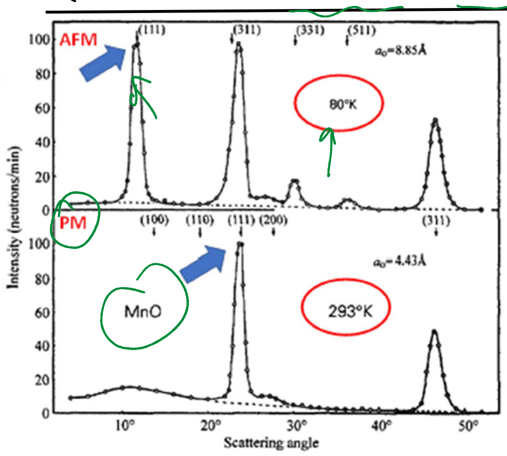
Lecture 28

Thursday, February 3, 2022 2:33 PM

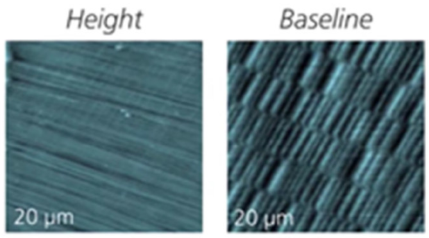
Review

(inelastic) neutron scattering



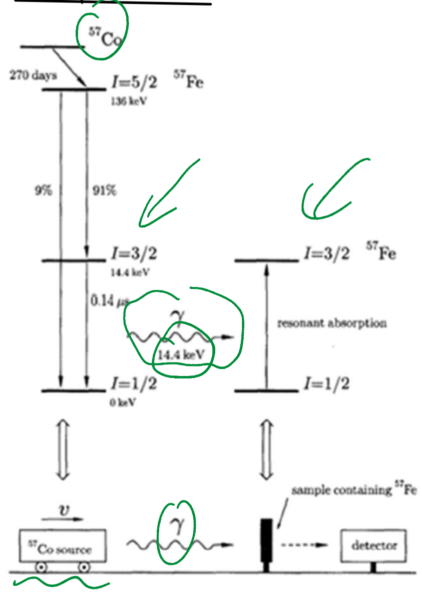
SPM

Topography and magnetic structure of a hard disc



AFM Magnetic

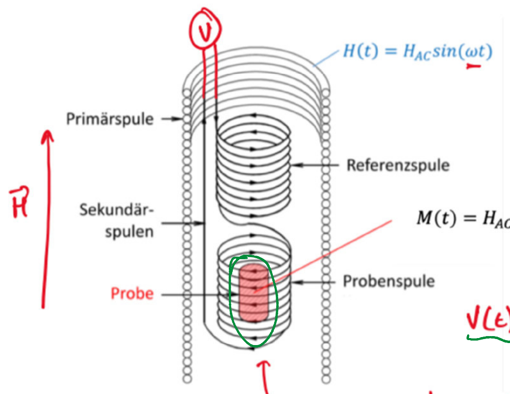
Mößbauer



1) Magnetization

magnetic susceptibility

$$\chi_{ij} = \frac{\partial m_i}{\partial h_j} = \text{tensor}$$



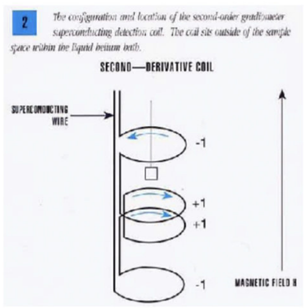
$$M(t) = H_{AC} \sum_{n=1}^{\infty} \chi_n' \sin(n\omega t) + \chi_n'' \cos(n\omega t)$$

higher harmonics.

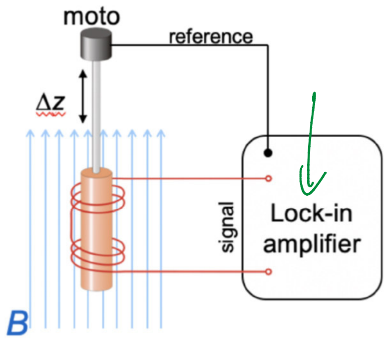
$V(t) \sim M(t) \Rightarrow$ magnetic susceptibility $n=1$

two coils wounded in opposite directions

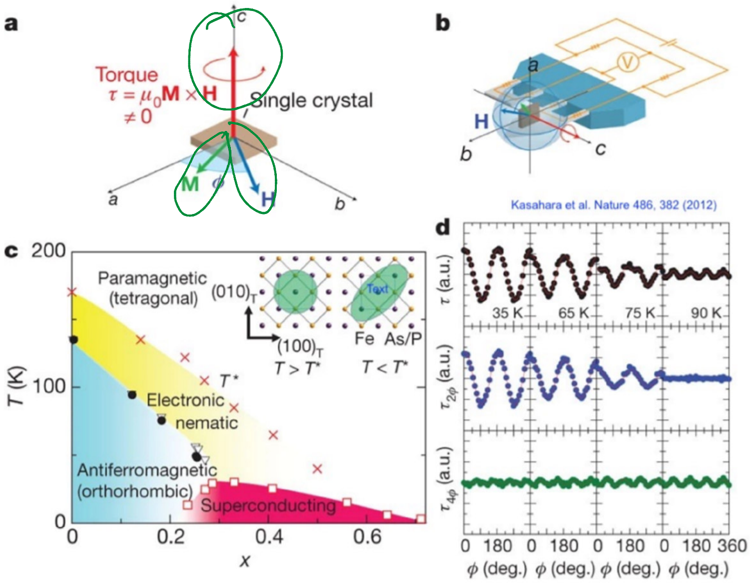
SQUID magnetometer



vibrating sample magnetometer (VSM)



