# Magnetic Resonance(s)
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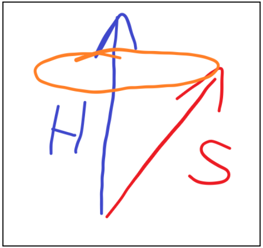
# Error Bars


This lecture will last 90 minutes $\pm 180$.
Should I rush ?

# Outline




- Dynamics of one (electronic) spin
    - Electron Spin Resonance (ESR)
- Ferromagnetic dynamics
    - Ferromagnetic Resonance (FMR)
    - Uniform, Non uniform Modes
    - Magnetic Objects : Domain Wall, Vortex
- Mossbauer, NMR

# Resonance vs "usual" Magnetometry

Classical Magnetometry = Magnetic Moment m(H,T,angle ...)

An alternative is to detect a Magnetic Resonance to determine :

- resonance field (or resonance frequency)
- amplitude of the resonance
- width of the resonance line

as a function of external parameters (Applied Magnetic Field, Geometry, Temperature ...)

and hopefully to extract interesting magnetic infos

# Gyromagnetic factor

A magnetic atom is characterised by its quantum number J (could be J=S only)

The atom angular momentum is $L = \hbar J$.
The atom magnetic moment is $m = g\mu_B J$.

The gyromagnetic factor is the ratio magnetic moment / angular momentum i.e.

$$\gamma = -\frac{g\mu_B}{\hbar} = -\frac{ge}{2m_e}$$

$\gamma$ is negative (today), both moments are antiparallel.

UNLIKE the usual choice in spintronics where electrons magnetised up are labelled spin up (and in reality are spin down).

# Larmor precession

When a magnetic field H is applied, a Zeeman energy appears :

$$E_z = -\mu_0 \vec{m}.\vec{H}$$

The torque $\vec{\Gamma}$ which is applied to the magnetic moment is :

$$\vec{\Gamma} = \vec{m} \wedge \mu_0 \vec{H}$$

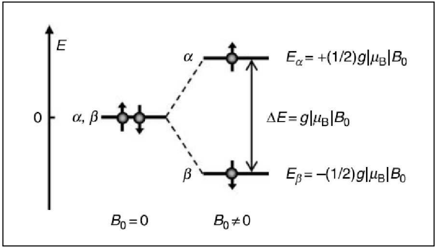
The torque corresponds to a change of angular momentum :

$$\vec{\Gamma} = \frac{d\vec{L}}{dt}$$

Finally : $\frac{d\vec{m}}{dt} = \gamma \vec{m} \wedge \mu_0 \vec{H}$

The equation corresponds to a precession around the applied field :
Larmor Precession
Angle $(\vec{m}, \vec{H})$ = constant (constant energy, no relaxation).

# Electron Spin Resonance (ESR)




In an applied magnetic field H, a spin 1/2 can absorb a photon = electromagnetic wave

$$h\nu = g\mu_B\mu_0 H$$

To allow the transition, the ac field from the wave must be

perpendicular to the applied field
($S_z$ is not anymore an eigen state)

# What can we learn from Larmor precession ?

$$\frac{d\vec{m}}{dt} = \gamma \vec{m} \wedge \mu_0 \vec{H}$$

$$h\nu = g \mu_B \mu_0 H$$

- if we know $\nu$ and g : field sensor, calibration
- if we know $\nu$ and H : g sensor, orbital/spin contributions, chemical infos

# Numbers

Applied Field $\mu_0 H_z$, J=S=$\frac{1}{2}$

$$\Delta E = g\mu_B\mu_0 H_z = h\nu$$

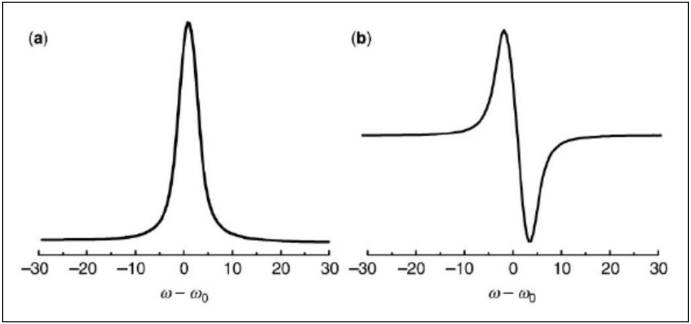
When g=2
$\nu$=10 GHz gives resonance at 0.357 Tesla
$\nu$=100 MHz gives resonance at 3.57 mTesla

