From local moment EPR in superconductors to nanoscale ferromagnets

Klaus Baberschke

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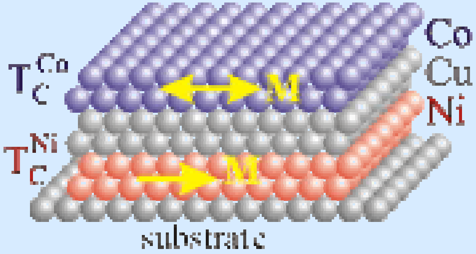
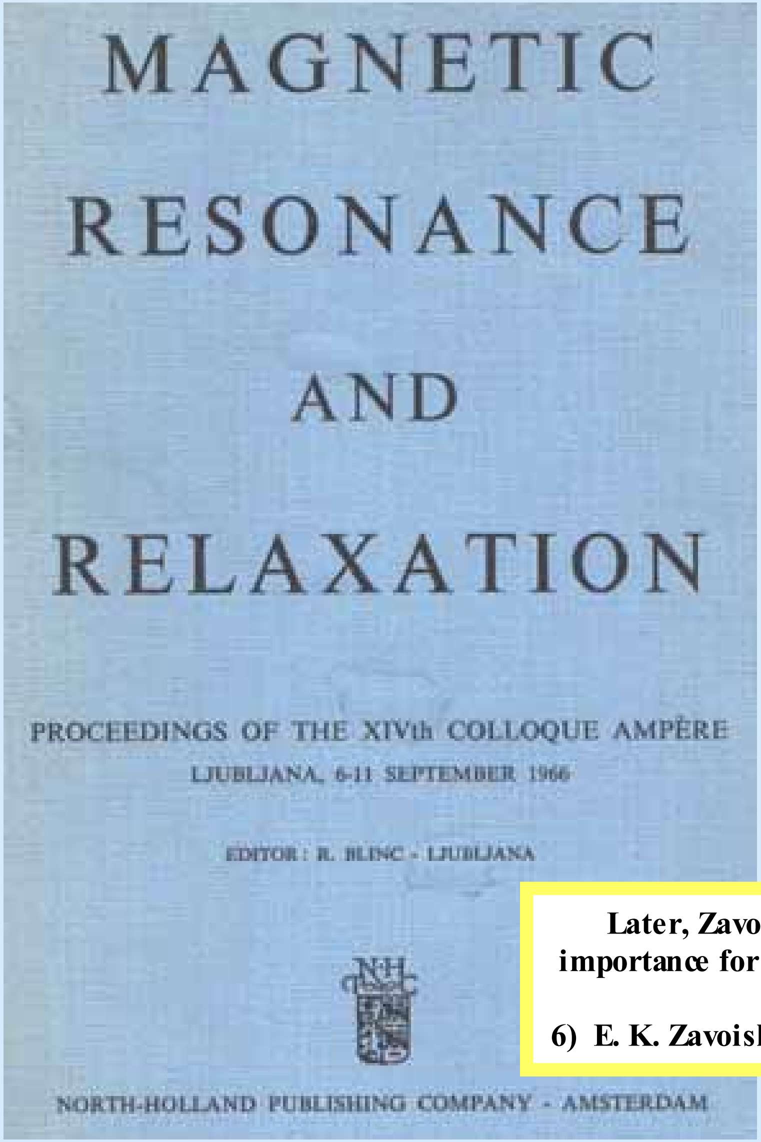
Freie Universität Berlin
Arnimallee 14 D-14195 Berlin-Dahlem Germany

60 ЛЕТ ЗПР

1.	Local moment EPR in superconductors	(dilute alloys)
2.	Single ion Kondo effect and EPR	(dilute alloys)
3.	FMR in ferromagnetic nanostructure	



⇒ **http://www.physik.fu-berlin.de/~ag-baberschke**

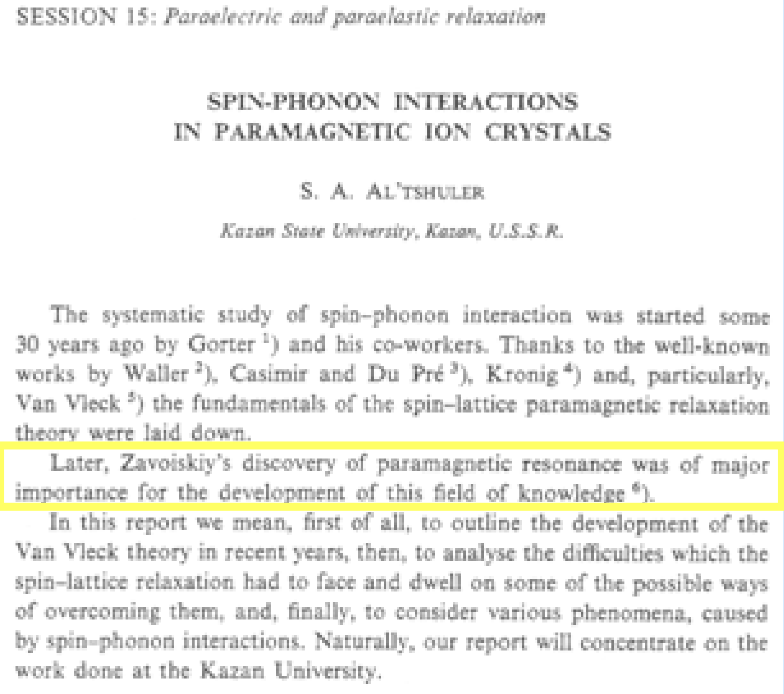


MAGNETIC
RESONANCE
AND
RELAXATION

PROCEEDINGS OF THE XIVth COLLOQUE AMPÈRE
LJUBLJANA, 6-11 SEPTEMBER 1966

EDITOR: R. BLINC - LJUBLJANA

NORTH-HOLLAND PUBLISHING COMPANY - AMSTERDAM



SESSION 15: *Paraelectric and paraelastic relaxation*

SPIN-PHONON INTERACTIONS
IN PARAMAGNETIC ION CRYSTALS

S. A. AL'TSHULER

Kazan State University, Kazan, U.S.S.R.

The systematic study of spin-phonon interaction was started some 30 years ago by Gorter [1]) and his co-workers. Thanks to the well-known works by Waller [2]), Casimir and Du Pré [3]), Kronig [4]) and, particularly, Van Vleck [5]) the fundamentals of the spin-lattice paramagnetic relaxation theory were laid down.

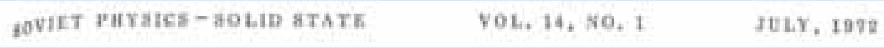
Later, Zavoiskiy's discovery of paramagnetic resonance was of major importance for the development of this field of knowledge [6]).

In this report we mean, first of all, to outline the development of the Van Vleck theory in recent years, then, to analyse the difficulties which the spin-lattice relaxation had to face and dwell on some of the possible ways of overcoming them, and, finally, to consider various phenomena, caused by spin-phonon interactions. Naturally, our report will concentrate on the work done at the Kazan University.

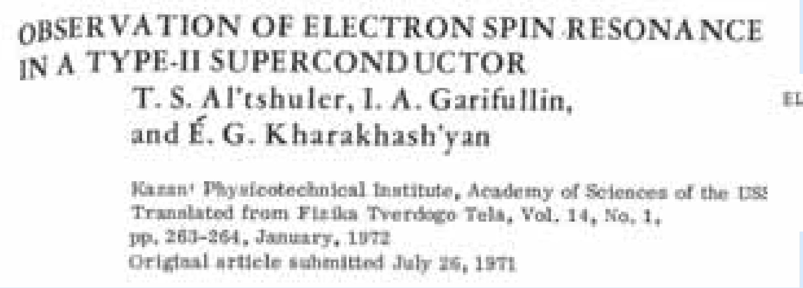
Later, Zavoiskiy's discovery of paramagnetic resonance was of major importance for the development of this field of knowledge [6]).

6) E. K. Zavoiskiy, Doctoral thesis , Moscow (1944); J. Phys. USSR 9, 245 (1945).

1. Local moment EPR in superconductors



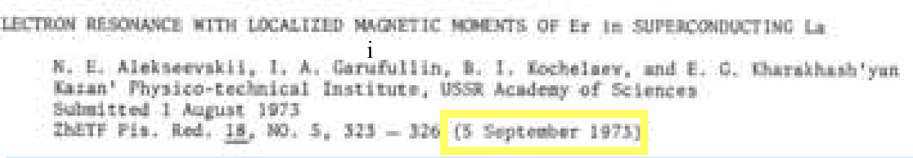
SOVIET PHYSICS – SOLID STATE VOL. 14, NO. 1 JULY, 1972



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 US
Translated from Fizika Tverdogo Tela, Vol. 14, No. 1,
pp. 263–264, January, 1972
Original article submitted July 26, 1971



ELECTRON 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)

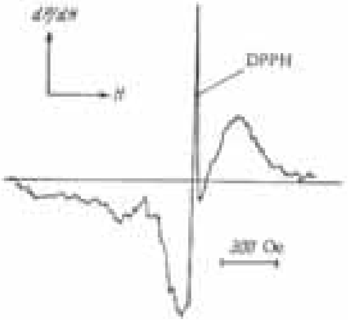


Fig. 1. ESR spectrum of a sample of $La_{2.98}Gd_{0.02}In$ recorded together with the signal of diphenyl picryl hydrazyl at 9320 MHz at 4.2°K.