- detect the dipole moment of a sample by mechanically vibrating the sample inside of an inductive pickup coil or inside of a SQUID coil.
- Induced current or changing flux in the coil is measured.
- The vibration is typically created by a motor or a piezoelectric actuator.



Electron spin Resonance

LETTER Nature 2015

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Potential for spin-based information processing in a thin-film molecular semiconductor

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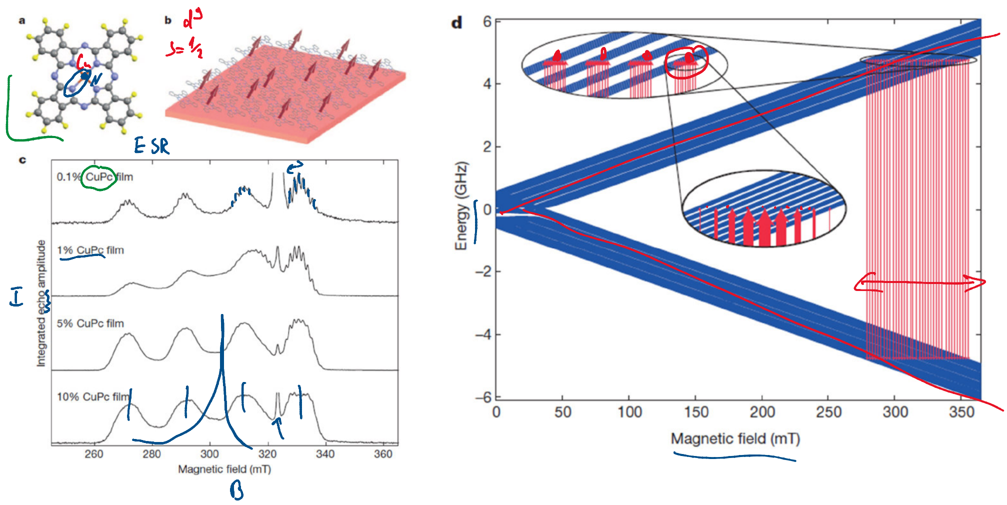
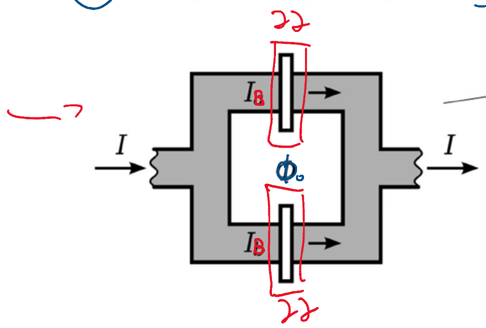


lar plane parallel to the applied field, as in our measurements. These are simulated in EASYSPIN[21] using the Hamiltonian $H = g\mu_B \boldsymbol{BS} + \sum \boldsymbol{IAS}$ (see Methods for details), the two terms of which respectively represent the Zeeman energy for the electrons within the external field $\boldsymbol{B}$ (μ_B, Bohr magneton) and the sum of the various hyperfine interactions[19]. Copper(II) complexes have been studied extensively[22]: for CuPc the electronic spin is $S = 1/2$ and for both naturally occurring copper isotopes (^{63}Cu and ^{65}Cu) the nuclear spin is $I = 3/2$. The hyperfine coupling of ^{63}Cu is defined by the diagonal matrix $\boldsymbol{A}$ with $A_{xx} = A_{yy} = -83$ MHz and $A_{zz} = -648$ MHz in the molecular frame[19] (these values scale for ^{65}Cu according to the ratio between gyromagnetic ratios). The predominant (>99%) naturally occurring nitrogen isotope (^{14}N) has $I = 1$ and the four nearest-neighbour nitrogens have a hyperfine coupling to the d^9 Cu^{2+} of $A_{xx} = 57$ MHz and $A_{yy} = A_{zz} = 45$ MHz (ref. 23). The red arrows in Fig. 1d indicate the allowed transitions, which, as indicated in the first magnified view, cluster into four groups (owing to the interaction with the spin-3/2 copper nuclei) of nine transitions (owing to the four identical spin-1 nitrogen nuclei). The second magnified view shows the expected intensity variation of the transitions (1:4:10:16:19:16:10:4:1).