MHz electronics = small field resonance (mT)
GHz microwave = Tesla field $\mu_0 H_{res}$
(electromagnets and superconducitng coils)

Two types of setups/measurements to get the resonance

At fixed field, scan the frequency, detect absorption

At fixed frequency, scan the field, detect absorption



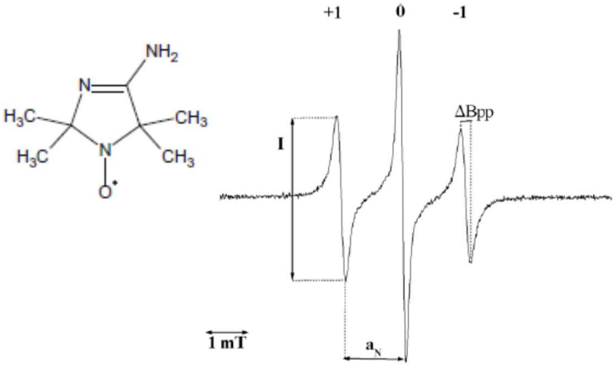

The absorption line or its derivative is measured

Extract resonance field, amplitude of absorption, width of the line (peak-to-peak)

# Table ESR

10-100 MHz ESR for practicals
Helmholz Coils for the applied field

# What to learn from ESR ?




X-band
Kempe EJPB 2010

Fig. 2. EPR spectrum of AT (see structure 4 in Fig. 1) dissolved in PEG 400 illustrating typical EPR parameter: $a_N$ – hyperfine splitting constant; I – signal amplitude; $\Delta B_{pp}$ – peak-to-peak line width.

# What to learn from ESR ?

Amplitude of the resonance signal : number of resonating species

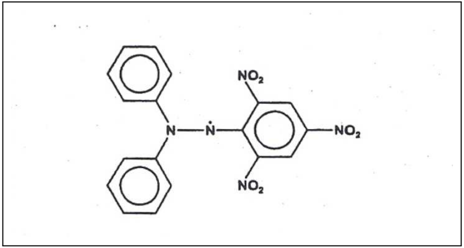
Position of the resonance line :

- shift from free electron g-factor
- environment effects on the orbitals (orbital moment is impacted)
- interaction with nucleus moment (hyperfine splitting of the energy lines)

Line width :

- intrinsic (narrow)
- distribution of g-factors (wider line)
- inhomogeneous field, sample

# DPPH calibration




DPPH : 2,2-Diphenyl-1-picrylhydrazyl (free radical)
Chemical Formula $C_{18}H_{12}N_5O_6$

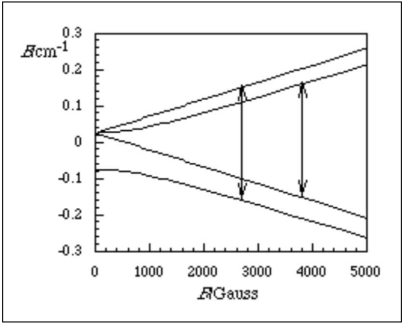
# DPPH for calibration

For a free electron $g = 2.0023$ (2 + correction QED)
For DPPH (very light atoms, small SO), $g = 2.0035$
$\gamma = 1.76\ 10^{11} Hz/T$(28.041 GHz/T)

The resonance field at 9.750 GHz for DPPH is 0.347703 T (g=2.0035)

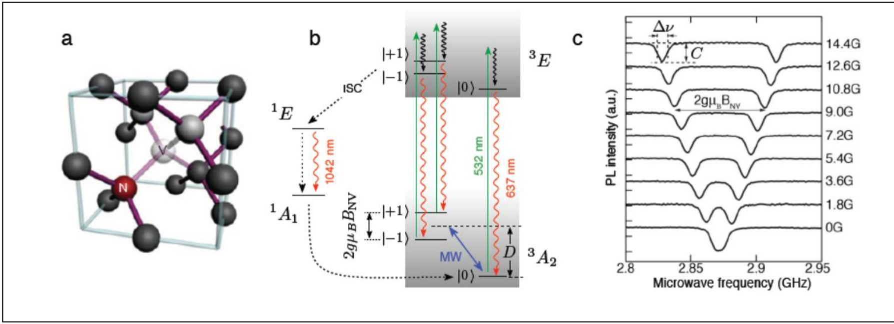
For DPPH, g factor varies from 2.003 to 2.0045 depending on preparation and environment (solvant in particular).

