Ferromagnetic resonance in nanostructures, rediscovering its roots in paramagnetic resonance

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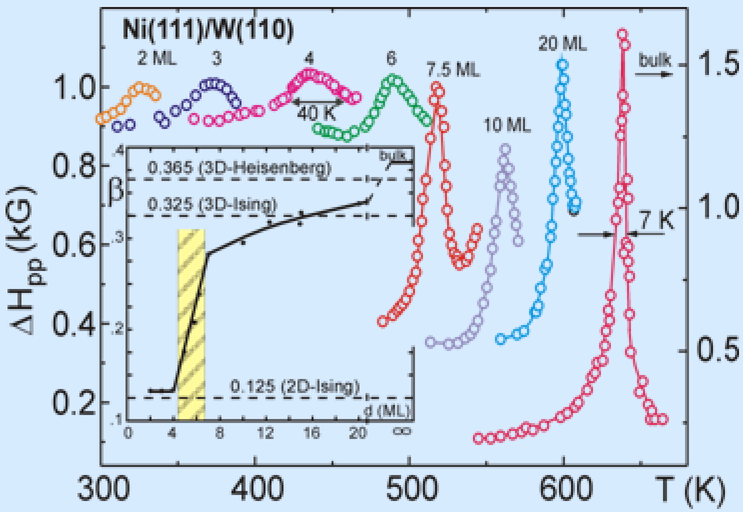
1. **Historical reminiscences**
2. **Orbital- and spin-magnetic moments in ferromagnetic monolayers**
3. **Spin-phonon, spin-spin dynamics**
4. **Summary and future**



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

1. Historical reminiscences

EPR was discovered in 1944.   2004 we celebrated this, here in Kazan.

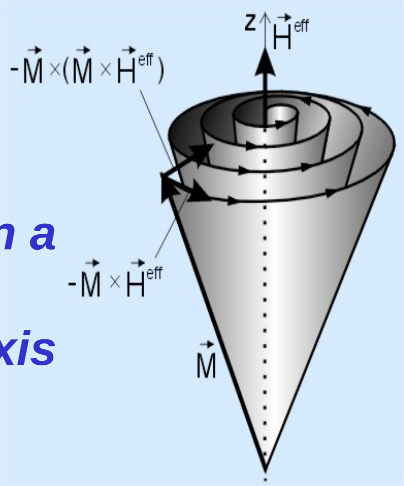
The resonant microwave absorption in ferromagnetic metals (FMR) was discovered shortly after (Griffith 1946, Zavoiskii 1947)

Usually the **Landau-Lifshitz-Gilbert equation (1935)** is used to analyze and interprete the experimental results

$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H}_{\mathrm{eff}} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt}$$

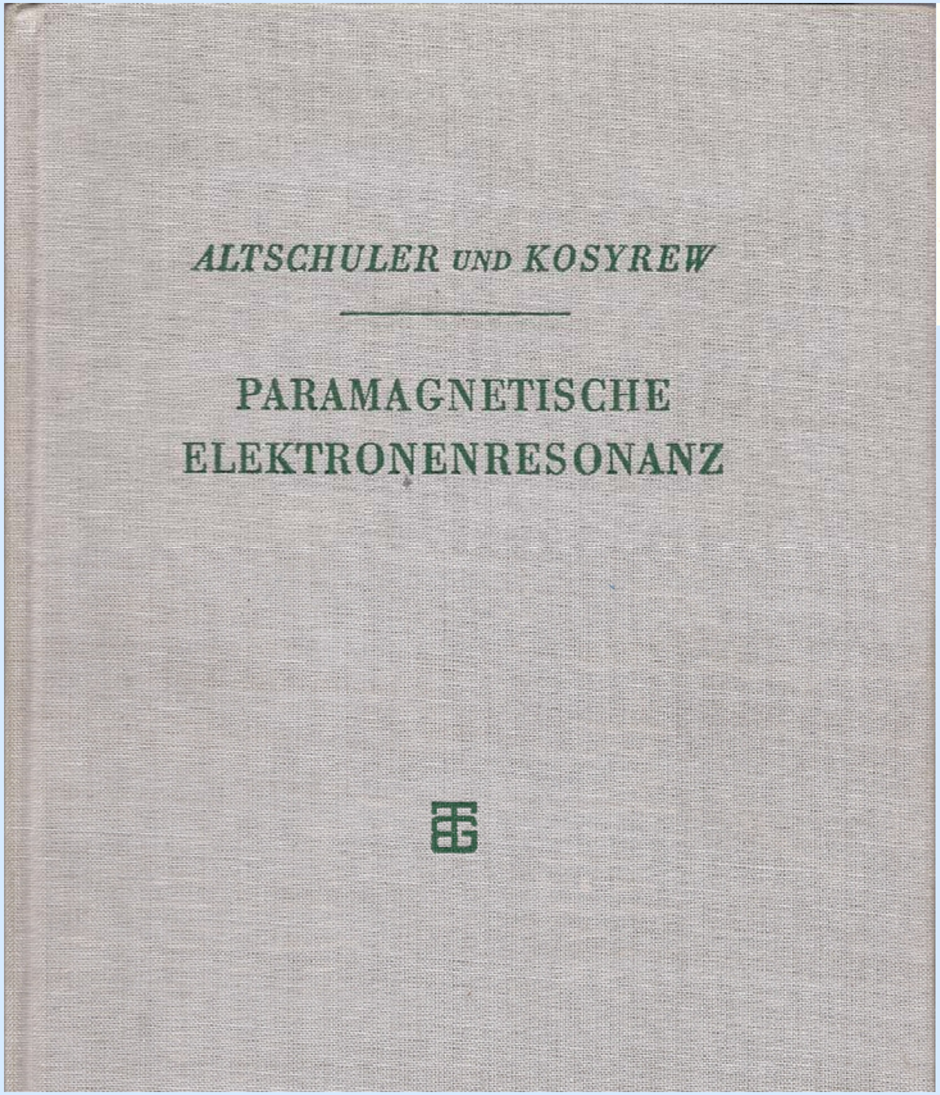
with $\gamma = \frac{g \cdot \mu_B}{\hbar}$ Gilbert damping

|M|=const.
M spirals on a sphere into the z-axis



It was difficult to measure g because of various contributions to the internal anisotropy field $\mathbf{H}_{\mathbf{eff}}$.

For itinerant ferromagnets (Fe, Co, Ni) often the g-factor was assumed to be g~2 and |M|= const (see Section 3) .