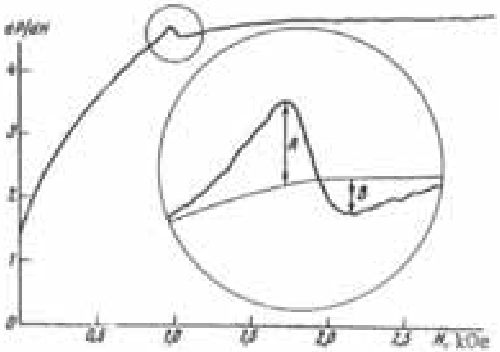


Fig. 1. Plot of EPR signal (dP/dH in relative units) for a sample of La + 1.5 at.% Er at T = 2.5°K and ν = 9369.4 MHz.

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

LOCAL MOMENT SPIN RESONANCE IN A SUPERCONDUCTOR

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

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.

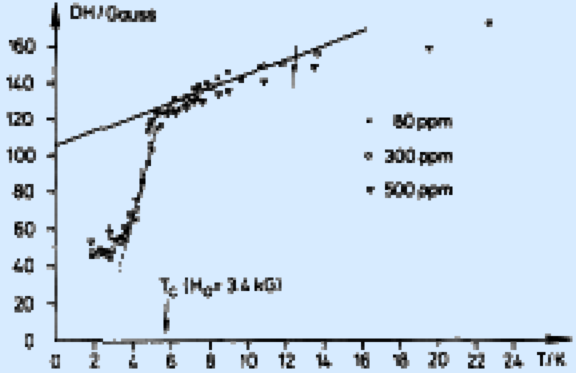


FIG. 1. Temperature dependence of the linewidth *DH* (*for a definition see reference 1*) *in Gd:*$CeRu_2$ *at X*-band frequencies; concentrations are given in the figure.

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)

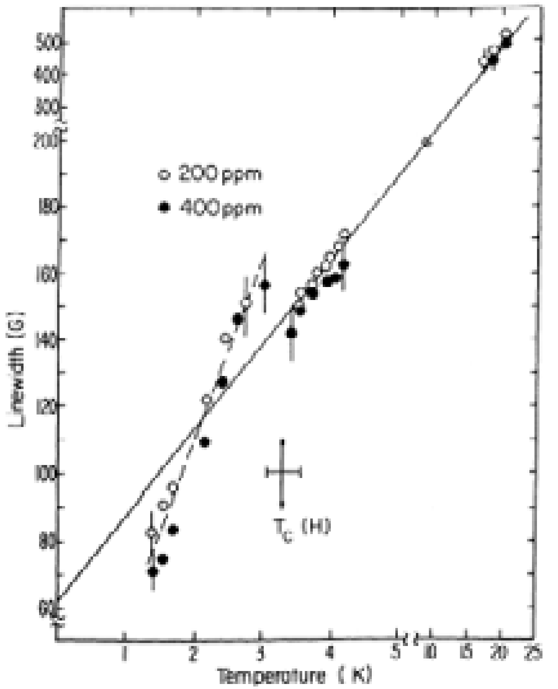


FIG. 1. Linewidth as a function of temperature for two $LaRu_2$:Gd samples. The 200-ppm sample was measured in the form of a powder; 400-ppm, in the form of a ball. The value of $T_c(H)$ is shown. Solid line, fit to our data in the normal state; dashed line, in the superconducting state.

CONTRIBUTION TO THE THEORY OF SUPERCONDUCTING ALLOYS WITH PARAMAGNETIC IMPURITIES

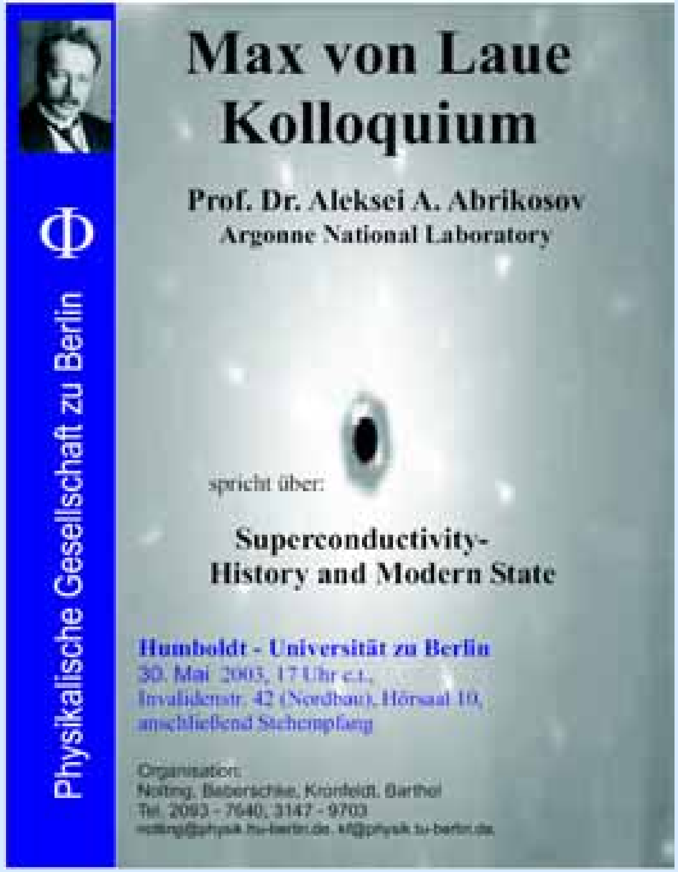
A. A. ABRIKOSOV and L. P. GOR'KOV

Institute for Physics Problems, Academy of Sciences, U.S.S.R.

Submitted to JETP editor July 25, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) 39, 1781-1796 (December, 1960)

$$\ln(T_c/T_{c0}) = \psi(1/2) - \psi\left(1/2 + 0.14\,\frac{\alpha}{\alpha_{cr}}\,\frac{T_{c0}}{T_c}\right).$$



Max von Laue Kolloquium

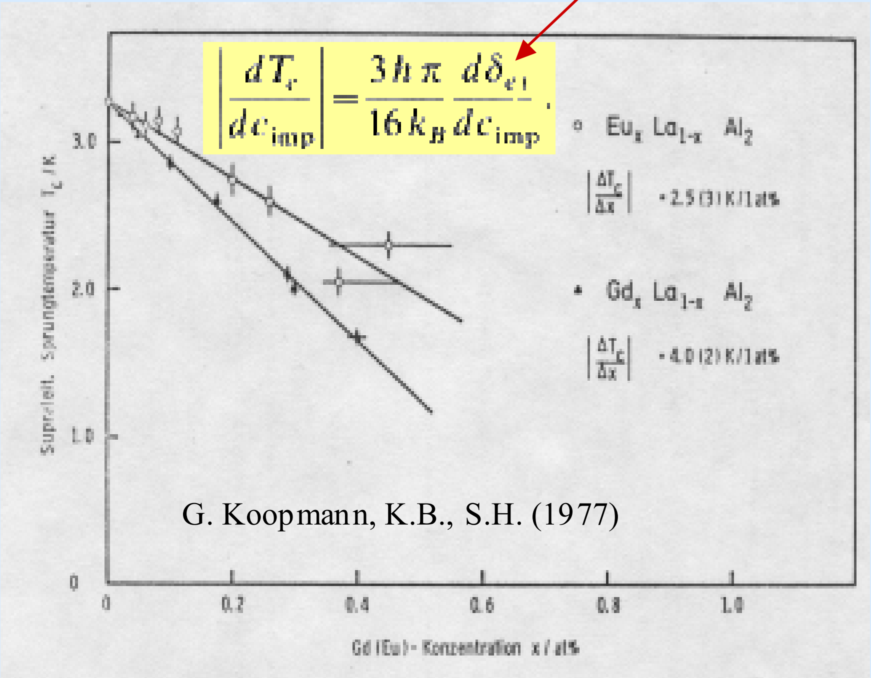
Prof. Dr. Aleksei A. Abrikosov
Argonne National Laboratory

spricht über:

**Superconductivity-
History and Modern State**

Humboldt - Universität zu Berlin
30. Mai 2003, 17 Uhr c.t.,
Invalidenstr. 42 (Nordbau), Hörsaal 10,
anschließend Stehempfang

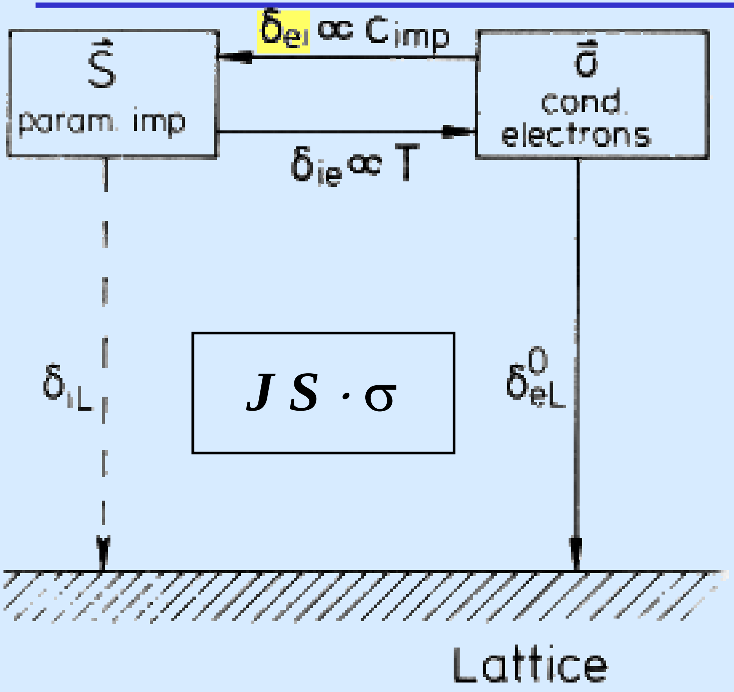
Organisation:
Nolting, Baberschke, Kronfeldt, Barthel
Tel. 2093 - 7640, 3147 - 9703
nolting@physik.hu-berlin.de, kf@physik.tu-berlin.de



$$\left|\frac{dT_c}{dc_{\mathrm{imp}}}\right| = \frac{3\hbar\pi}{16k_B}\,\frac{d\delta_{el}}{dc_{\mathrm{imp}}}\,.$$

