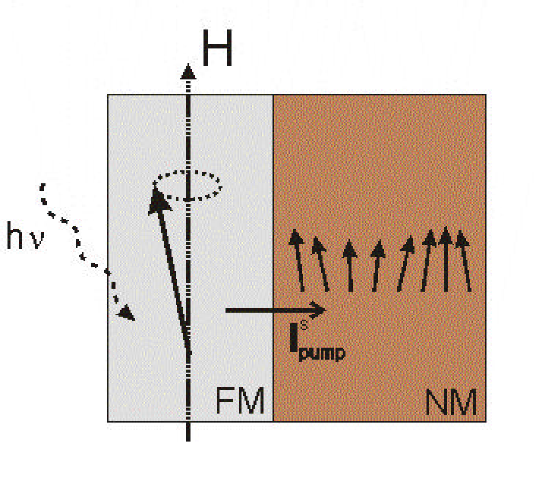
*J. Lindner et al., PRB **68**, 060102(R) (2003)*

HF FMR *A. Janossy et al.*
Budapest Univ. of Technology and Econ.

	Γ (kOe)	γ·Γ (10^8 s^{-1})	G (10^8 s^{-1})	α (10^{-3})	ΔH_0 (Oe)
■ Fe_4V_2 ; H||[100]	0.270	50.0	0.26	1.26	0
● Fe_4V_4 ; H||[100]	0.139	26.1	0.45	2.59	0
□ Fe_4V_2 ; H||[110]	0.150	27.9	0.22	1.06	0
○ Fe_4V_4 ; H||[110]	0.045	8.4	0.77	4.44	0
● Fe_4V_4 ; H||[001]	0	0	0.76	4.38	5.8

- **recent publications with similar results:**
  - Pd/Fe on GaAs(001) – network of misfit dislocations *G. Woltersdorf et al. PRB **69**, 184417 (2004)*
  - NiMnSb films on InGaAs/InP *B. Heinrich et al. JAP **95**, 7462 (2004)*

6b "Spin pump" effects,



s-d-exchange between spin wave and s-electron

R.H. Silsbee, A. Janossy, P. Monod, PRB **19**, 4382 (1979)

Y. Tserkovnyak, A. Brataas, G.E.W. Bauer, PRB **66**, 224403 (2002)

Landau-Lifshitz equation + extension

precession   Gilbert-damping   spin-pump current

$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = -\gamma\,\mathbf{M}\times\mathbf{H}_{\mathrm{eff}} + \frac{G}{\gamma M_S^2}\,\mathbf{M}\times\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} + \frac{\gamma}{M_S V}\,\mathbf{I}^{\mathrm{s}}_{\mathbf{pump}}$$

Precession drives spin current into NM

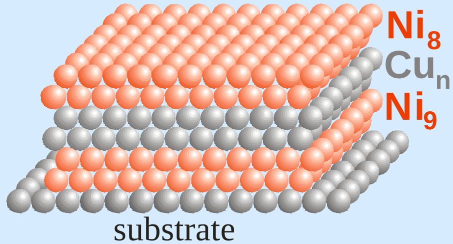
$$\mathbf{I}^{\mathrm{s}}_{\mathbf{pump}} = \frac{\hbar}{4\pi}\left(A_r\,\mathbf{M}\times\frac{\mathrm{d}\mathbf{M}}{dt} - A_i\,\frac{\mathrm{d}\mathbf{M}}{dt}\right)$$

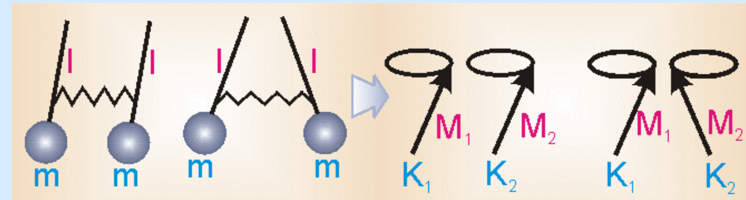
NM-substrate acts as spin-sink $\Rightarrow I^S_{back} = 0$