С. А. Альтшулер, Б. М. Козырев

Электронный парамагнитный резонанс

Moskau 1961

Kazan, Juli 1959

Shortly after it was translated into German

Wissenschaftliche Redaktion:

Prof. Dr. A. Lösche und Dipl.-Phys. W. Windsch

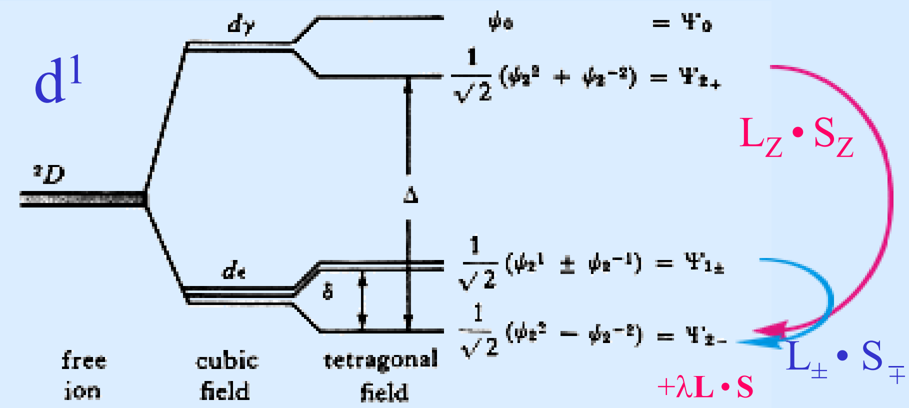
Kazan, Januar 1962

Printed in the German Democratic Republic

Orbital magnetism in second order perturbation theory

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

d^1



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

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

g_{exp} $B_2^0 \rightarrow K_2^0$

$$+ \text{ diamagnetic terms in } H_i H_j \tag{3-23}$$

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

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

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

In the principal axis system of a crystal with axial symmetry, the Λ 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

$$\mathcal{H} = g_{\parallel}\beta H_z S_z + g_{\perp}\beta(H_x S_x + H_y S_y) + D[S_z^2 - \tfrac{1}{3}S(S+1)] \tag{3-25}$$

where

$$\begin{aligned} g_{\parallel} &= g_e(1 - \lambda\Lambda_{\parallel}) \\ g_{\perp} &= g_e(1 - \lambda\Lambda_{\perp}) \\ D &= \lambda^2(\Lambda_{\perp} - \Lambda_{\parallel}) \end{aligned} \tag{3-26}$$

G.E. Pake, p.66

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

The orbital moment is quenched in cubic symmetry

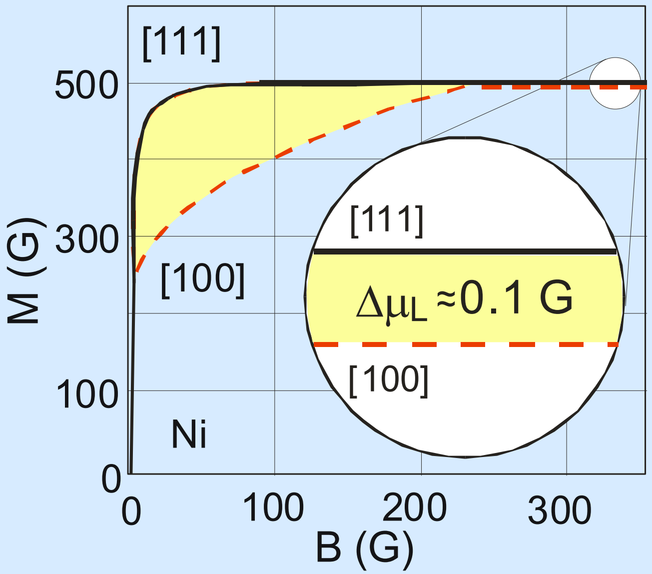
$\langle 2- | L_Z | 2- \rangle = 0,$

but not for tetragonal symmetry

Are generated by the same matrix element

Magnetic Anisotropy Energy (MAE) and anisotropic μ_L

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



$$g_{||} - g_{\perp} = g_e \lambda (\Lambda_{\perp} - \Lambda_{||})$$

anisotropic μ_L ↔ MAE

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

↕

$$MAE \propto \frac{\xi_{LS}}{4\mu_B} \Delta\mu_L$$ Bruno ('89)

$MAE = \int M \cdot dB \approx \frac{1}{2} \Delta M \cdot \Delta B \approx \frac{1}{2}\, 200 \cdot 200\ G^2$

$MAE \approx 2 \cdot 10^4\ erg / cm^3 \approx 0.2\ \mu eV / atom$

≈ 1μeV/atom is very small compared to
≈ 10 eV/atom total energy but all important

Characteristic energies of metallic ferromagnets

binding energy	1 - 10 eV/atom
exchange energy	10 - 10^3 meV/atom
cubic MAE (Ni)	0.2 μeV/atom
uniaxial MAE (Co)	70 μeV/atom

K. Baberschke, Lecture Notes in Physics, Springer **580**, 27 (2001)

2. Orbital- and spin- magnetic moments μ_L ,μ_S in ferromagnetic monolayers

Determination of MAE K_i and g-tensor

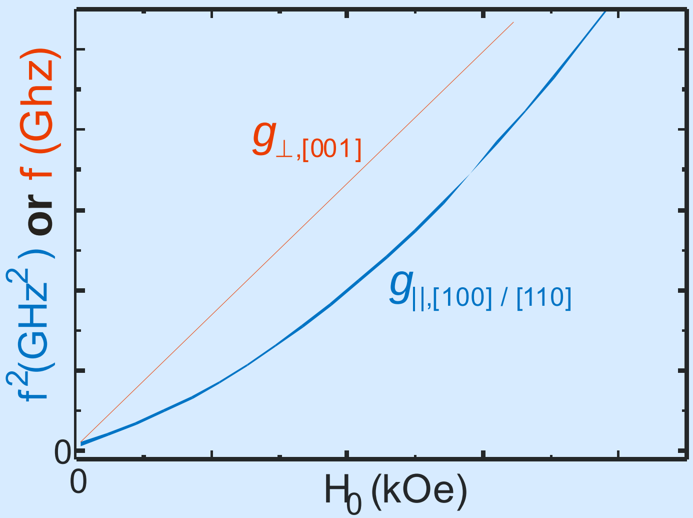
$$\frac{\omega^2}{\gamma^2_{||,[100]}} = H^2_{0,[100]} + H_{0,[100]}\left(4\pi M - 2\frac{K_2}{M} + \frac{4K_{4||}}{M}\right) + 2\frac{K_{4||}}{M}\left(4\pi M - 2\frac{K_2}{M} + \frac{2K_{4||}}{M}\right)$$

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

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

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

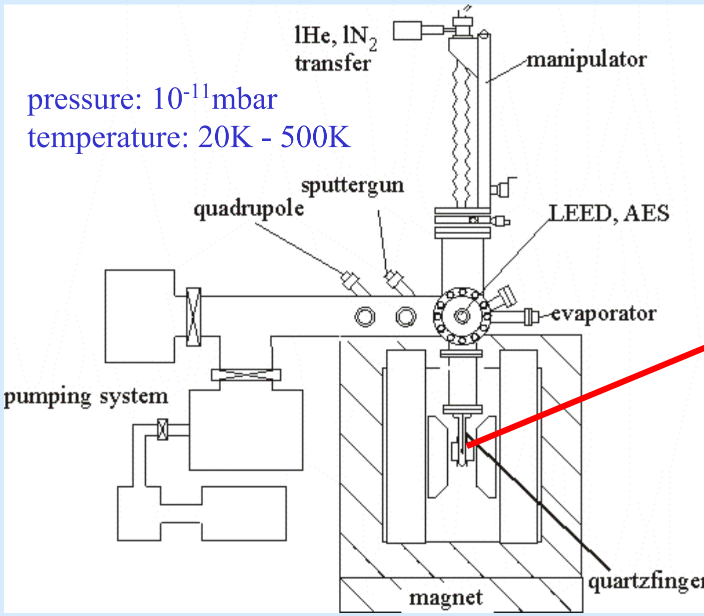
C. Kittel, *J.Phys. Radiat.* ***12***, *291 (1951)*