# Hyperfine Structure



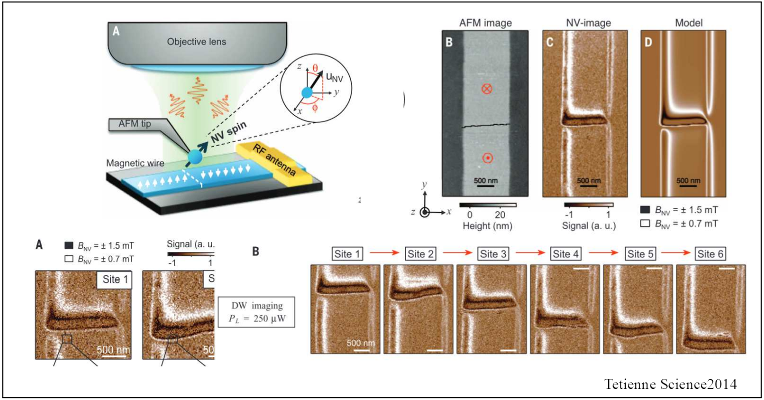

The electronic spin feels the field of the nuclear spin.
It is then a (S=1/2,I=1/2) system : singlet state + triplet state
Singlet-triplet degeneracy is lifted when the field is applied

NV center magnetometry




Balasubramanian et al. NatMat2009

# NV center magnetometry




Ta/CoFeB (1.5 nm)/MgO, perpendicular M.

# Ferromagnetic Resonance (FMR)

In a ferromagnetic material :
The volume torque acting on magnetisation is : $\vec{\Gamma} = \mu_0 \vec{M} \wedge \vec{H}_{eff}$.

The variation of volume angular momentum is $\frac{d\vec{L}}{dt} = \vec{\Gamma}$

$\frac{d\vec{M}}{dt} = \gamma \vec{\Gamma}$, $\gamma < 0$
So, $\frac{d\vec{M}}{dt} = \gamma \vec{\mu}_0 \vec{M} \wedge \vec{H}_{eff}$
Similar to Larmor

# LLG equation

Experimentally Larmor precession does not last forever and the magnetisation aligns with the field
Need relaxation

Landau-Lifshitz (LL) equation (1935) :
$$\frac{d\vec{M}}{dt} = \mu_0 \gamma \vec{M} \wedge \vec{H} + \alpha \frac{\vec{M}}{Ms} \wedge (\vec{M} \wedge \vec{H})$$

Landau-Lifshitz-Gilbert (LLG) equation (1955)
$$\frac{d\vec{M}}{dt} = -\mu_0 \gamma \vec{M} \wedge \vec{H} + \alpha_{LLG} \frac{\vec{M}}{Ms} \wedge \frac{d\vec{M}}{dt}$$

$\alpha_{LLG}$ has no unit
Typically 0.001 (low damping) to 0.1 (fast relaxation)

Mathematically, one can transform LL into LLG : same dynamics.

# Relaxation of the magnetic moment

The field is applied along z.
In NMR, Bloch equations (1946) are used and take into account two relaxations
The relaxation of $m_z$ : longitudinal relaxation
Characteristic time $T_1$

$$\frac{d\vec{m}_z}{dt} = \gamma \vec{m} \wedge \mu_0 \vec{H} - \frac{m_z - m_{sat}}{T_1}$$

Energy needs to be transferred out, to the lattice (spin-lattice relaxation time)

The relaxation of $m_x$ and $m_y$ : transverse relaxation, in Bloch equations : Characteristic time $T_2$

$$\frac{d\vec{m}_x}{dt} = \gamma \vec{m} \wedge \mu_0 \vec{H} - \frac{m_x}{T_2}$$

Energy stays in the spin system (spin-spin relaxation time)

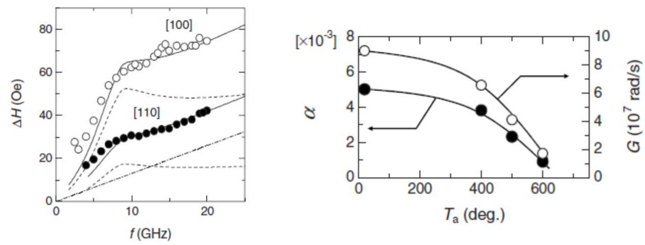
# Alpha

In ferromagnets, LL and LLG introduced a phenomelogical constant (isotropic) relaxation, characterised by damping constant $\alpha$.