G. Koopmann, K.B., S.H. (1977)

EPR in superconducting materials



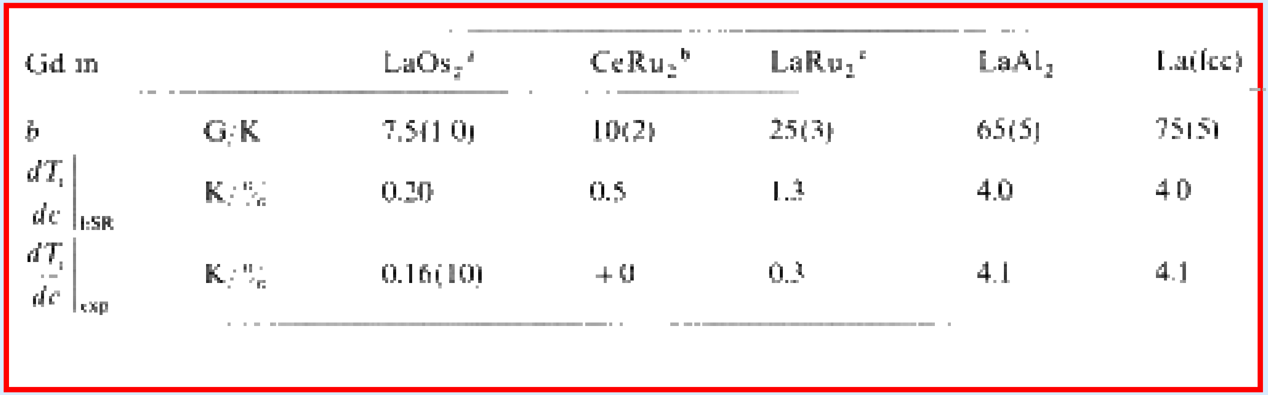
Korringa

$$\hbar\delta_{ie} = \pi N^2(E_F)\langle J^2(k,k')\rangle kT$$

$$\hbar\delta_{ei} = \pi N(E_F)\langle J^2(k,k')\rangle 2S(S+1)\cdot c_{imp}$$

Pair breaking parameter δ_{ei} can be measured in two ways

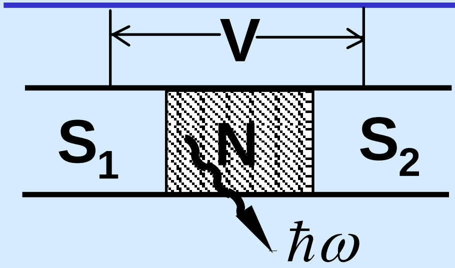
$\Delta T_C \leftrightarrow$ ESR



Gd in		LaOs$_2$^{a}	CeRu$_2$^{b}	LaRu$_2$^{c}	LaAl$_2$	La(fcc)
b	G/K	7.5(1.0)	10(2)	25(3)	65(5)	75(5)
$\left.\frac{dT_c}{dc}\right\|_{ESR}$	K/%	0.20	0.5	1.3	4.0	4.0
$\left.\frac{dT_c}{dc}\right\|_{exp}$	K/%	0.16(10)	+0	0.3	4.1	4.1

K. B., Z. Physik B **24**, 53 (1976)

EPR with ac-Josephson effect

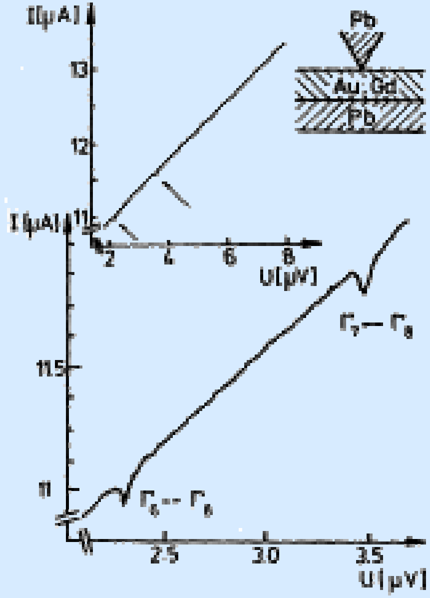


$$\partial(\theta_2-\theta_1)/\partial t = -2eV/\hbar$$

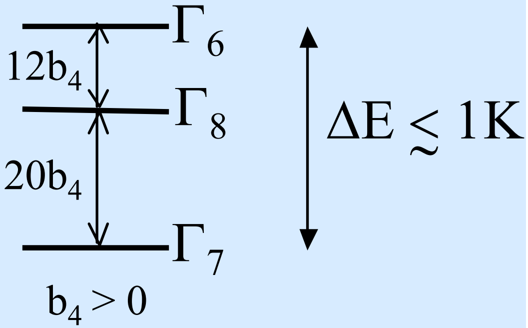
$$\boxed{\hbar\omega = 2eV}$$

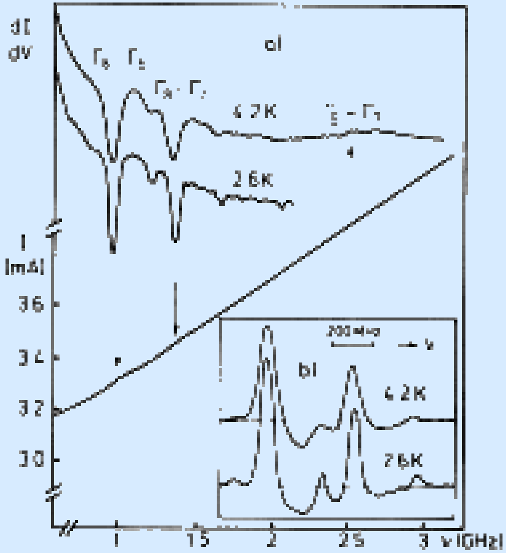
483,6 MHz ≙ 1μV

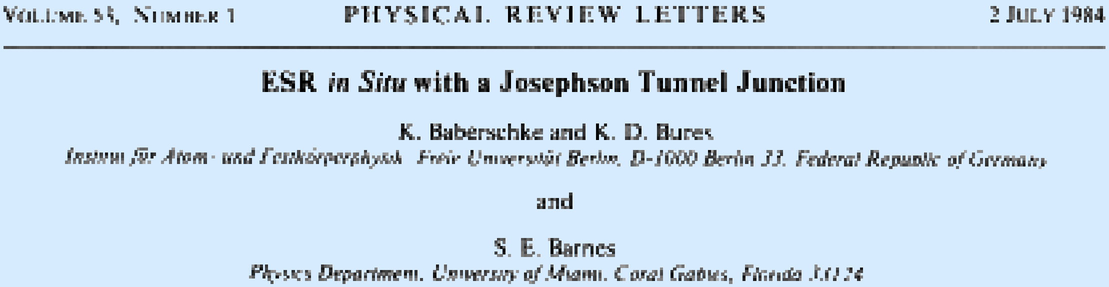
use ac-Josephson effect as a microwave generator and tunneling current as a detector.



Gd^{3+} in fcc Au







VOLUME 53, NUMBER 1 PHYSICAL REVIEW LETTERS 2 JULY 1984

ESR *in Situ* with a Josephson Tunnel Junction

K. Baberschke and K. D. Bures
Institut für Atom- und Festkörperphysik, Freie Universität Berlin, D-1000 Berlin 33, Federal Republic of Germany

and

S. E. Barnes
Physics Department, University of Miami, Coral Gables, Florida 33124

2. Kondo effect in the ESR

g–shift ∝ J : $\Delta g = \alpha d \,|\, \ln(T_K / T) \,|^{-1}$

linewidth ∝ J^2 : $\delta_{ie} / \pi k T = \alpha^2 d \,|\, \ln(T_K / T) \,|^{-2}$

Yb in Au

K. B. et al.
PRL **45**, 1512 (1980)

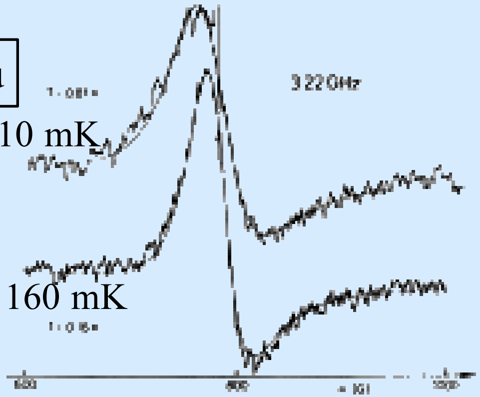
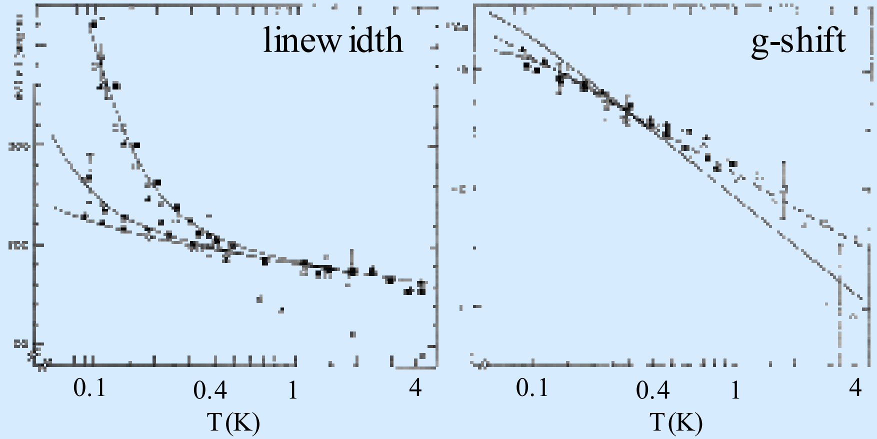


FIG. 1. Spectra of 1200-ppm Yb in Au. The arrows indicate the shift of the resonance field as a function of temperature. Γ=0.3 sec is used.