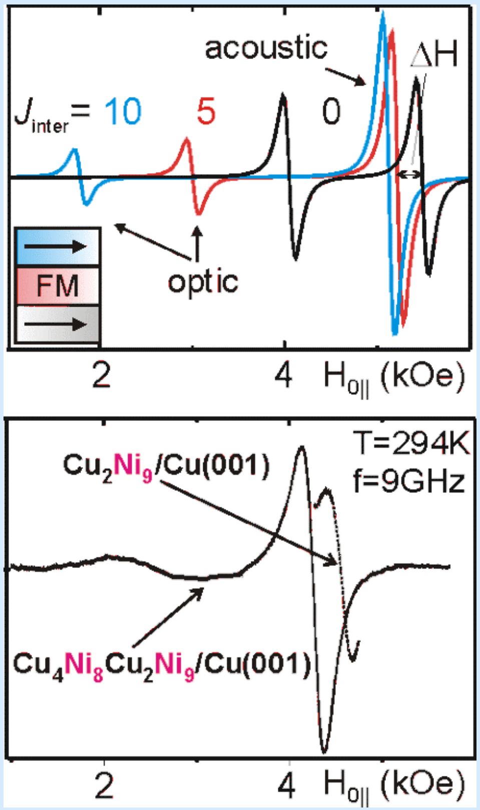
$\Rightarrow$ torque is carried away

$\Rightarrow$ Gilbert damping enhanced by spin-pump effect!