Its value is measured from resonance experiments or relaxation experiments

Its minimum theoretical value is not zero (intrinsic damping) can be evaluated from band structure calculation.

# Low alpha material




Co2FeAl/MgO (Heusler)
Mizukami JAP2009

$Co_2FeAl$, effect of annealing.
Low damping when well ordered.

# Damping Contributions

- intrinsic
- inhomogeneous sample
- eddy currents
- Spin Transfer Torque
- Spin Pumping

# Inhomogeneous Samples

FMR : allows to compare series of samples (with thickness or growth conditions)

Easier to estimate homogeneity than Magnetometry
(think of a M(H) loop)

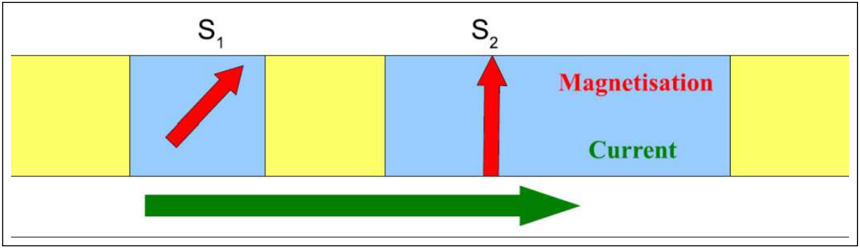
# Eddy Currents

skin depth (conductivity dependent)
Typically 100 nm at 10 GHz

negligible for ultrathin films (the field penetrates)
eddy current : losses, heating (microwave oven).

Water-based large samples (bio environment) $\Rightarrow$ need to go to lower frequency for ESR

# Spin Transfer Torque




Spin Transfer Torque : acts as an extra contribution to LLG

$$\frac{d\vec{M}}{dt} = \mu_0 \gamma \vec{M} \wedge \vec{H} + (\alpha_{LLG} + \alpha_{STT}) \frac{\vec{M}}{Ms} \wedge \frac{d\vec{M}}{dt}$$

$\alpha_{STT} \propto j.P$ = electron flow. spin polarisation

- Increase damping (faster relaxation, less ringing)
- Decrease (Cancel) damping (spin pumping, STT oscillators)

# Effective field

Landau-Lifschitz-Gilbert equation

$$\frac{d\boldsymbol{M}}{dt} = \gamma \boldsymbol{M} \times \boldsymbol{H}_{\boldsymbol{eff}} + \alpha \boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{H}_{\boldsymbol{eff}}) \tag{1}$$

$\boldsymbol{H}_{\boldsymbol{eff}}$ the effective field :

$$\boldsymbol{H}_{\boldsymbol{eff}} = -\frac{1}{\mu_0} \frac{\partial E}{\partial \boldsymbol{M}}$$

The effective field includes contributions from the applied field

(Zeeman energy), the demagnetising field (shape anisotropy), magnetocrystalline and exchange energies.

# What to do with this equation ?

Once the external parameters are known (geometry, field).

- Write the Total energy : $E_Z + E_d + E_{mc} + E_A$
- Look for $\vec{M}$ equilibrium position
- Determine the shape of the energy minimum (curvature)
- Determine the natural frequency of the oscillations around the equilibrium position

# Resonance Fields

Linear development around the equilibrium position of $\vec{M}$
Free energy F (spherical coordinates), $\vec{M} = M_s \vec{u}_r$ :

$$dF = -\mu_0 d\vec{M}.\vec{H}_{eff} = d\vec{M}.\frac{\partial F}{\partial \vec{M}}$$

$$Heff_\theta = -\frac{1}{\mu_0 M_s}\frac{\partial F}{\partial \theta}, Heff_\phi = -\frac{1}{\mu_0 M_s sin\theta}\frac{\partial F}{\partial \phi}$$