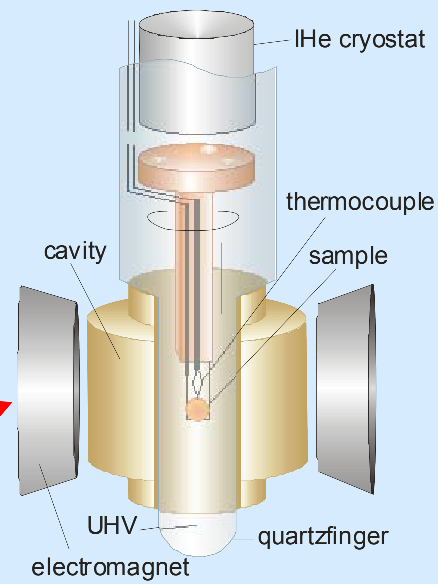


In FMR a large range of frequencies is needed 1 to >200 GHz

In situ UHV-FMR set up 1, 4, 9 GHz

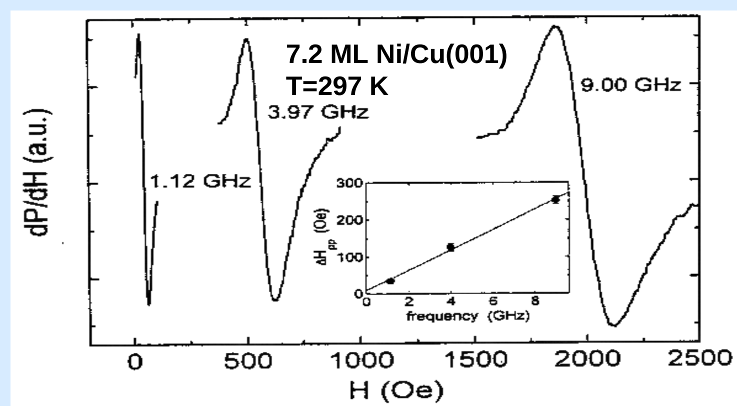
pressure: 10^{-11}mbar
temperature: 20K - 500K





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

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



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

VOLUME 82, NUMBER 11 PHYSICAL REVIEW LETTERS 15 MARCH 1999

Orbital Magnetism and Magnetic Anisotropy Probed with Ferromagnetic Resonance

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Department of Physics, Uppsala University, Box 530, S-75121 Uppsala, Sweden
(Received 27 July 1998)

Via ferromagnetic resonance both the magnetic anisotropy energy (MAE) and the spectroscopic splitting tensor (g tensor) for a bcc $Fe_2/V_5(001)$ superlattice are measured independently. The theoretically proposed proportionality between the anisotropy of the orbital moment μ_L and the MAE is quantitatively checked and its limitations are discussed. From layer-resolved *first-principles* calculations we find a reduced spin moment $\mu_S = 1.62\mu_B$ for Fe and $\mu_S^V = -0.67\mu_B$ in the first V layer. The g-tensor elements reveal a 300% enhanced ratio $\mu_L/\mu_S = 0.133$ in comparison to bulk Fe. The MAE and the orbital moment anisotropy is found to be unusually small for Fe monolayers. [S0031-9007(99)08741-4]

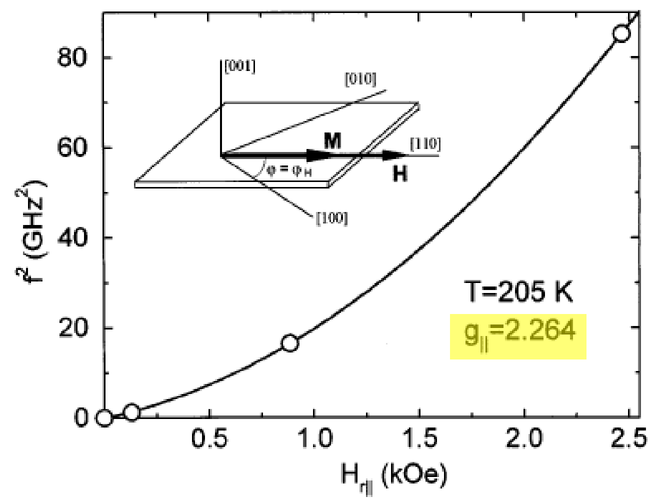
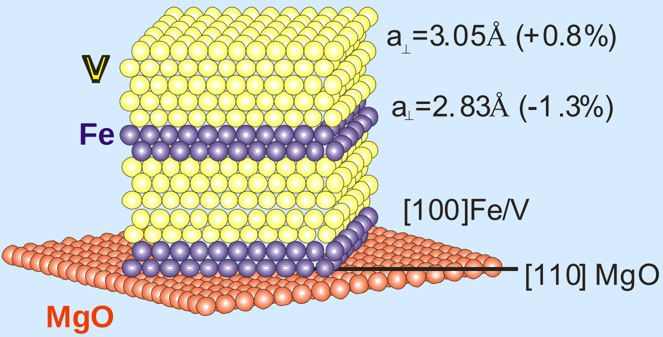
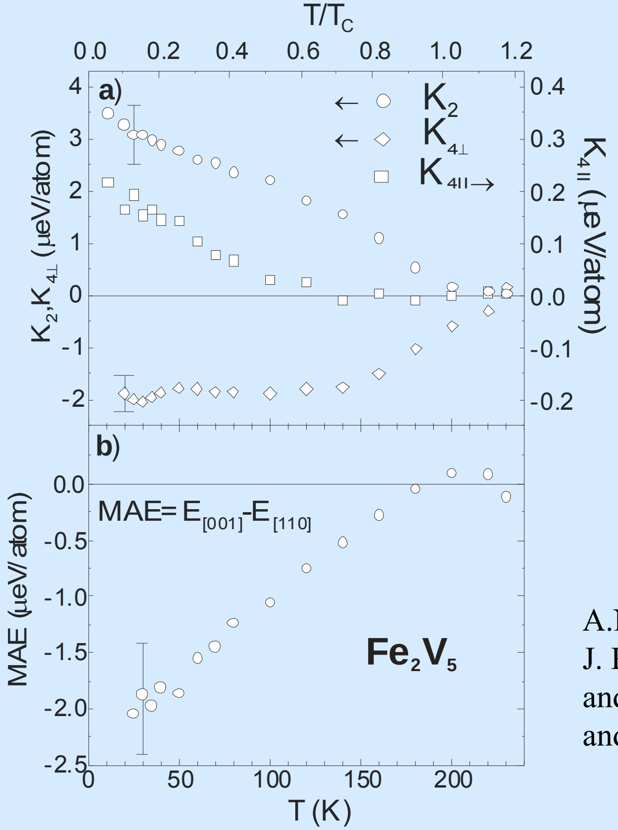


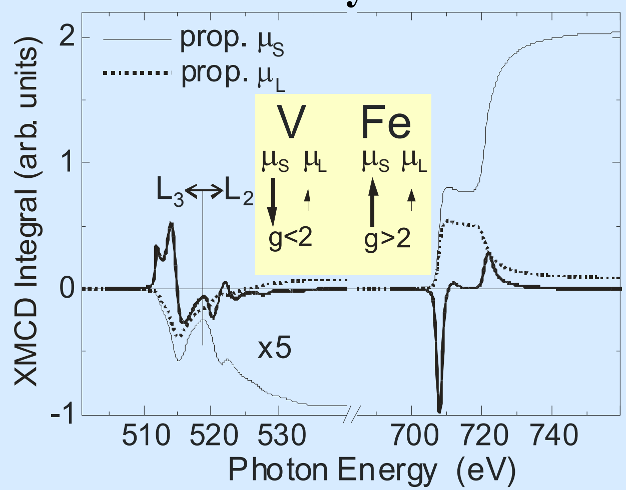
FIG. 1. Analysis of $g_{||}$ according to Eq. (4) at $T = 205$ K. The solid line is a fit to the experimental $H_{r||}$ (circles).