in-situ FMR in coupled films



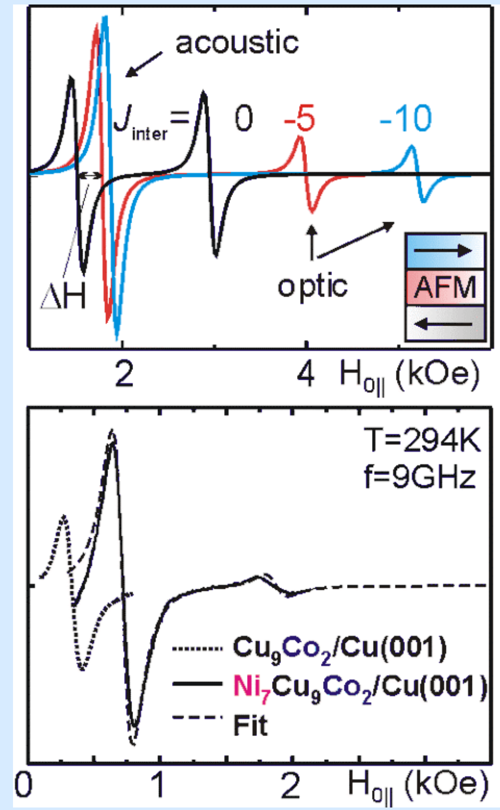




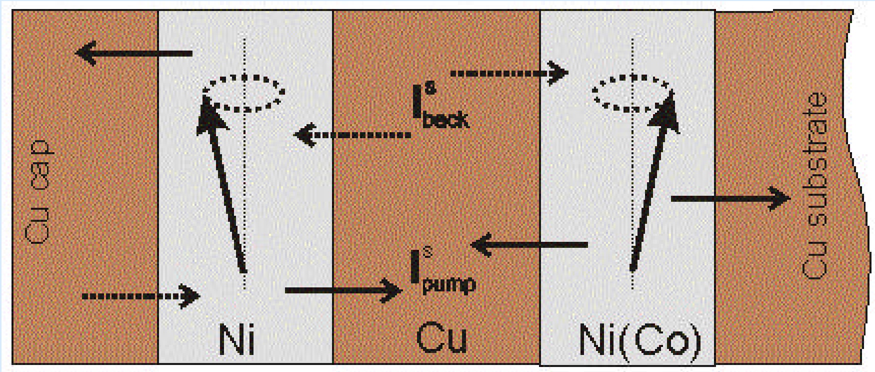
theory

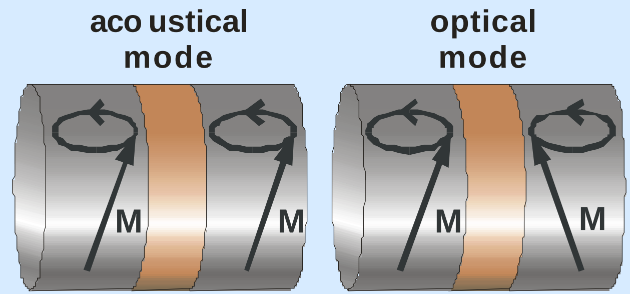
FMR

in-situ
UHV-experiment

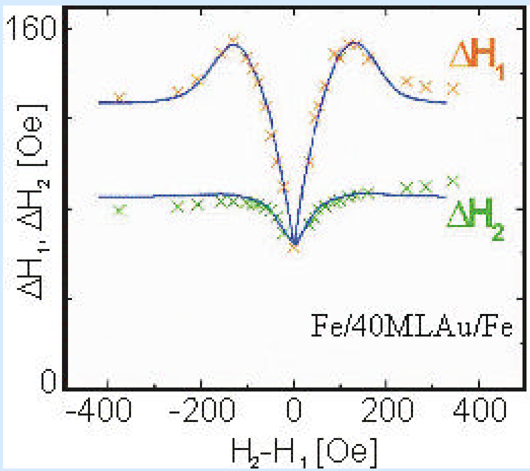


J. Lindner, K. B. Topical Rev., J. Phys. Condens. Matter **15**, R193-R232 (2003)





at „point of contact“ compensation of pumped currents decrease the linewidth



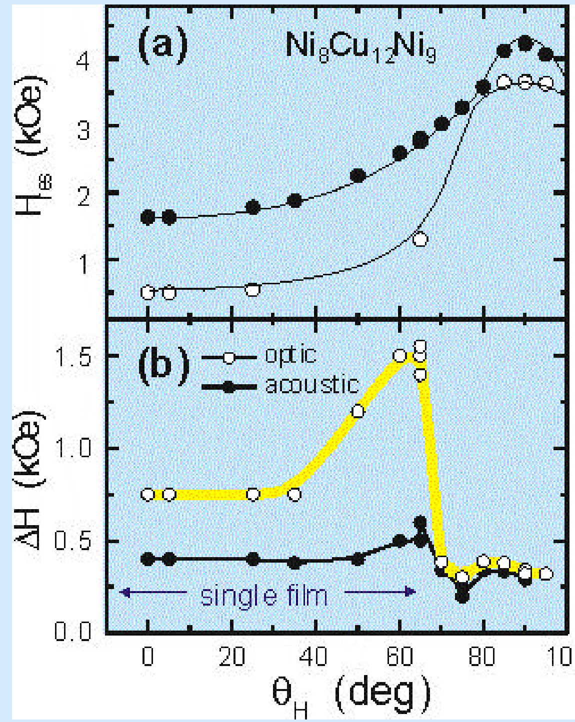
B. Heinrich et al., PRL **90**, 187601 (2003)

$d_{NM} \geq \lambda_{SF}$ $\Rightarrow$ no spin-accumulation $\Rightarrow$ $I^s_{back} = 0$

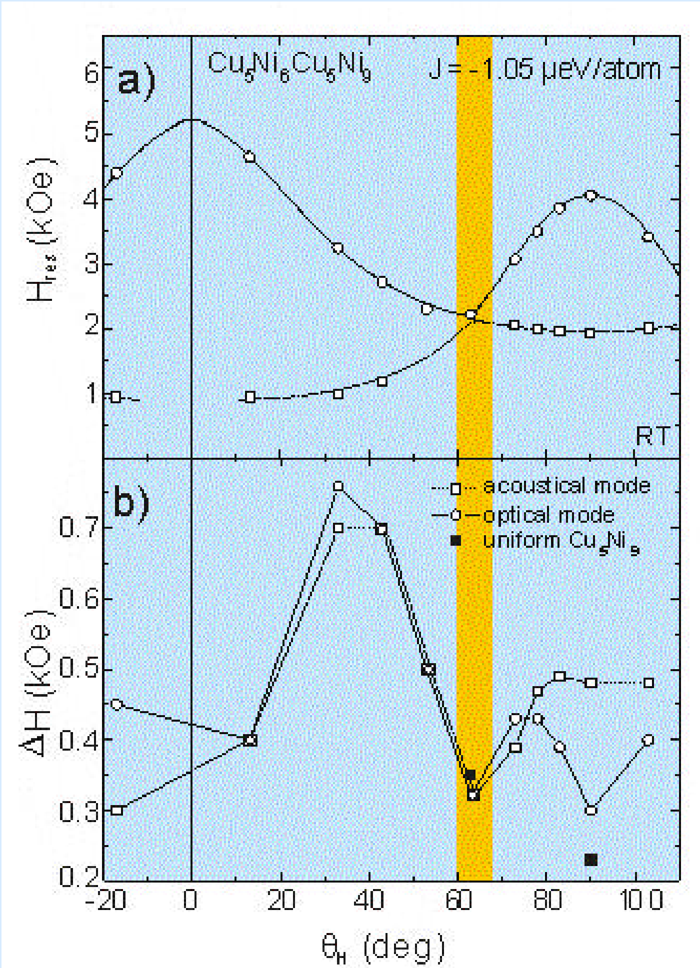
$\Rightarrow$ Gilbert-damping enhanced by spin-pump effect

compensation, if both films precess simultaneously (H_{res1}=H_{res2})

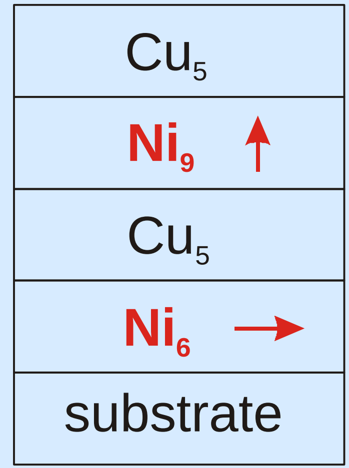
$\Rightarrow$ only Gilbert contribution remains!