(all steps in Baselgia et al. PRB 1988)

$$(\frac{\omega^2}{\gamma^2}) = \frac{1}{M_s^2}(F_{\theta\theta}(\frac{F_{\phi\phi}}{sin^2\theta} + \frac{cos\theta}{sin\theta}F_\theta) - (\frac{1}{sin\theta}F_{\theta\phi} - \frac{cos\theta}{sin^2\theta}F_\phi)^2)$$

Line-width FWHM :

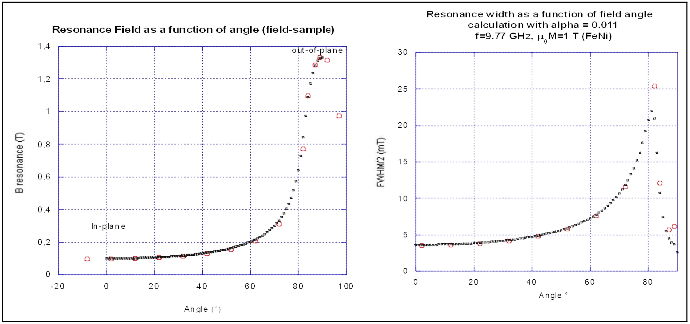
$$\Delta H = \frac{\alpha}{d\omega/dH}\frac{\gamma}{M_s}(F_{\theta\theta} + \frac{1}{sin^2\theta}F_{\phi\phi})$$

# Example : Soft Film

Uniform film, not patterned
Only Zeeman + Shape anisotropy :

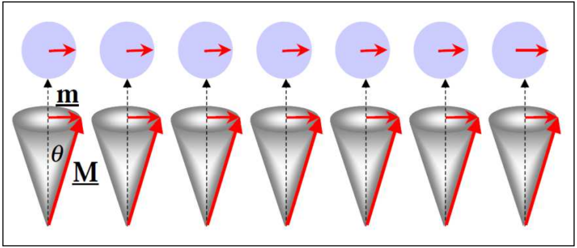
Field in-plane : $B_{res} = \frac{\sqrt{(\mu_0 M)^2 + 4 * \frac{\omega^2(1+\alpha^2)}{\gamma^2}} - \mu_0 M}{2}$
At 10 GHz : $B_{res} = \frac{\sqrt{(\mu_0 M)^2 + 4 * 0.34^2} - \mu_0 M}{2}$

Field out-of-plane : $B_{res} = \frac{\omega(1+\alpha^2)}{\gamma} + \mu_0 M$
At 10 GHz : $B_{res} = 0.34\,T + \mu_0 M$

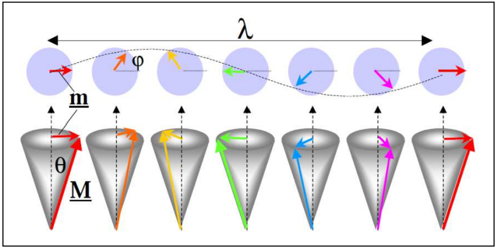



FMR gives M (magnetisation)
magnetometry (VSM-SQUID) gives m (magnetic moment)
Useful to compare