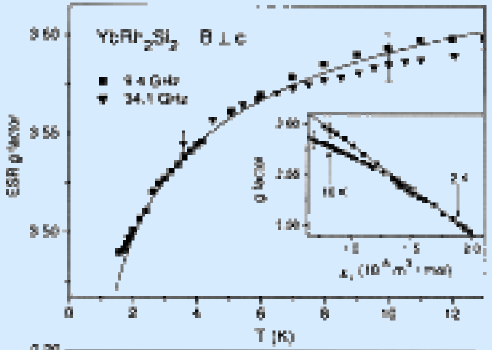


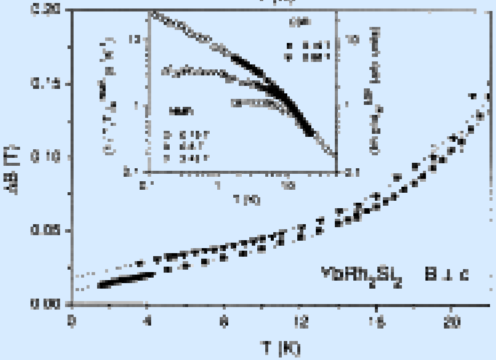
PHYSICAL REVIEW LETTERS **91** 10 Oct. 2003

Low Temperature Electron Spin Resonance of the Kondo Ion in a Heavy Fermion Metal: $YbRh_2Si_2$

J. Sichelschmidt,[1] V. A. Ivanshin,[2] J. Ferstl,[1] C. Geibel,[1] and F. Steglich[1]

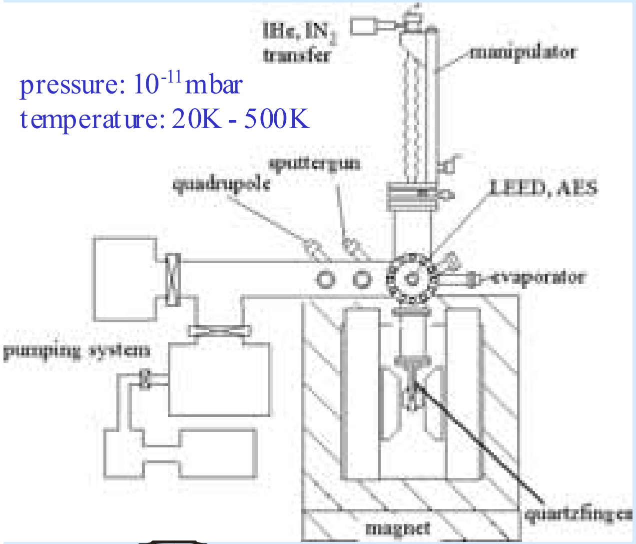
[1] *Max Planck Institute for Chemical Physics of Solids, D-01187 Dresden, Germany*
[2] *MRS Laboratory, Kazan State University, 420008 Kazan, Russia*
(Received 12 May 2003, published 6 October 2003)





3. 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 8 September 1986)

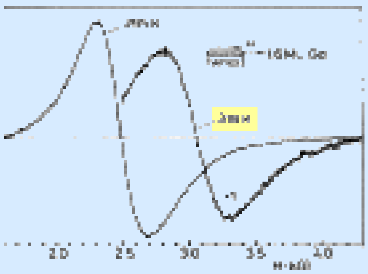


Fig. 4. ESR spectra for the new 1.6 ML sample (not cited in [2, 3]). Note the significant change in intensity and resonance field from 16 to 39 K above T_c.

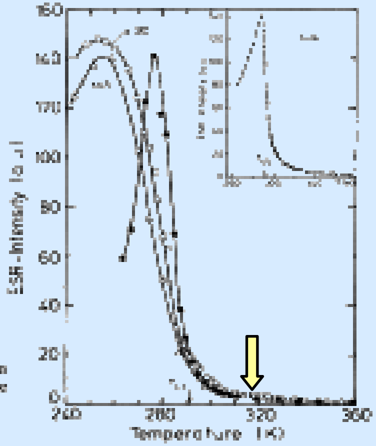
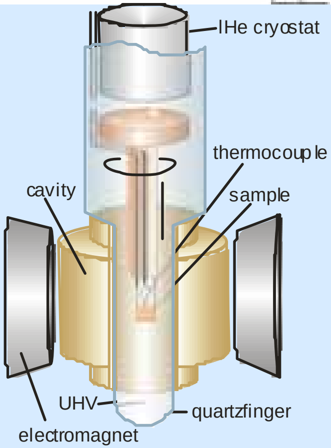
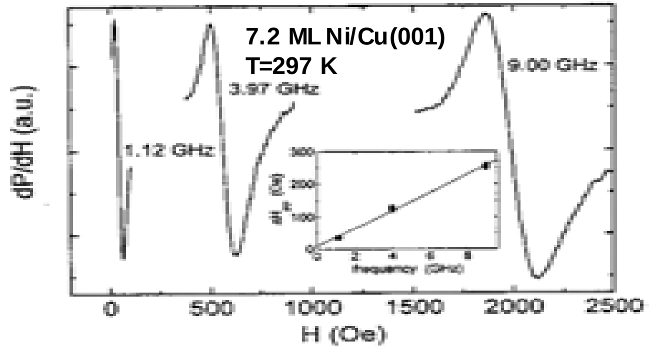


Fig. 5. Area of the ESR signal as a function of temperature for 80 Å (■), the new 1.6 ML (○), and the 0.8 ML (△). The insert shows the same data for a 18 µm thick Gd foil (bulk). Solid lines are guides to the eye. The 1.6 and 0.8 ML have a vertical gain factor of 20 and 44 with respect to 80 Å. The insert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



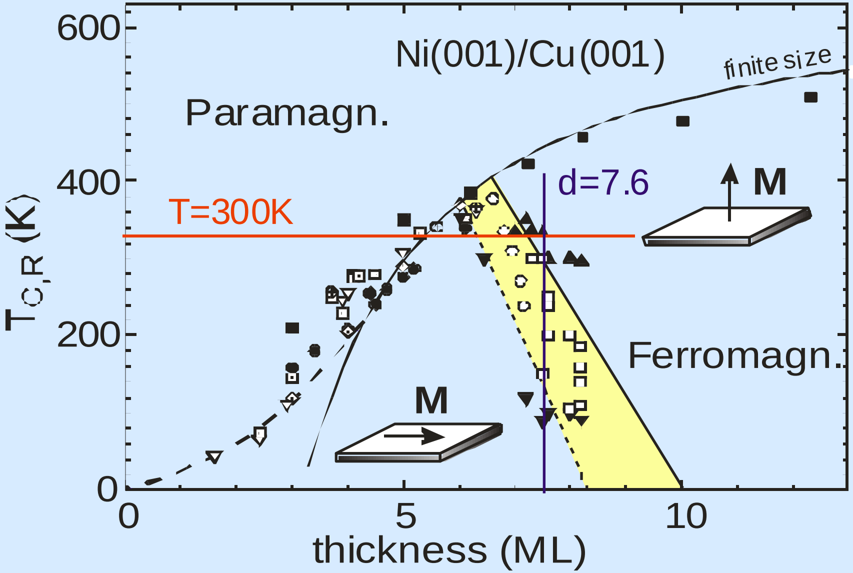
M. Zomak et al.,
Surf. Sci. **178**, 618 (1986)

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

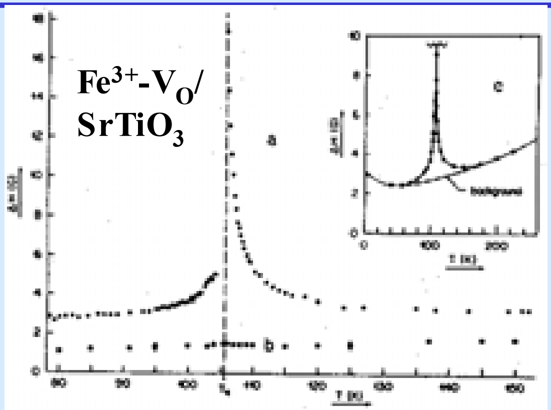


W. Platow,
Ph.D. thesis
(1999)

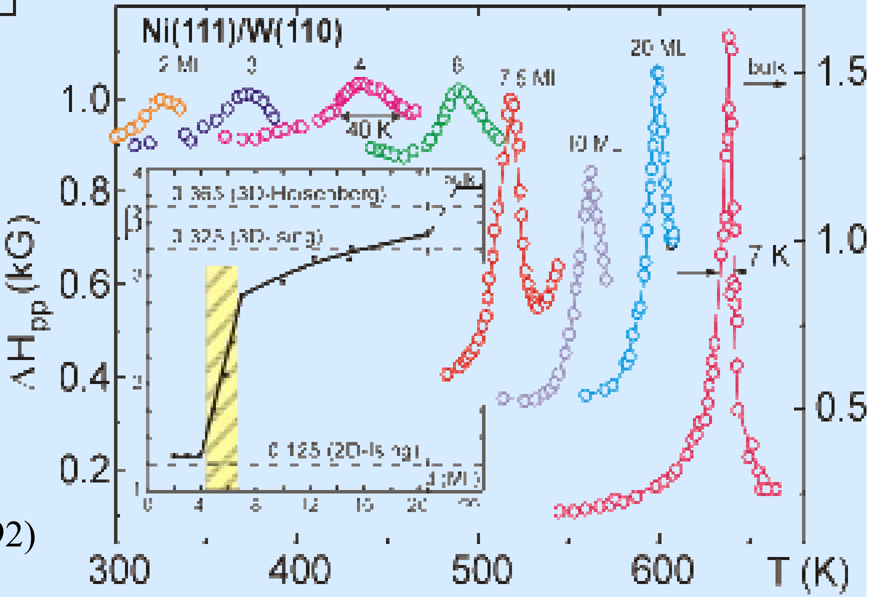
For thin films the Curie temperature can be manipulated