K. Lenz et al.,
Phys. Rev. B **69**, 144422 (2004)



Trilayers with non-collinear easy axes



strong decrease in ΔH when $H^{ac} = H^{op}$

$\Delta H^{op} = \Delta H^{ac} < \Delta H^{uni}$

K. Lenz et al. SCM 2004,
Physica Status Solidi (c) **1**, 3260 (2004)

ΔH as function of J_{inter} and d_{Cu} respectively

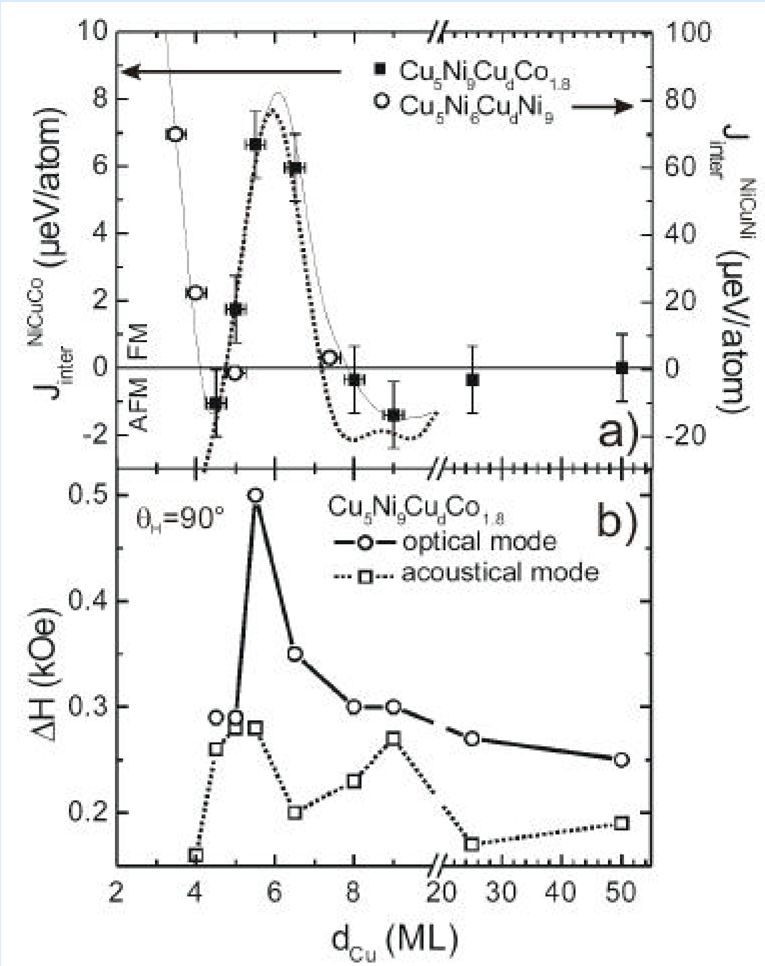
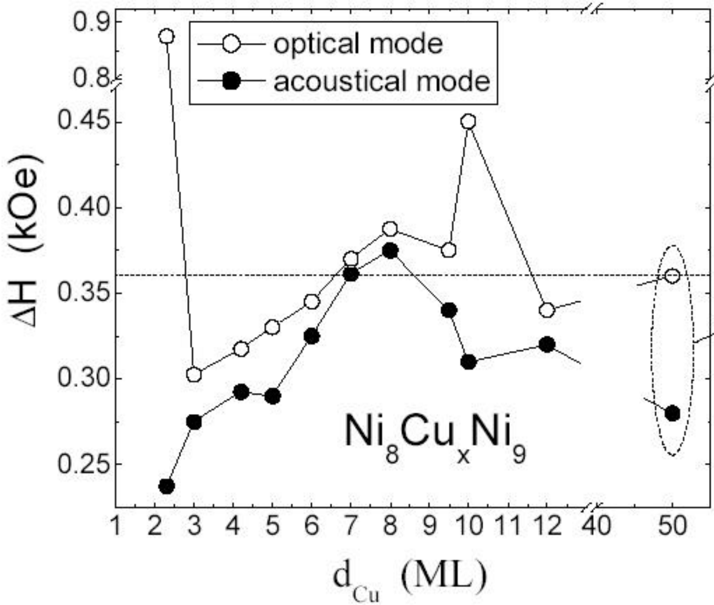