# Uniform vs Non Uniform modes

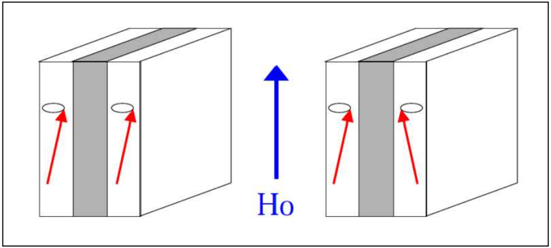



Uniform Mode : all spin precess together




Non Uniform Mode : FMR can excite non uniform modes

# Coupled Modes

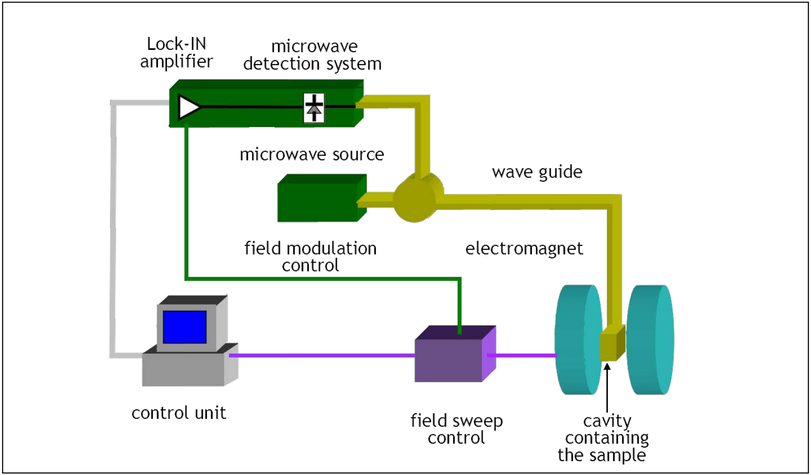



A coupled Bilayer can give rise to acoustic (in phase) and optical (out-of-phase) modes

# Experimental set-ups for FMR

Cavity (fixed f, scanning H) vs BroadBand (scanning f)

- X-band (10 GHz), generator, waveguide, detection scheme (diode) ...
- Broadband Source (VNA), waveguide, VNA




Fixed frequency, Resonating Cavity FMR

# Fixed f spectrometer

| Band | Frequency (GHz) | Wavelength (cm) | $B_{res}$ (T) free electron |
|---|---|---|---|
| S | 2-4 (3) | 10 | 0.11 |
| X | 8-12 (9.5) | 3 | 0.34 |
| K | 18-27 | 1.3 | 0.8 |
| Q | 35 | 0.86 | 1.3 |
| W | 75-110 (95) | 0.31 | 3.3 |

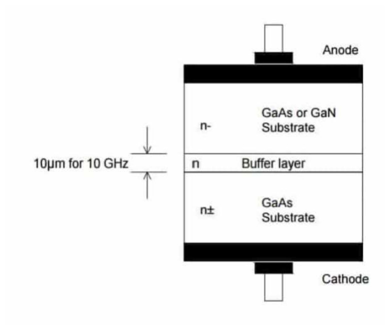
9.8 GHz (X-band) resonant cavity (mode $TE_{102}$)

# GHz sources

Older Technology : Klystrons
it is a type of vacuum tube. A beam of electrons is shaped into ac current and then coupled to transfer its energy to an electromagnetic wave.

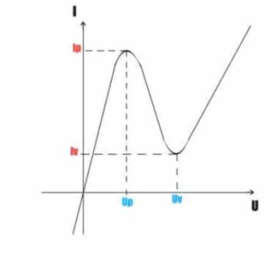
Newer Technology : Gunn diode
Solid State technology. Negative differential resistance which makes total resistance zero and creates oscillations.

# Gunn diode



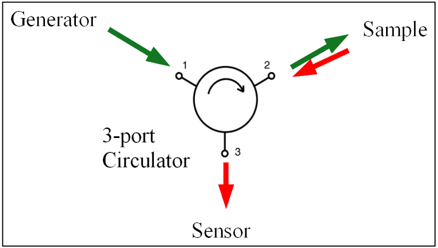
Anode
n-
GaAs or GaN
Substrate
10µm for 10 GHz
n
Buffer layer
n±
GaAs
Substrate
Cathode


ZAX

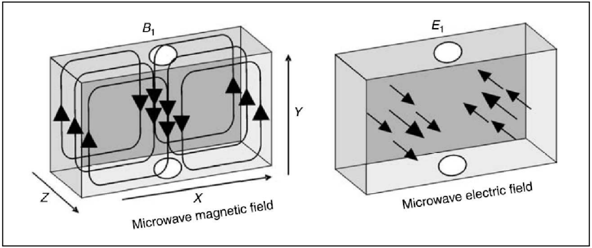
I
Ip
Iv
Up
Uv
U

One frequency : Dedicated Guide




Non reciprocal device (circulator)

# X-band cavity




rectangular cavity. Applied field is along short direction.
$E_{rf}$ is minimum in center, $B_{rf}$ is maximum.
( ! pumping direction)

# Detection

- RF diode + lock-in
- integrated analyser (power meter)
- Electric detection (small sample)