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



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



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

Determination of MAE K_i and g-tensor

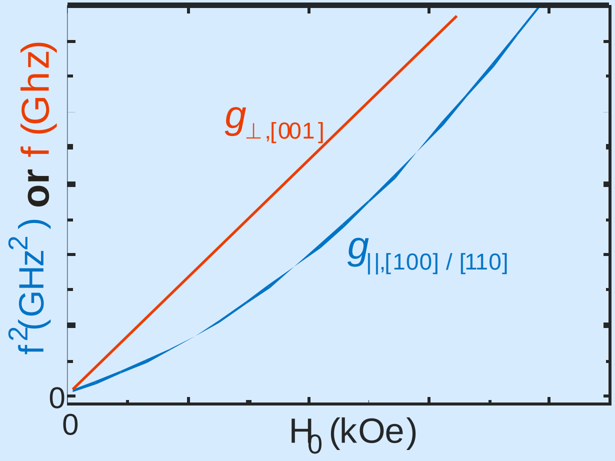
$$\frac{\omega^2}{\gamma^2_{||,[100]}} = H^2_{0,[100]} + H_{0,[100]}\left(4\pi M - 2\frac{K_2}{M} + \frac{4K_{4||}}{M}\right) + 2\frac{K_{4||}}{M}\left(4\pi M - 2\frac{K_2}{M} + \frac{2K_{4||}}{M}\right)$$

$$\frac{\omega}{\gamma_{\perp,[001]}} = H_{0,\perp} - 4\pi M + \frac{2(K_2 + K_{4\perp})}{M}$$

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

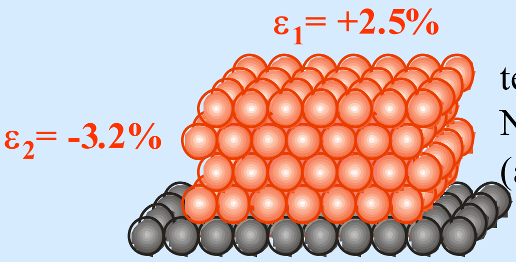
$$\frac{\mu_l}{\mu_s} = \frac{g-2}{2}$$

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



Growth of artificial nanostructures

bcc, fcc → tetragonal, trigonal

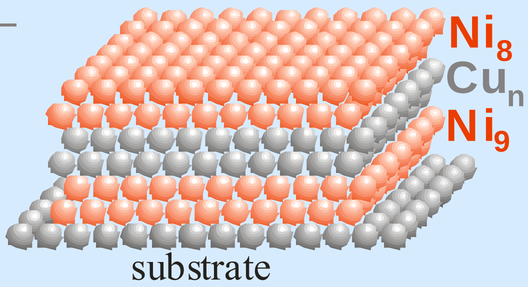


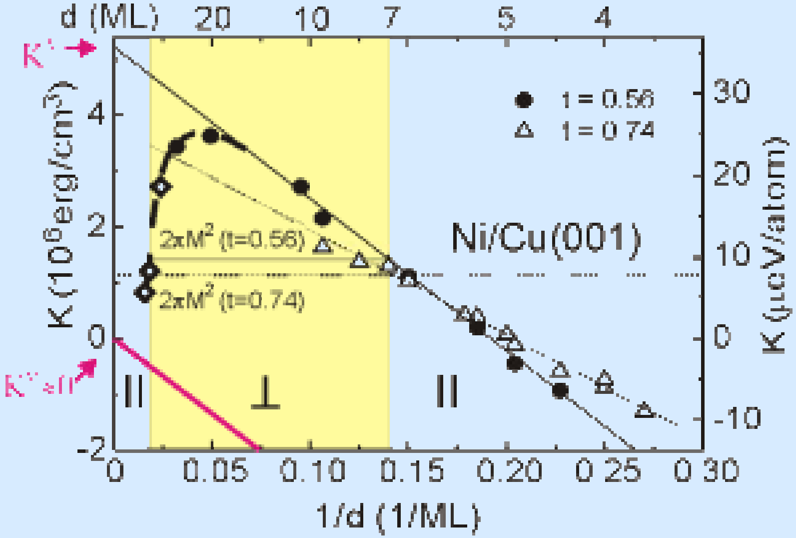
tetragonal
Ni(001)
($a_p^{\text{Ni bulk}}$=2.49Å)

fcc Cu(001) substrate (a_p=2.55Å)

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

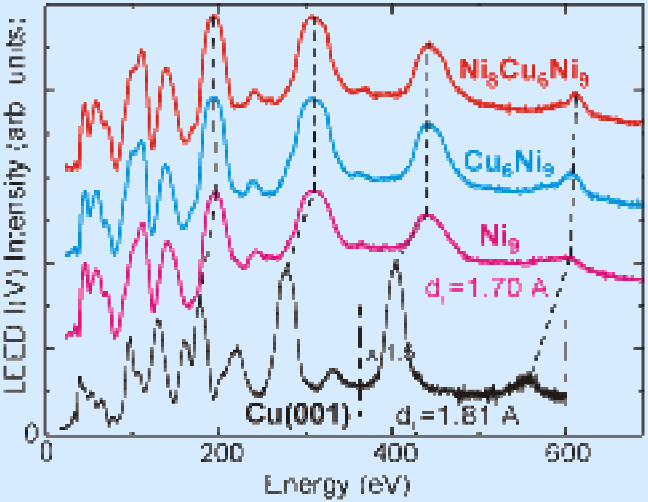
$t=T/T_C(d)$





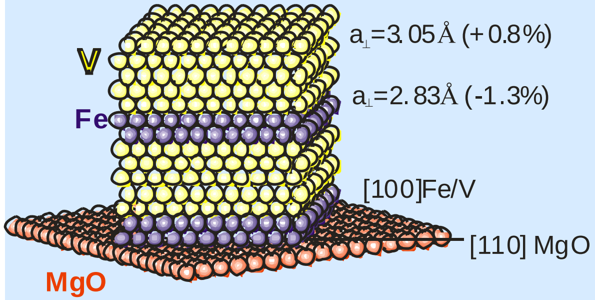
Structural changes by ≈ 0.05 Å increase MAE by 2-3 orders of magnitude (~0.2→100μeV/atom)

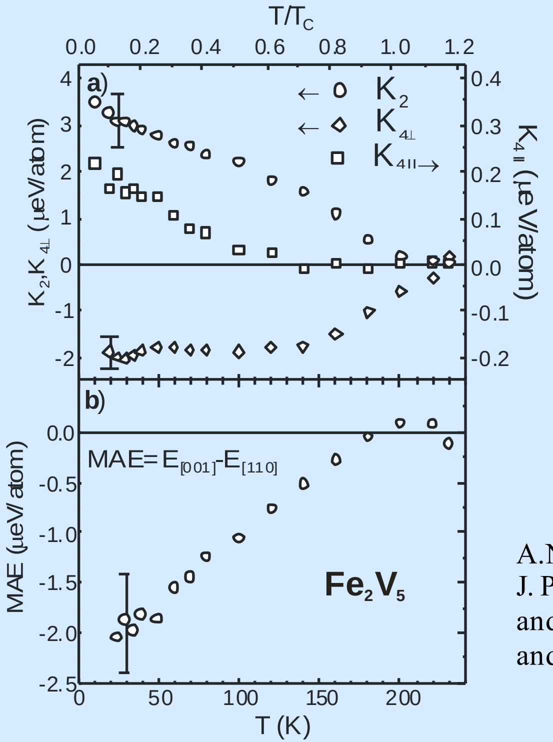
full trilayer grows in fct structure



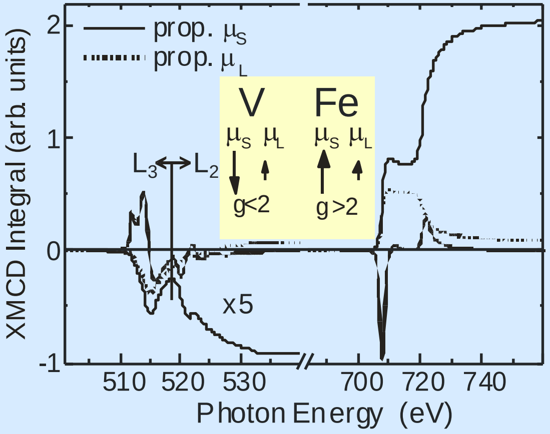
R. Hammerling et al., PRB **68**, 092406 (2003)