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

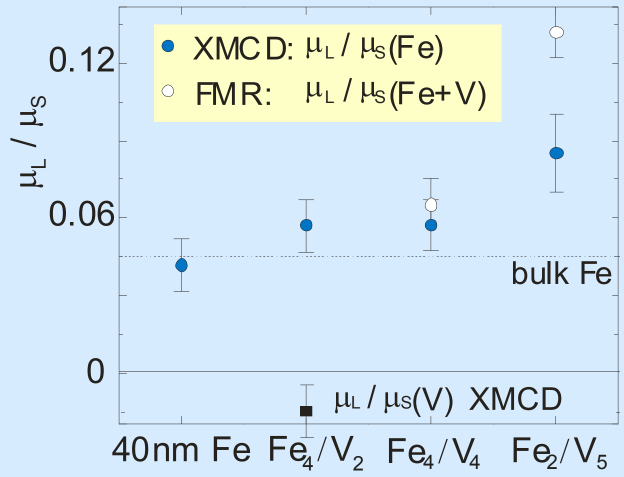




X-rayMCD



FMR



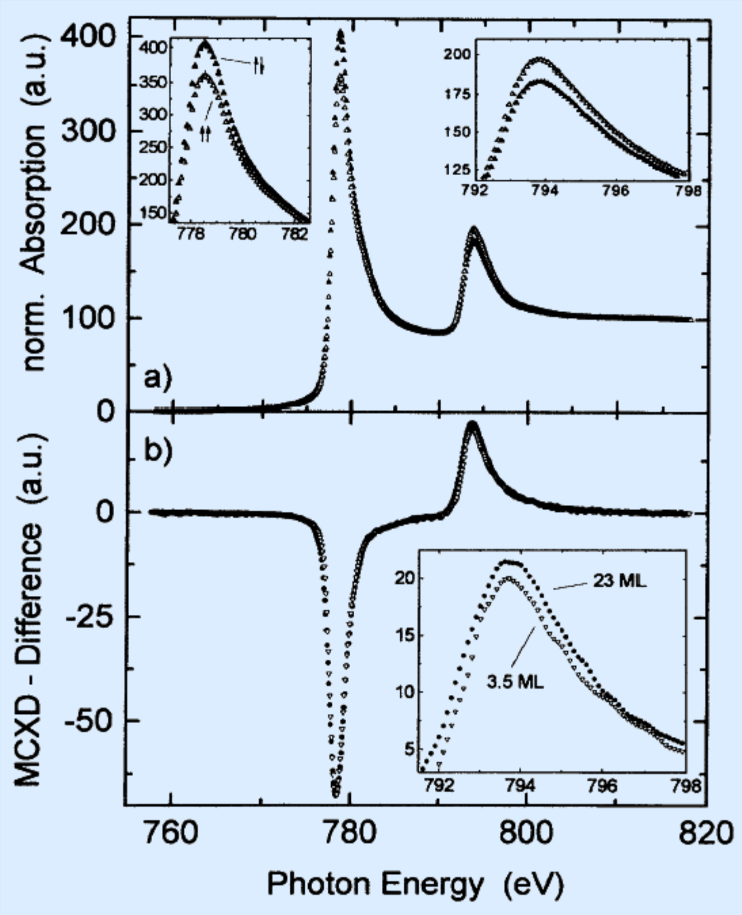
$$\frac{\mu_L}{\mu_S} = \frac{g-2}{2}$$ (Kittel'49)

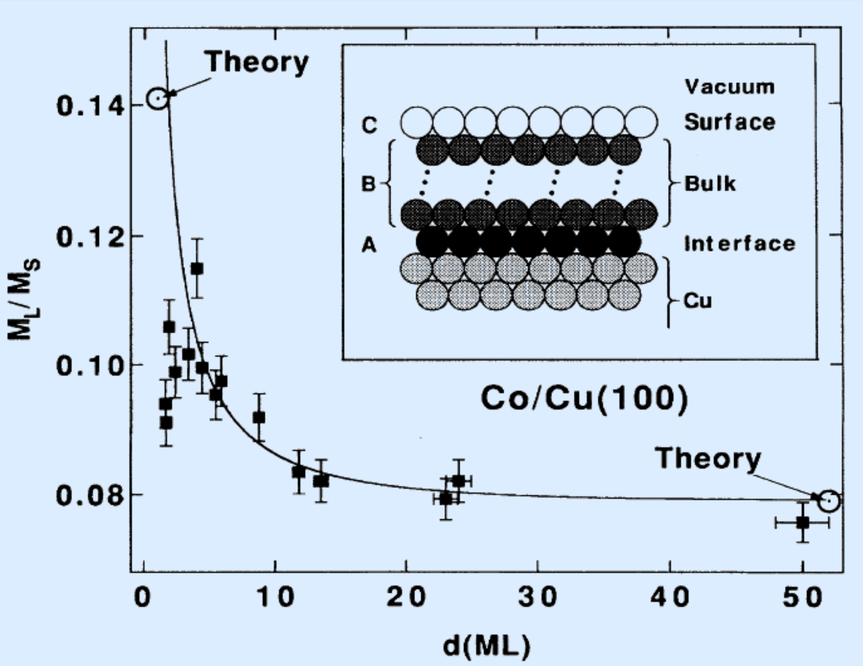
In solids g and μ_L are tensors

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					
$g_{\|\|}$	$g_{\perp}$	μ_L/μ_S	μ_L (μ_B)	μ_S (μ_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

Enhancement of Orbital Magnetism at Surfaces: Co on Cu(100)

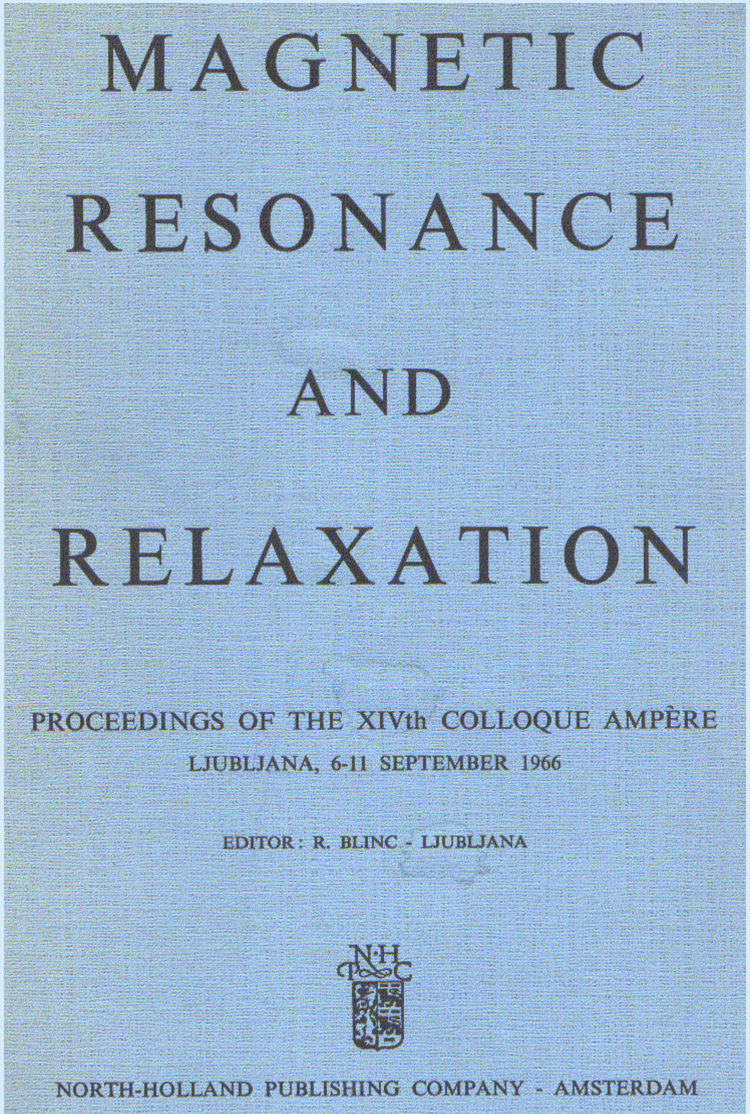




$$\left(\frac{M_L}{M_S}\right)_{\exp} = \frac{Ae^{-D(d-1)/\lambda} + B\Sigma_{n=3}^{d} e^{-D(n-2)/\lambda} + C}{\Sigma_{n=0}^{d-1} e^{-nD/\lambda}}$$