Fig. 2 (a) Oscillations of J_{inter} with respect to the spacer thickness for $Cu_5Ni_9Cu_dCo_{1.8}$ (left y-axis) and $Cu_5Ni_6Cu_dNi_9$ trilayers (right y-axis). The dotted line is a fit to the Ni/Cu/Co-samples according to the Bruno model. The solid line is a guide to the eye only. (b) Spacer thickness dependent oscillation of the linewidth of the optical (open circles) and acoustical (open squares) mode for the $Cu_5Ni_9Cu_dCo_{1.8}$ system.



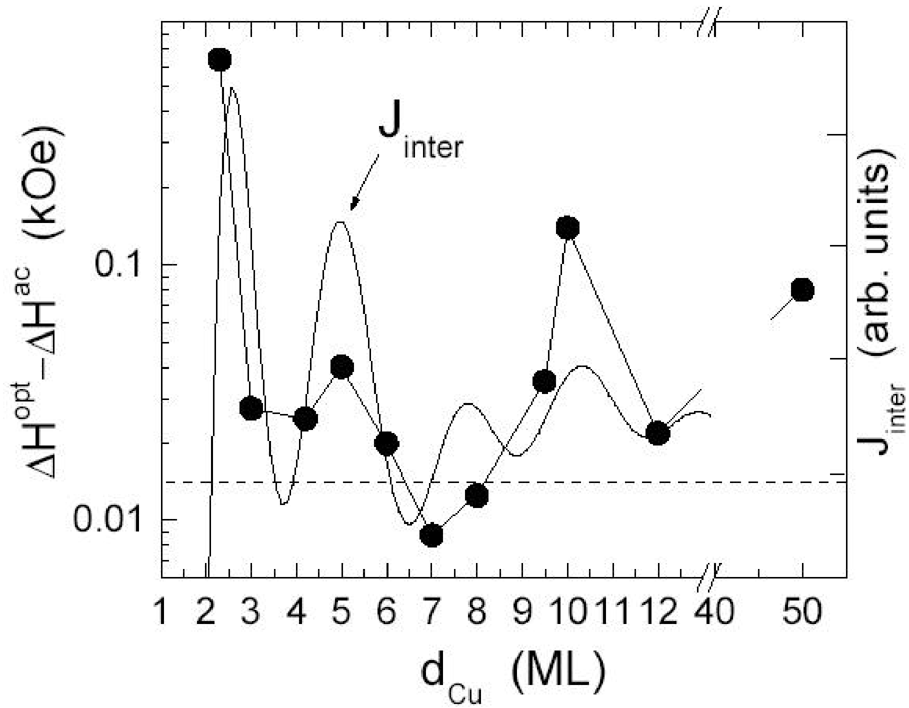
ΔH (Oe)	preparation step
250	Ni_9
310	$Cu_{10}Ni_9$
320	$Cu_{50}Ni_9$
360	$Cu_5Ni_8Cu_{50}Ni_9$
280	$Cu_5Ni_8Cu_{50}Ni_9$

Fig. 3. Linewidth of the optical and the acoustical mode versus the spacer thickness. On the right hand side the evolution of the linewidth of the Ni_9 film is shown for various steps of the trilayer preparation (uncoupled system, spacer of 50 ML). The details are explained in the text

Tolinski et al. Mol. Phys. Rep. **40**, 164 (2004)

$\Delta H^{opt} - \Delta H^{ac}$ as function of d_{Cu} (see Heinrich plot)

Fig. 4. Oscillatory behavior of the difference between the linewidth of the acoustical and the optical mode representing mainly the contribution due to the pumped spin-currents. The oscillations of IEC calculated from Bruno model and reflecting the measured IEC oscillations [11] are displayed for comparison. The vertical scale of J_{inter} is in arbitrary units and linear, therefore only the periods can be compared



Conclusion

- High sensitivity of ESR/FMR to investigate submonolayers
- *in-situ* UHV-ESR/FMR
- Large frequency range of 1 to >200GHz is needed to study relaxation, dynamics
- spin dynamics cannot be described by viscous damping, only.
  Scattering within the magnetic system is also important, before energy dissipates to the thermal bath.
- Spin pumping is an "old" phenomenon (mid 1970th's). Today's experiments measure a phenomenological number, superimposing many different mechanisms (i.e. cuplayer effects, J_{inter}, different modes of spin waves, etc.)