# X-band Sensitivity

10 GHz cavity
Best sensitivity : $10^{12}$ spins
(narrow line, not hyperfine splitted).

# Peak-to-peak line width

If the FMR resonance line has a Lorentzian shape :

$$f(B) = \frac{A}{\frac{(B-B_r)^2}{D^2} + 1}$$

Line amplitude : A. Line center : $B_r$. FWHM=2D

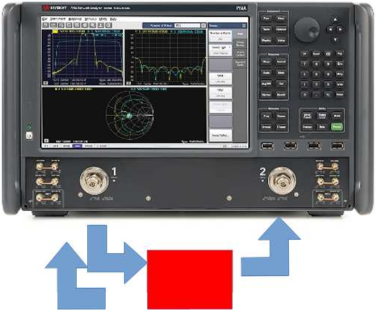
$$\frac{df}{dB} = \frac{-2A(B - B_r)}{D^2(\frac{(B-B_r)^2}{D^2} + 1)^2}$$

Peak to peak width of the line derivative (FMR measurement)

$$\Delta B_{pp} = \frac{2D}{\sqrt{3}} = \frac{FWHM}{\sqrt{3}}$$

# BroadBand FMR

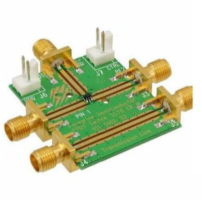
Choosing the applied field is often necessary
Frequency must be swept to find the resonance
Generator, waveguide, sample holder must accept a broadband signal.

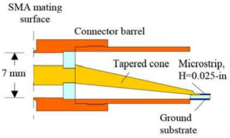


GHz waves

S11 : reflexion coefficient
S12 : transmission coefficient

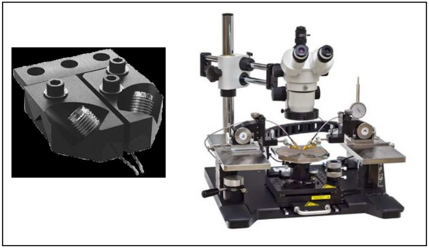
Vector Network Analyser (wave out, wave in).
The phase of the electric wave can be analysed (not only the intensity).



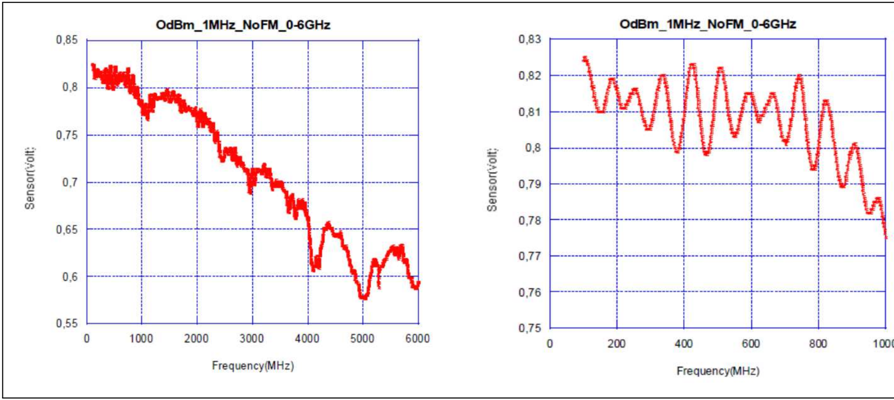



Signal is transmitted using coaxial cables, coax connectors, microbonding to striplines / coplanar waveguide

# Connecting the Sample



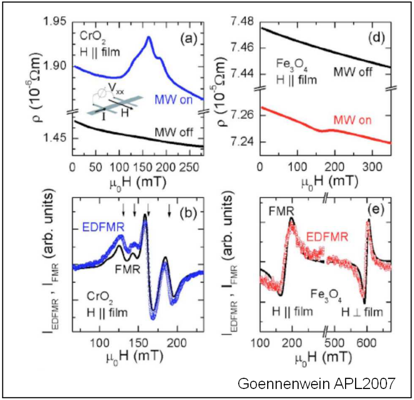
RF Probes can also be used to mechanically connect the sample.