M. Tischer et al., Phys. Rev. Lett. **75**, 1602 (1995)

3. spin-phonon, spin-spin dynamics



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]).

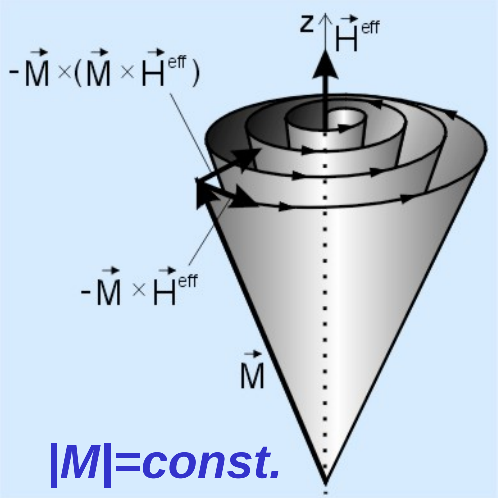
In this report we mean, first of all, to outline the development of the Van Vleck theory in recent years, then, to analyse the difficulties which the spin–lattice relaxation had to face and dwell on some of the possible ways of overcoming them, and, finally, to consider various phenomena, caused by spin–phonon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

90% of today's FMR experiments use

Landau-Lifshitz-Gilbert equation(1935)

$$\frac{d\mathbf{m}}{dt} = -\gamma\,\mathbf{m}\times\mathbf{H}_{\text{eff}} + \alpha\,\mathbf{m}\times\frac{d\mathbf{m}}{dt}$$

Gilbert damping



|M|=const.

M spirals on a sphere into z-axis

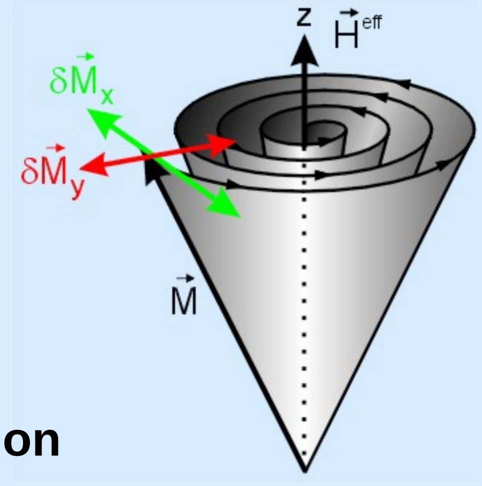
Bloch-Bloembergen Equation (1956)

$$\frac{dm_z}{dt} = -\gamma(\,\mathbf{m}\times\mathbf{H}_{\text{eff}})_z - \frac{m_z - M_S}{T_1}$$

$$\frac{dm_{x,y}}{dt} = -\gamma(\,\mathbf{m}\times\mathbf{H}_{\text{eff}})_{x,y} - \frac{m_{x,y}}{T_2}$$

spin-lattice relaxation *(longitudinal)*

spin-spin relaxation *(transverse)*



M_z=const.

Gilbert damping versus magnon-magnon scattering.

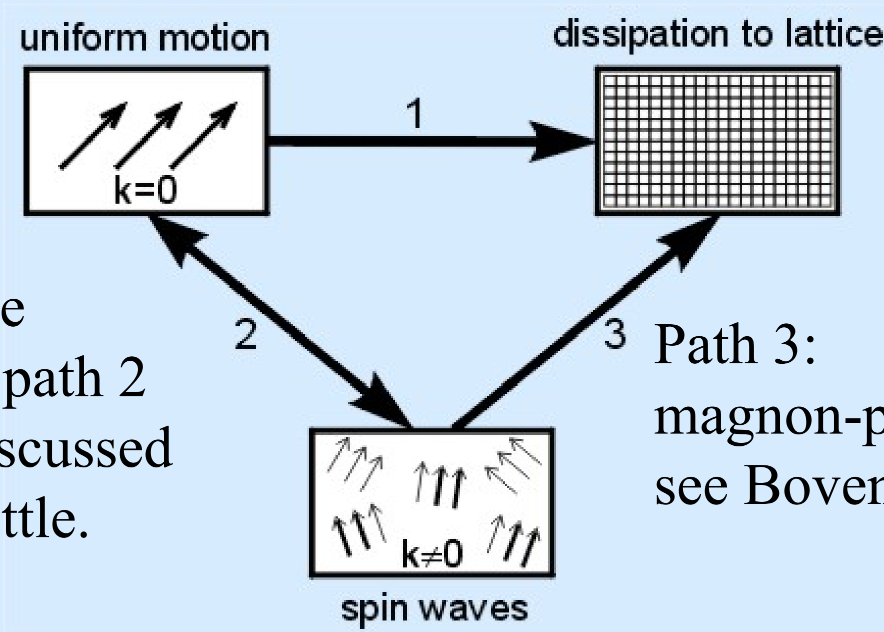
1834 IEEE TRANSACTIONS ON MAGNETICS, VOL. 34, NO. 4, JULY 1998

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.

Uniform Motion Dissipation in Lattice

Mostly an effective damping (path 1) is modeled/fitted.



In nanoscale magnetism path 2 has been discussed very very little.

Path 3:
magnon-phonon scattering, see Bovensiepen PRL 2008

the uniform mode to spin wave k. (for realistic imperfec-
tions, the calculation of the p's is non-trivial [6]). All these processes have one thing in common: they do not preserve the magnitude of the uniform mode. Therefore, in the desired equation of motion for the uniform mode alone, they cannot be described by a damping term of either Gilbert or Landau-Lifshitz form. Clearly this feature must carry over to the case of large motions also. It follows that this kind of damping, leaving aside the above mentioned instabilities for the moment, must in general give an equation of motion of the form (m now refers to the uniform component only)

$$\delta\dot{m}_i = \left(\vec{m}\times\vec{H}\right)_i - \sum_{j=1}^{3}\frac{1}{T_{ij}}\delta m_j \qquad i = 1,2,3 \qquad (7)$$

reminiscent of the equations used in paramagnetic and nuclear resonance. δm_j is the deviation of m_j from its equilibrium value. Of course, the relaxation times T_{ij} are

All these processes…do not preserve the magnitude of the uniform mode…

Longitudinal T_1 and transvers T_2 - scattering

that depends on spatial variation of the magnetization field. However, for samples of this size, degradation of the uniform motion by spin wave excitations needs to be taken into account. Then the damping of the uniform motion no longer conserves its length, and the GLL damping term no longer applies. Instead, damping terms take forms similar to those found in paramagnetic resonance. Finally, an estimate is made of the initial