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

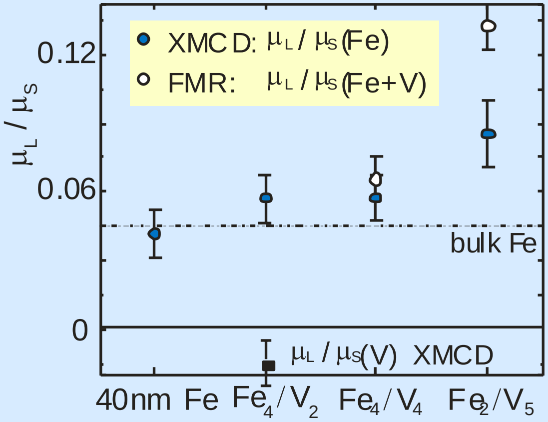




XMCD



FMR



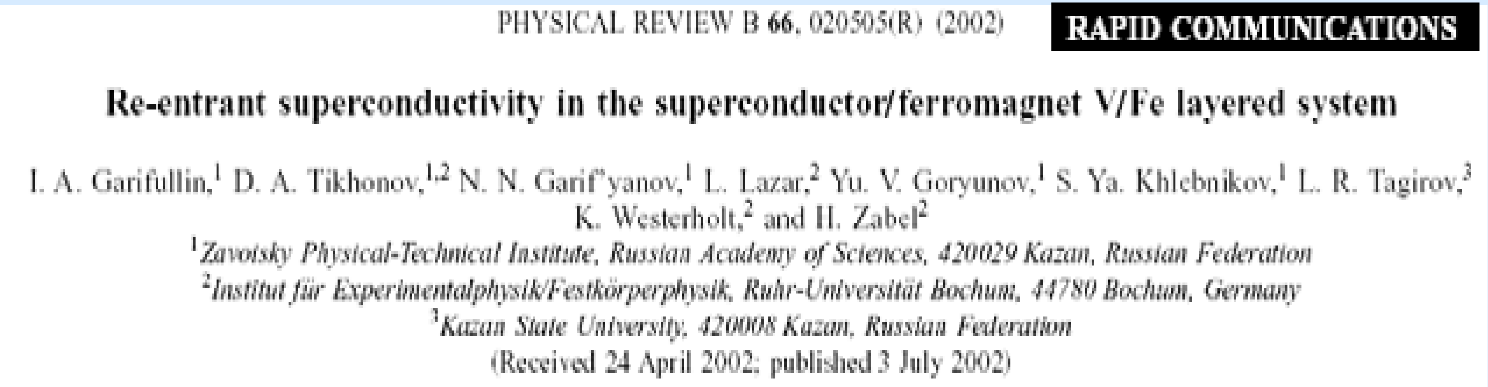
$$\frac{\mu_L}{\mu_S} = \frac{g-2}{2}$$ (Kittel'49)

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

$Fe_n/V_m(001)$ superlattices



PHYSICAL REVIEW B 66, 020505(R) (2002)

RAPID COMMUNICATIONS

Re-entrant superconductivity in the superconductor/ferromagnet V/Fe layered system

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[1]*Zavoisky Physical-Technical Institute, Russian Academy of Sciences, 420029 Kazan, Russian Federation*
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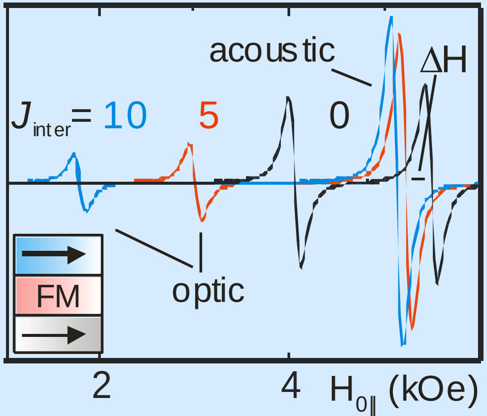
Coupled films, magnetic trilayers in the FMR

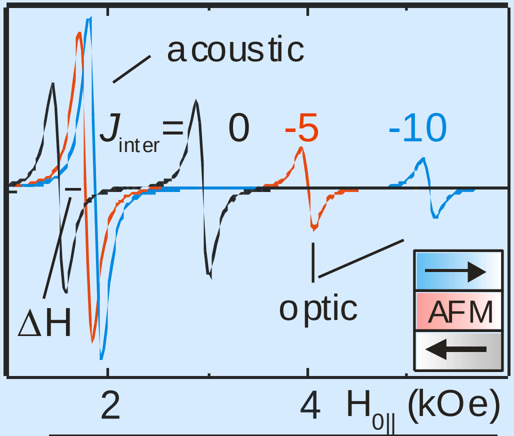
Landau-Lifshitz-Gilbert-Equation

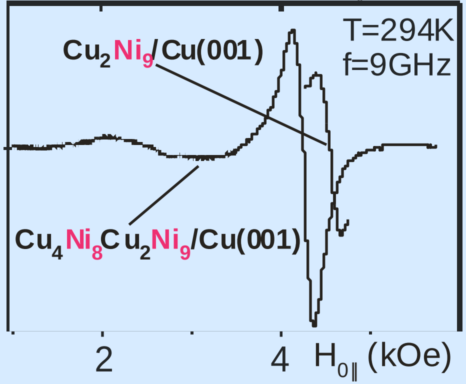
$$\frac{1}{\gamma}\frac{\partial M}{\partial t} = -(M \times H_{eff}) + \frac{G}{\gamma^2 M_S^2}\left(M \times \frac{\partial M}{\partial t}\right)$$