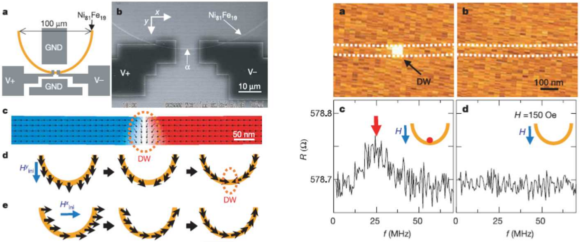

the signal is an electromagnetic wave. It can be reflected at many interfaces.

A cable is a resonating object.

Evaluating the electric field at the sample is a complicated task




Bolometric response : Heating of the sample when Wave is absorbed.




Saitoh Nat2004

A domain wall in a potential minimum is equivalent to a mass in a potential well

# Nuclear Magnetic Resonance

Some nuclei carry a nuclear spin I

Since $\frac{m_p}{m_e}$=2000

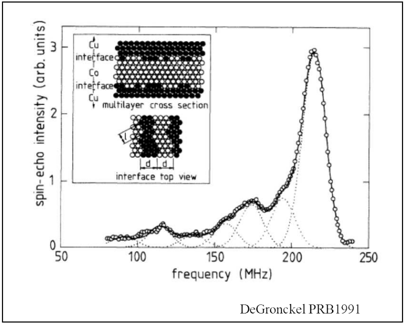
for a nucleus $\gamma_n = -\frac{ge}{2m_n}$ is 2000 times smaller compared to $\gamma_e$

NMR frequencies (MHz) are 2000 smaller compared to EPR frequencies (GHz)

Similar interest to go to high frequency to improve resonance line resolution

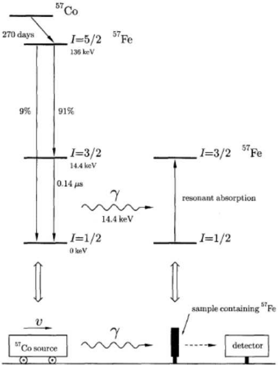
# NMR example

Co/Cu multilayer : where is Co ?




NMR in Spin-echo mode. Sensitivity $10^{16}$ Co spins
Environment (Co-Cu mixing) and strain (line shift)
See P. Mendels'presentation ESM2011 for more details about NMR

# Mossbauer : Principle

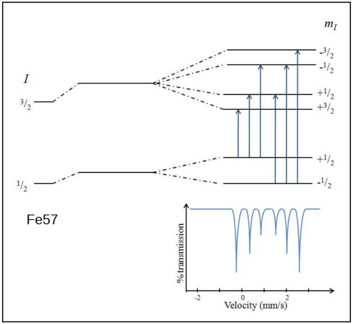



Mossbauer Spectroscopy

Recoil less emission
Recoil less absoprtion

Doppler to shift energy

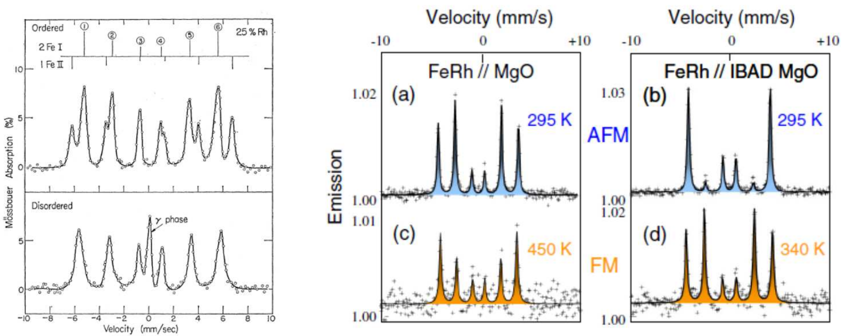
# Mossbauer : Fe57




6 allowed transitions when a gamma photon is absorbed (ground state I=1/2, excited state I=3/2)

# Mossbauer

FeRh : Are all Fe equivalent ?




Fe75Rh25 (bulk) Shirane PR1963 FeRh (films) Bordel PRL 2012

Need $Fe^{57}$ ($S_n$=1/2) in the sample (only 2% in natural Fe).

here 150nm thick films

Get local field on the nucleus (line splitting)

Get local field direction (ratio of lines intensities)

# Bibliography


Bland-Heinrich Book series (Ultrathin Magnetic Structures I,II, III)

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Review (70 pages) on metallic films FMR : M. Farle, Rep. Prog. Phys. 61, 755 (1998)