…the GLL damping term no longer applies…

FMR Linewidth - Damping

Landau-Lifshitz-Gilbert-Equation

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

viscous damping,
energy dissipation

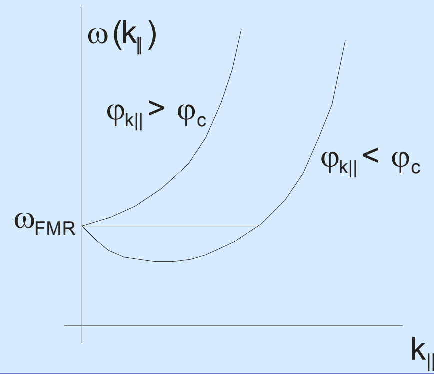
Gilbert-damping ~ω

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

in conventional FMR

2-magnon-scattering

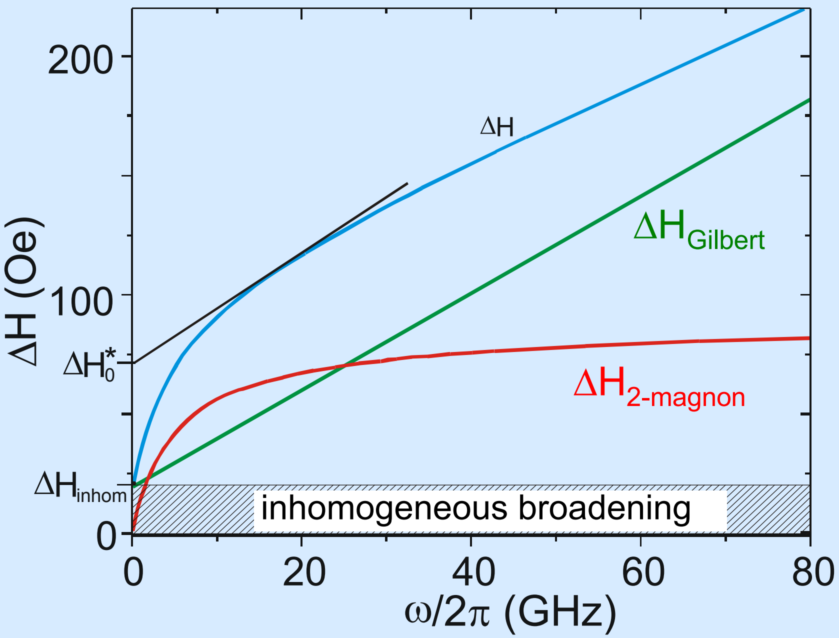
R. Arias, and D.L. Mills, *Phys. Rev. B* ***60****, 7395 (1999);*
D.L. Mills and S.M. Rezende in
'*Spin Dynamics in Confined Magnetic Structures*',
edt. by B. Hillebrands and K. Ounadjela, Springer Verlag

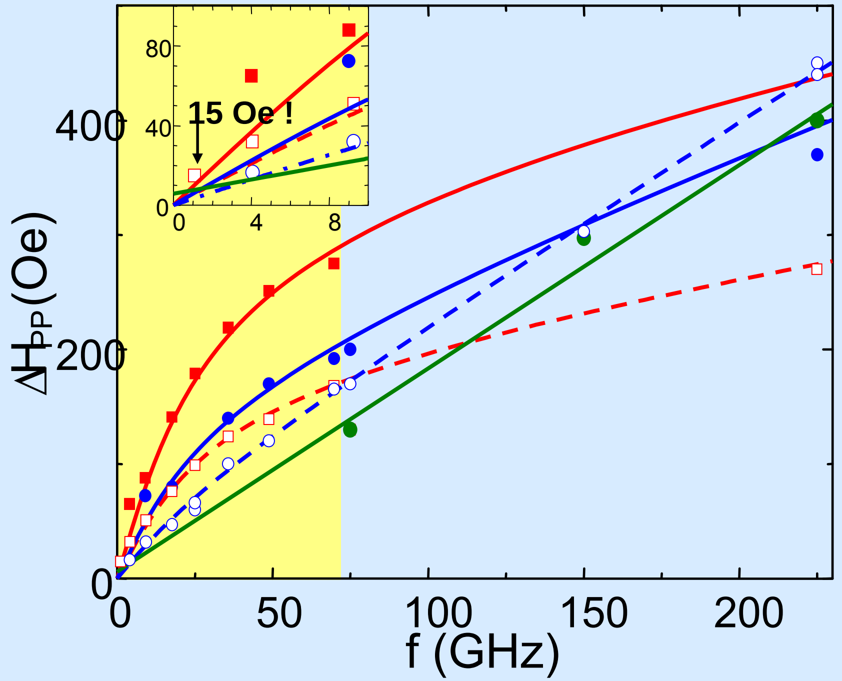


$$\Delta H^{2Mag}(\omega) = \Gamma \arcsin\sqrt{\frac{[\omega^2+(\omega_0/2)^2]^{1/2} - \omega_0/2}{[\omega^2+(\omega_0/2)^2]^{1/2} + \omega_0/2}}$$

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

Which (FMR)-publication has checked (disproved) quantitatively this analytical function?





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

*K. Lenz et al. PRB **73,** 144424 (2006)*

two-magnon scattering dominates Gilbert damping by two orders of magnitude:

T_2~ 0.2 n s vs. T_1~ 40 n s

Γ ≈ anisotropic spin wave scattering
G ≈ isotropic dissipation
no anisotropic conductivity is need

	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

Angular- and frequency-dependent FMR on

Fe_3Si binary Heusler structures epitaxially grown on MgO(001)

d = 40nm

Kh. Zakeri et al.

PRB **76**,104416 (2007)

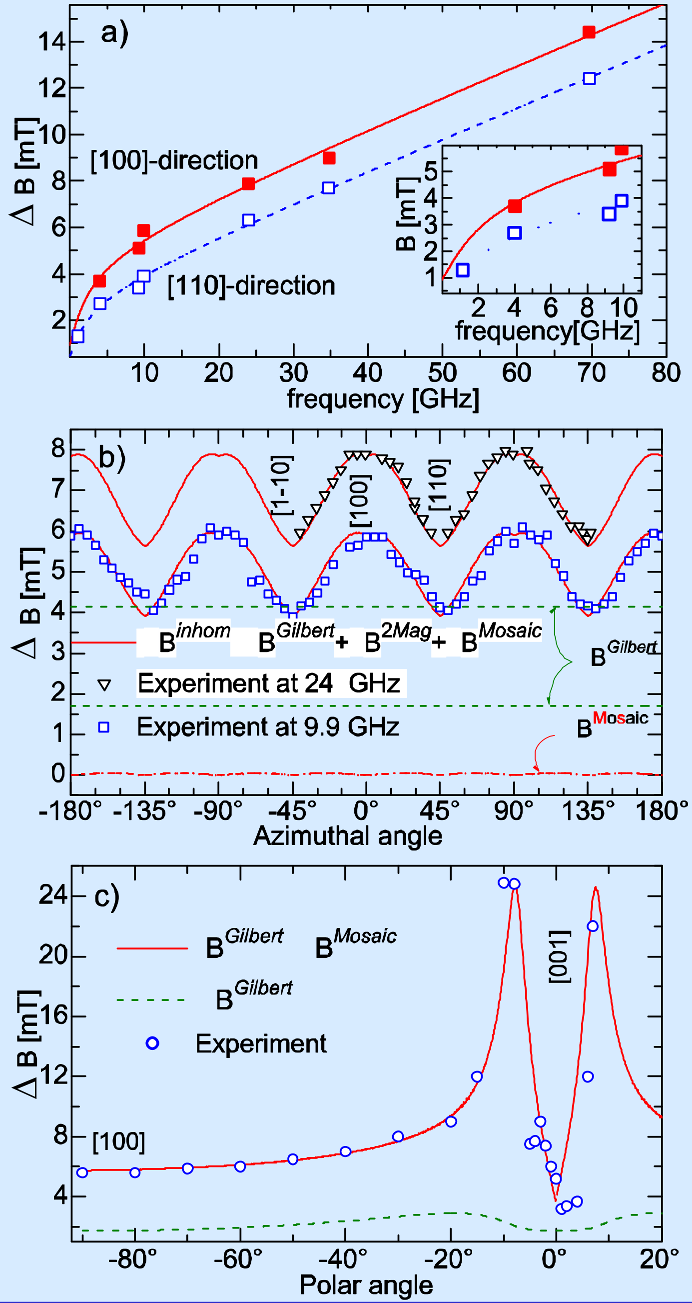
PRB **80**, 059901 (2009)