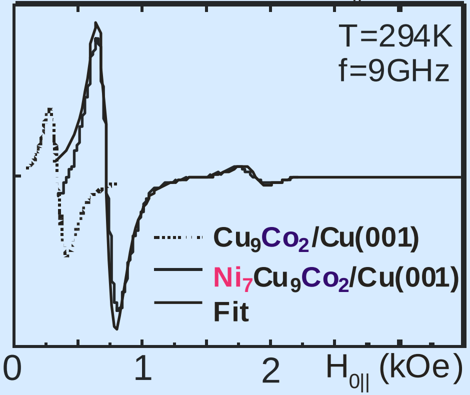
theory

FMR



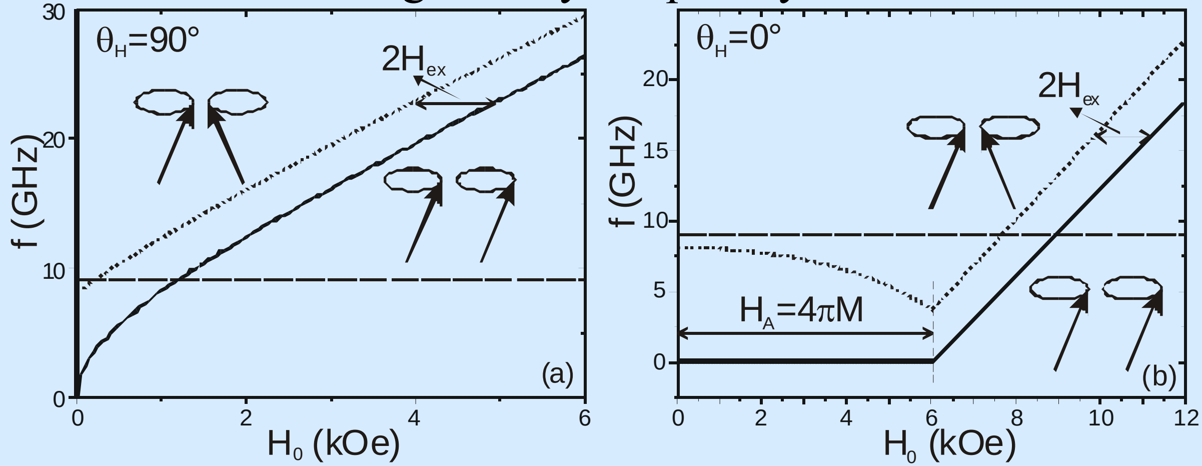


in-situ
UHV-experiment

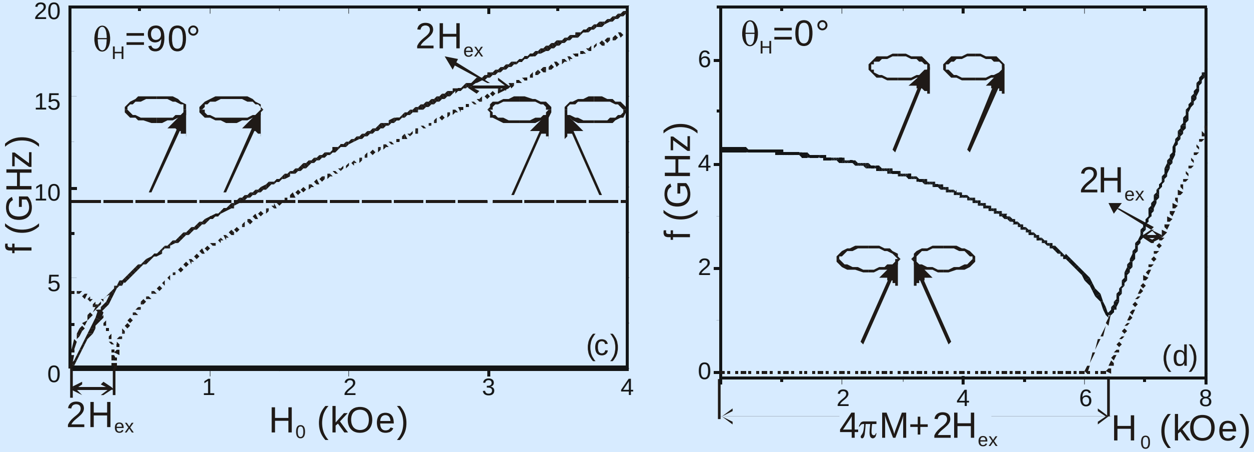


J. Lindner, K. B. Topical Rev., J. Phys. Condens. Matter **15**, R193-R232 (2003)

Ferromagnetically coupled system

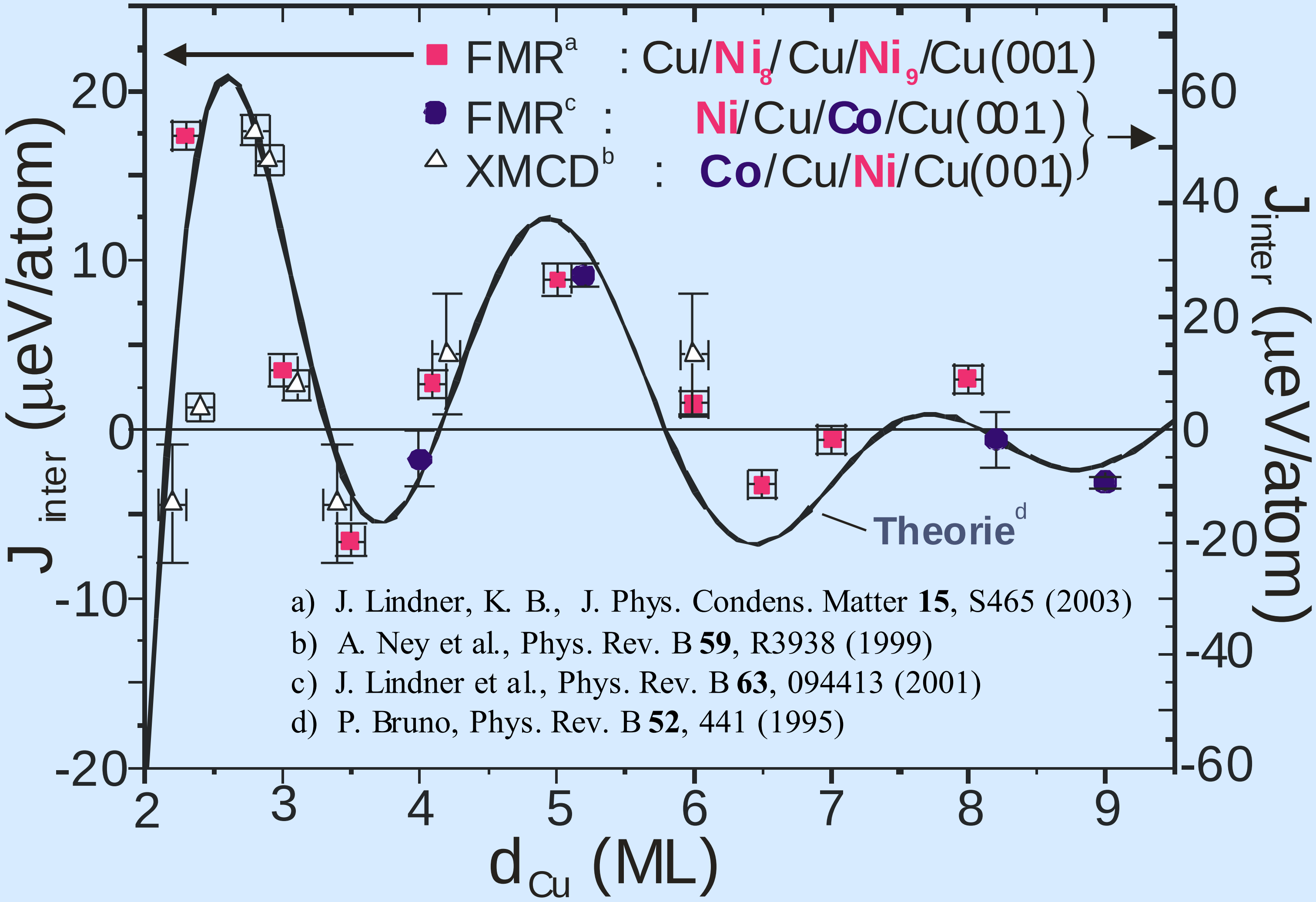


Antiferromagnetically coupled system



in-situ UHV-FMR measures FM **and** AFM
and determines K_i and J_{inter} **in absolute units**, e.g. μeV/atom

Interlayer exchange coupling



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)

Temperature dependence of J_{inter} ⇔ Δ free energy

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

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

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

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

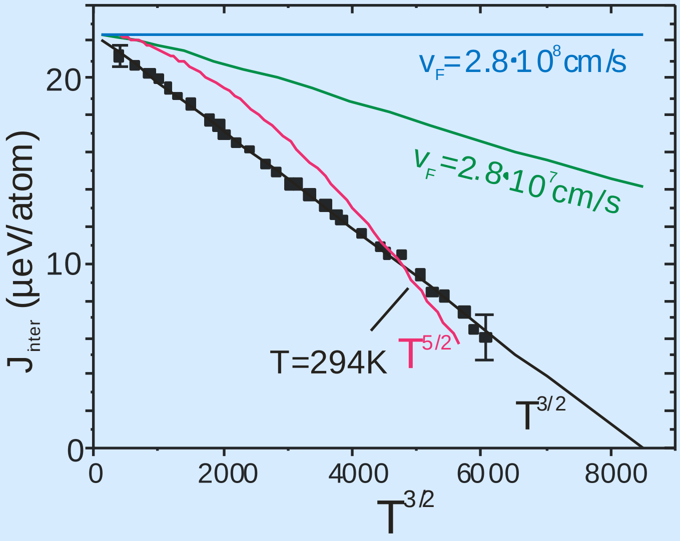
$Ni_7Cu_9Co_2/Cu(001)$

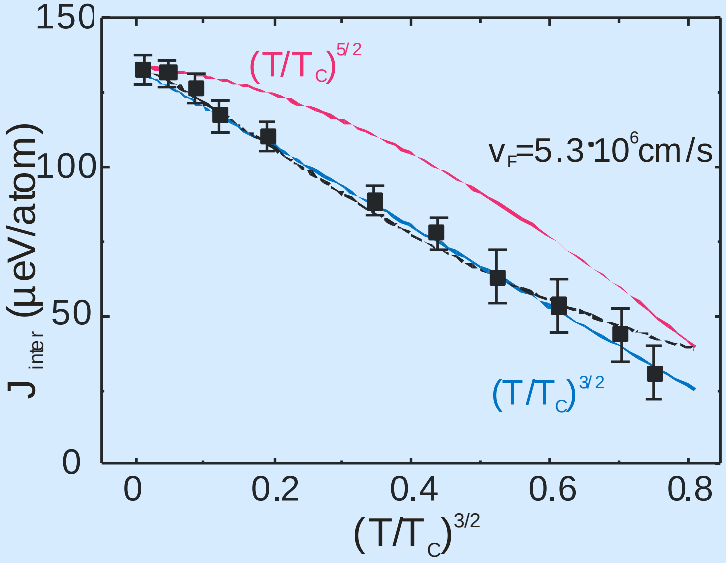
T=55K - 332K

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

$(Fe_2V_5)_{50}$

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





Origin of the temperature dependence of interlayer exchange coupling in metallic trilayers
S. Schwieger and W. Nolting, PRB **69**, 224413 (2004)

FMR Linewidth - Damping

Landau-Lifshitz-Gilbert-Equation

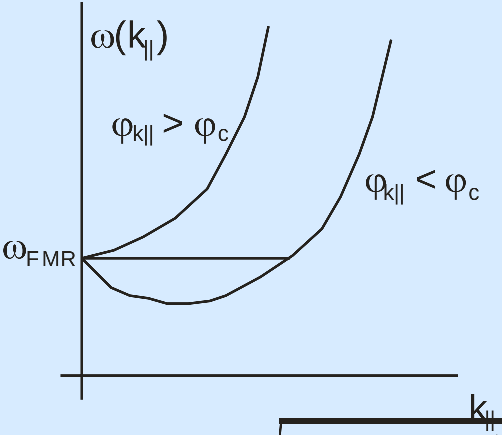
$$\frac{1}{\gamma}\frac{\partial M}{\partial t} = -(M \times H_{eff}) + \frac{G}{\gamma^2 M_S^2}\left(M \times \frac{\partial M}{\partial t}\right)$$

Gilbert-damping ~ω

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

2-magnon-scattering

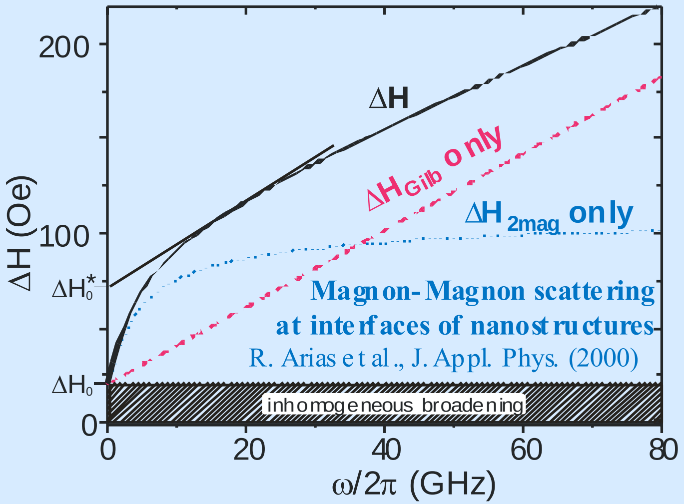
R. Arias, and D.L. Mills, Phys. Rev. B **60**, 7395 (1999);
D.L. Mills and S.M. Rezende in *'Spin Dynamics in Confined Magnetic Structures* ', edt. by B. Hillebrands and K. Ounadjela, Springer Verlag 2003



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

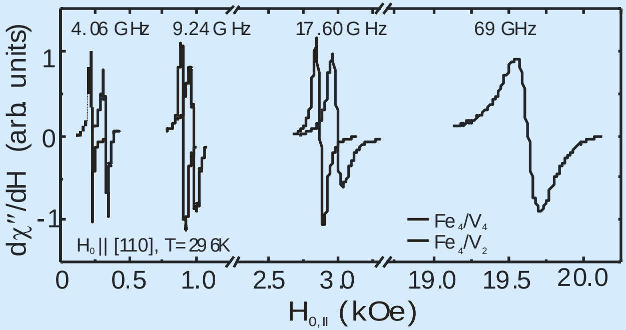
$\omega_0 = \gamma(2K_{2\perp} - 4\pi M_S)$, $\gamma=(\mu_B/h)g$
$K_{2\perp}$ - uniaxial anisotropy constant
M_S - saturation magnetization