Angular dependence at 9 and 24 GHz

$\gamma\Gamma \approx (26 - 53) \cdot 10^7\ sec^{-1}$, anisotropic

$G \approx 5 \cdot 10^7\ sec^{-1}$, isotropic

A phenomenological effective *Gilbert damping parameter* gives very little insight into the microscopic relaxation and scattering .



PHYSICAL REVIEW B **80**, 224421 (2009)

Two-magnon damping in thin films in case of canted magnetization: Theory versus experiment

J. Lindner,* I. Barsukov, C. Raeder,† C. Hassel, O. Posth, and R. Meckenstock
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(Received 19 May 2009; revised manuscript received 17 September 2009; published 18 December 2009)

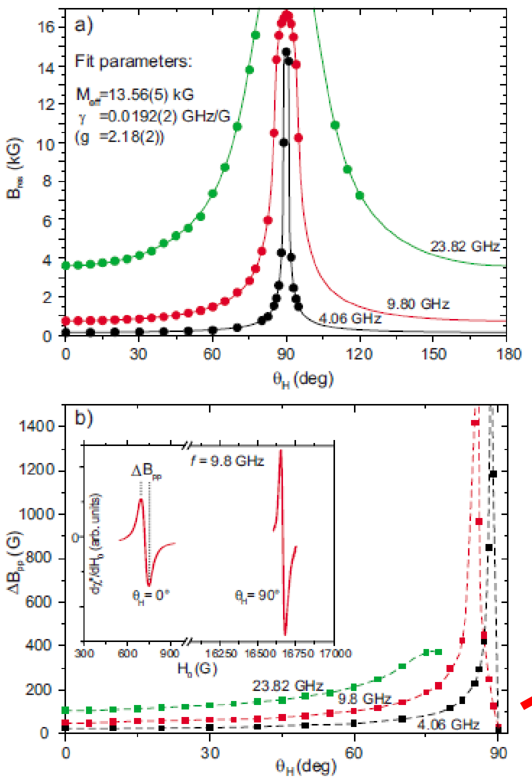

FIG. 1. (Color online) (a) Angular dependence of the resonance field for the frequencies of 4.06, 9.8, and 23.82 GHz. The dots are the experimental data, whereas the lines are fits obtained from Eq. (2) with the parameters mentioned in the text. (b) shows the angular dependence of the FMR linewidth. Note that the x axis is only half of the one shown in (a). Dashed line is a guide to the eyes. Inset shows the spectra detected at 9.8 GHz (X band) for θ_H=0° (external field in-plane) and θ_H=90° (external field normal to plane).

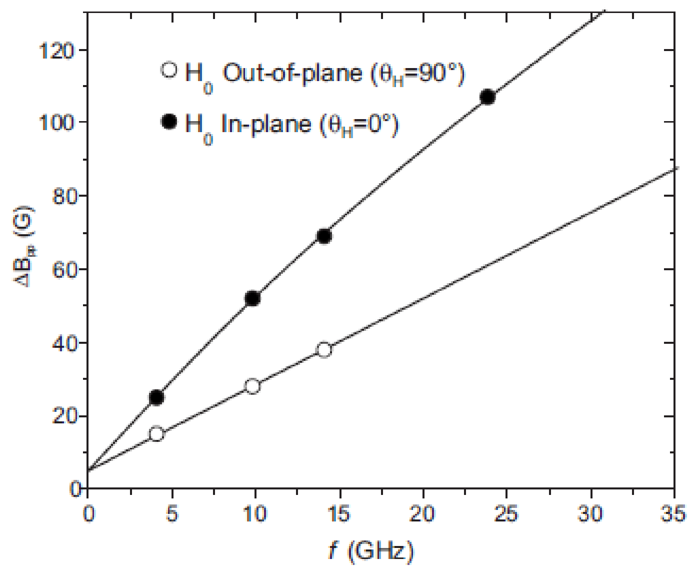

FIG. 2. Peak-to-peak FMR linewidth (ΔB_{pp}) as a function of the frequency for out-of-plane (open circles) and in-plane (filled circles) magnetizations.

PHYSICAL REVIEW B 74, 094436 (2006)

Dynamic approach for micromagnetics close to the Curie temperature

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(Received 30 August 2006; published 29 September 2006)

The basis of most of theoretical investigations of thermal magnetization dynamics is a micromagnetic approach which considers the magnetization of a small particle or a discrete magnetic nanoelement as a vector of a fixed length (referred to here as a macrospin) with the phenomenological Landau-Lifshitz-Gilbert (LLG) equation of motion augmented by a noise term.[5] However, contrary to the situation with atomic spins, there is no reason to assume a fixed magnetization length for nanoelements at nonzero temperature. For instance, the latter can decrease in time upon heating by a laser pulse. Hence, from the point of view of modeling of magnetization dynamics, there is a general need for further development of the micromagnetic theory in terms of its ability to deal with elevated temperatures.

III. LANDAU-LIFSHITZ-BLOCH EQUATION

The LLB equation following from Eq. (1) in the spatially homogeneous case can be written in the form[13]

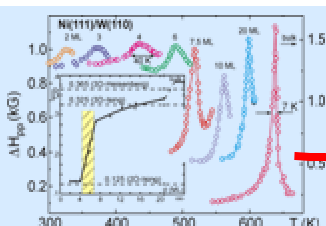
$$\dot{\mathbf{m}} = -\gamma[\mathbf{m}\times\mathbf{H}_{\mathrm{eff}}] + \gamma\alpha_{\parallel}\frac{(\mathbf{m}\cdot\mathbf{H}_{\mathrm{eff}})\mathbf{m}}{m^2} - \gamma\alpha_{\perp}\frac{[\mathbf{m}\times[\mathbf{m}\times\mathbf{H}_{\mathrm{eff}}]]}{m^2}, \qquad (2)$$

where $\mathbf{m}=\langle \mathbf{s}\rangle$ is the spin polarization and $\alpha_{\parallel}$ and $\alpha_{\perp}$ are dimensionless longitudinal and transverse damping parameters given by

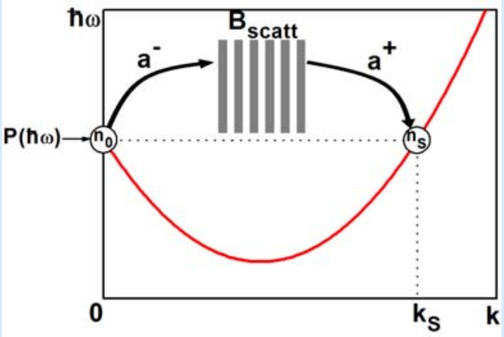
$$\alpha_{\parallel} = \alpha\frac{2T}{3T^{\mathrm{MFA}}}, \qquad \alpha_{\perp} = \alpha\left[1 - \frac{T}{3T^{\mathrm{MFA}}}\right] \qquad (3)$$

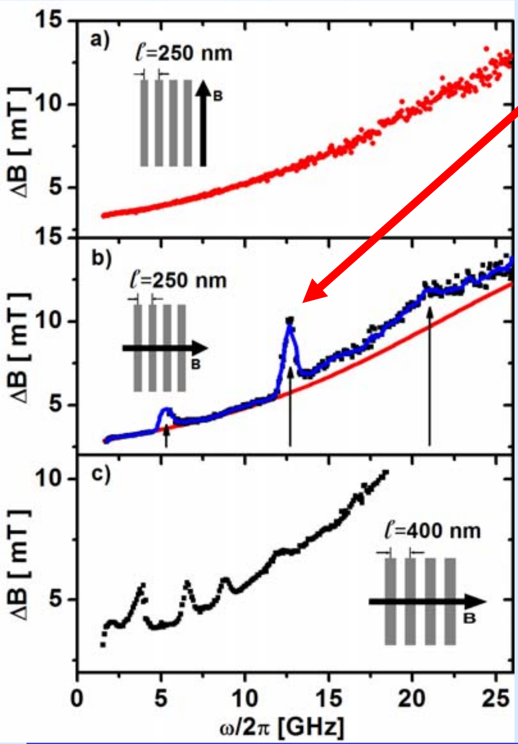
IV. CONCLUSIONS AND OUTLOOK

In conclusion, performing atomistic simulations of thermal magnetization dynamics we observe an increase of the macroscopic transverse damping approaching the Curie temperature. This increase is determined by the thermal dispersion of magnetization and would exist independently from any other possible thermal dependence of internal damping mechanisms such as phonon-magnon coupling. This effect explains the broadening of the resonance linewidth in classical FMR experiments.[16] Furthermore, the magnetization vec-

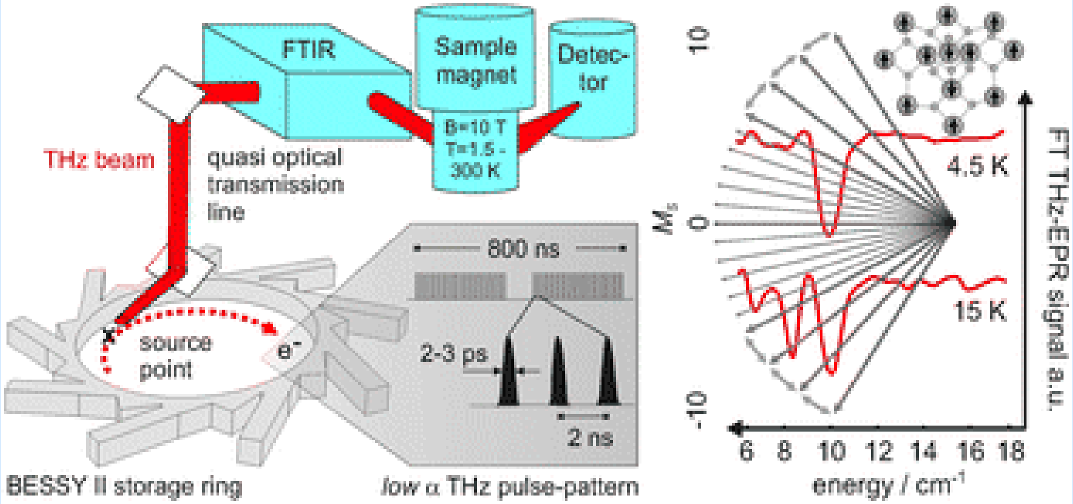


4. Summary and future





2 magnon scattering in permalloy = f(ω, l) ,
I. Barsukov, Farle-group, unpublished 2011



FMR using Synchrotron radiation in THz

•Todays analysis of spin-wave dynamics should not assume |M| = const, i. e. T=0 assumption.

•g – tensor and spin wave excitations are ignored in most cases

•Long wavelength spin-waves relax slowly with G ~ nano sec
2-magnon scattering with Γ~ 10-100 pico sec.

•All spin wave excitations need a second scattering –dephasing-constant. Important for femto sec. relaxation.

Thank you and prof. S. A. Al'tshuler

Don't follow the standard literature and reasoning.
FMR can be much more powerful in unexplored areas.

Ferromagnetic resonance in nanostructures, rediscovering its roots in paramagnetic resonance

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In 1944 Zavoiskii discovered the electron paramagnetic resonance (EPR), here in Kazan. Shortly after the resonant microwave absorption in ferromagnetic Fe, Co, Ni metals (FMR) was discovered (Griffiths 1946, Zavoiskii and Kittel 1947). Surprisingly both techniques went different routes: The EPR explored an enormous variety of para-magnets in solids, liquids, and gas phase. Already one decade later Altshuler and Kosyrew published a comprehensive book – the first "*EPR-bible*" [1]). The focus was to determine orbital- and spin-magnetic moments (g-tensor), hyperfine interactions, and from the linewidth the spin dynamics (T1, T2 relaxation). In FMR most of the experi-ments and theory assumed the total value $|M|$ to be constant in the equation of motion and used only one effective damping parameter (Gilbert). This is an enormous, unneces-sary limitation for today's analysis of magnetism in nanostructures and ultrathin films. To assume $|M| = \text{const}$ (p.196 in [2]) ignores spin wave excitations, scattering between longitudinal and transverse components of M. Moreover, in the framework of itinerant ferromagnetism, the magnetic moment/atom μ was assumed to be isotropic with g = 2! That ignores the anisotropy of μ in nanostructures and the importance of the orbital magnetic moments with $\mu_L/\mu_S = (g-2)/2$. Without finite μ_L we would have no magnetic anisotropy energy (MAE), no hard magnets. Only recently the "language" of EPR was adapted to FMR in ultrathin films [3]. A g-tensor is discussed and its interrelation with the MAE is pointed out. Also recent theory points out, that "…*there is no reason to assume a fixed magnetization length for nanoelements*…"[4]. This allows a detailed dis-cussion of magnon-magnon scattering, spin-spin, and spin-lattice relaxation – useful, for example, for fs spin dynamics.

We will discuss recent FMR experiments using frequencies from 1 GHz up to several hundred GHz, which allow measuring the proper g-factor components and μ_L, μ_S. From the frequency dependent linewidth magnon-magnon scattering can be separated from dissipative spin-lattice damping.

[1] *Paramagnetische Elektronenresonanz* S.A. Altshuler, B.M. Kosyrew Teubner Verlag Leipzig 1963 (Moskau 1961)
[2]*Ultrathin MagneticStructures II* B. Heinrich, J:A:C: Bland (Eds.) Springer Verlag Berlin Heidelberg 1994
[3] K. Baberschke in *Handbook of Magnetism and Advanced Magnetic Materials*, Vol.3 H. Kronmüller and S.S. Parkin (Eds.) John Wiley, New York 2007, p. 1617 ff
[4] O. Chubykalo-Fesenko et al. Phys. Rev. B 74, 094436 (2006)