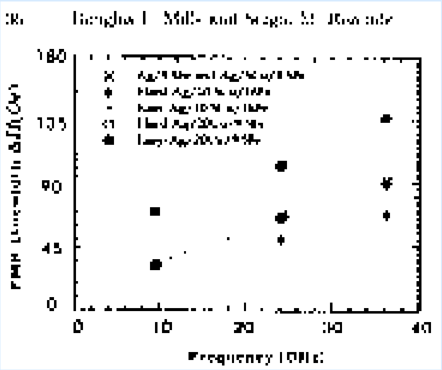
'Non-Gilbert-Type' spin-wave damping



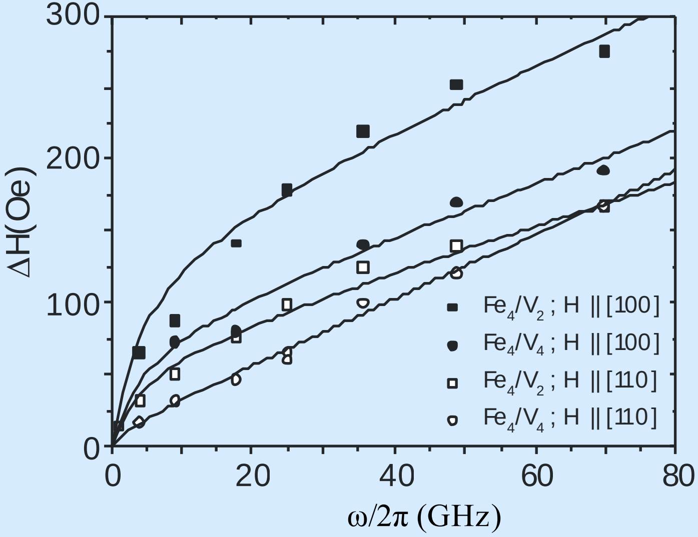
Magnon-Magnon scattering at interfaces of nanostructures

R. Arias et al., J. Appl. Phys. (2000)





Z. Celinski, B. Heinrich, JAP, **70**, 5935 (1991)



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

Non-viscosity (velocity) like damping (spin-scattering)

will be equally important at nanoscale magnets.

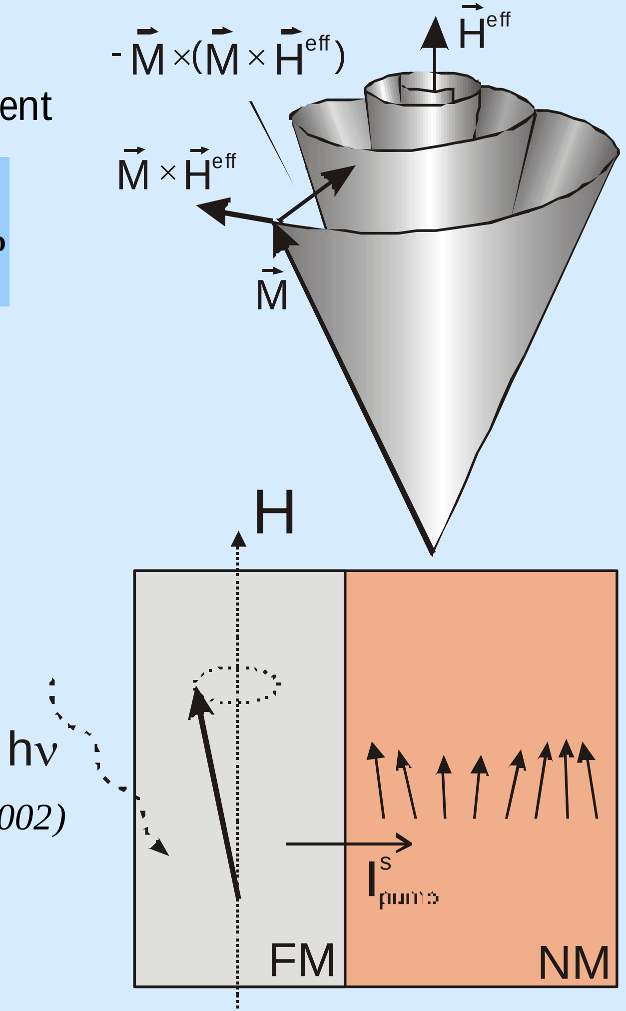
Landau-Lifshitz equation & spin-pump effect

Landau-Lifshitz equation + extension

precession　　Gilbert-damping　　spin-pump current

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

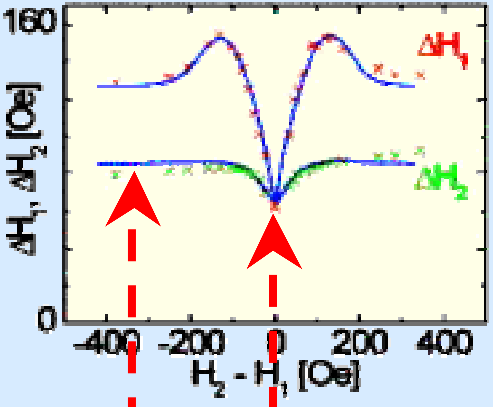
$$\mathbf{I}^{\mathrm{S}}_{\mathbf{pump}} = \frac{\hbar}{4\pi}\left(A_r \mathbf{M}\times\frac{\mathrm{d}\mathbf{M}}{dt} - A_i\frac{\mathrm{d}\mathbf{M}}{dt}\right)$$



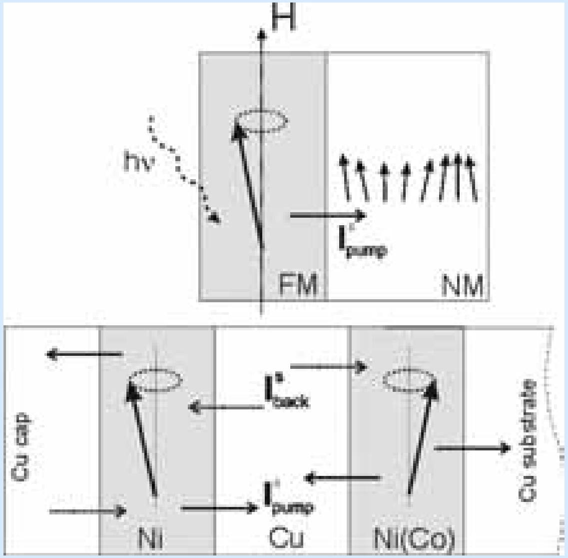
- *s*-*d*-exchange between spin wave and *s*-electron
  *R.H. Silsbee, A. Janossy, P. Monod, PRB **19**, 4382 (1979)*
- precession drives spin current into NM
  *Y. Tserkovnyak, A. Brataas, G.E.W. Bauer, PRB **66,** 224403 (2002)*
- NM-substrate acts as spin-sink ➡ $I^{s}_{\mathrm{back}} = \mathbf{0}$
  - torque is carried away
  - Gilbert damping enhanced by spin-pump effect!

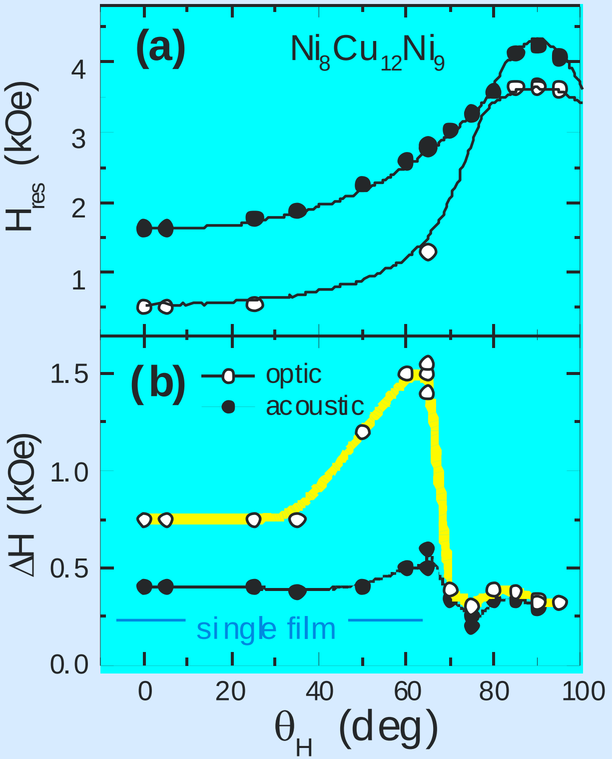
Evidence of spin-pumping effect in the FMR of coupled trilayers

Fe/40MLAu/Fe



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





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

$d_{NM} \geq \lambda_{SF}$ ➡ no spin-accumulation ➡ $I^s_{back} = 0$
➡ Gilbert-damping enhanced by spin-pump effect

compensation, if both films precess simultaneously ($H_{res1}=H_{res2}$)
➡ only Gilbert contribution remains!

Summary

ЗПР is mature

- It is applied at large variety of different fields: e.g. Millikelvin, in UHV, etc.
- Resonance field, line width, and intensity give many detailed information.
- For nanoscale magnetism it is very powerful,
  it measures to para- and ferromagnetism in absolute energy units (eV/particle),
  which some other technique (e.g. Kerr effect, SPE) can hardly do.

Later, Zavoiskiy's discovery of paramagnetic resonance was of major importance for the development of this field of knowledge [6].

The International Zavoisky Award 2004

Prof. Dr. Dietmar Stehlik, FU Berlin

60 ЛЕТ ЗПР

С ДНЁМ РОЖДЕНИЯ