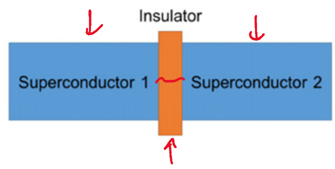
Superconducting Quantum Interference Device (SQUID)

- A DC SQUID consists of a superconducting loop with two Josephson Junctions
- a Josephson junction consists of two superconductors separated by an insulating material.
- It is a weak link, that has a lower critical current I_C than the rest of the junction
- Flux in the superconducting loop is quantized ($\Phi_0 = h/2e$)

- If a magnetic sample is passed through the ring, the persistent current induced is proportional to the magnetization of the sample.
- The loop is therefore able to act like a very sensitive quantum interferometer.

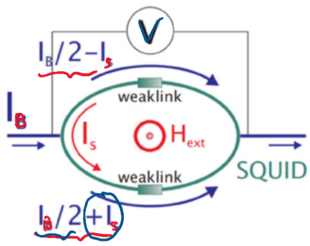


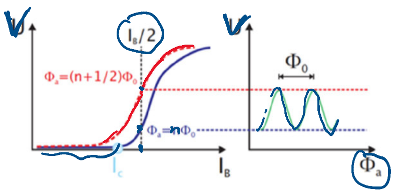
Josephson Junction



Superconducting Quantum Interference Device (SQUID)

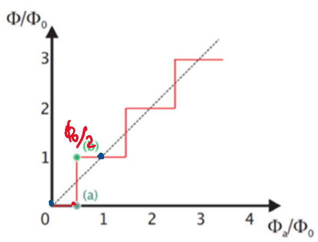
- If external flux Φ_A increases, a screening current I_S is generated in the loop. This adds on one side and subtracts on the other.
- the external flux is further increased until it exceeds $\Phi_0/2$. Starting from here the loop prefers to increase by one charge quantum in the opposite direction
- As soon as the current in either branch exceeds I_C of the Josephson junction, a voltage appears across the junction



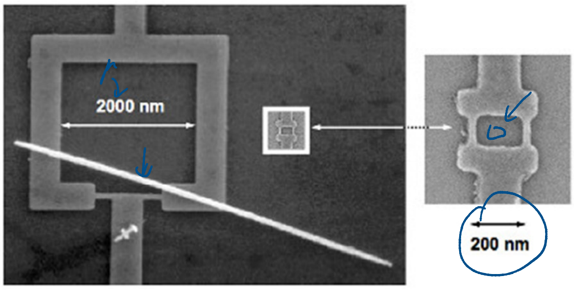


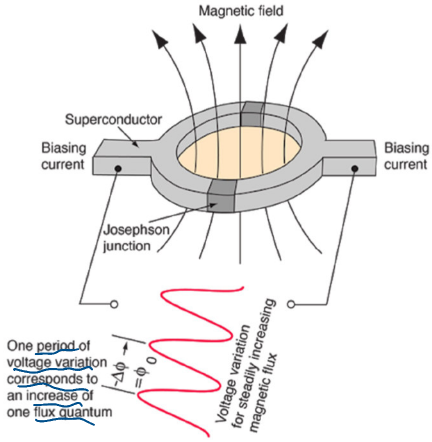
$$\Delta V = \frac{R}{L} \cdot \Delta\Phi$$

- L is the self inductance of the superconducting ring
- R is a shunt resistance



Superconducting Quantum Interference Device (SQUID)

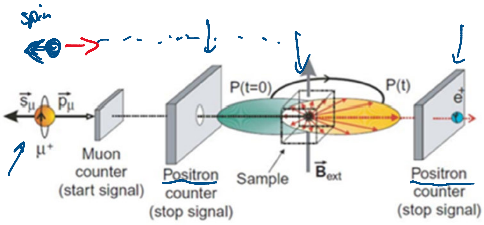




Muon-spin rotation (µSR)

- muon is a spin-1/2 particle (charge ±e, mass 250 me)
- Lifetime 2.2 μs,
- dominant constituent of cosmic rays arriving at sea-level.

(But synchrotrons and cyclotrons are used as sources)



Method

NO scattering is involved (unlike neutron scattering and X-RAY)

Muon Creation

Collision of a high energy proton beam with a suitable target which produces pions that decay very quickly (26 ns) into muons

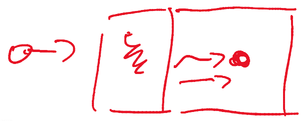
$$\pi^+ \rightarrow \mu^+ + \nu_\mu,$$

Neutrino: spin – antiparallel to momentum

Muon: spin – parallel to momentum

Pion: no spin

Positive spin-polarized muon: small, positively charged particle is attracted by areas of large electron density and stops in interstitial sites in inorganic materials or bonds directly on to organic molecules



Muon interaction in the sample

Muons are implanted into a sample of interest and reside there for the rest of their short lives

- Loose initial energy (~4 MeV) very quickly
- Scattering does not affect the muon spin
- Muon is not implanted in the region that suffers radiation damage

→ Positron decay is detected

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu.$$

muon-neutrino

e-neutrino

Muon: spin parallel to momentum

positron

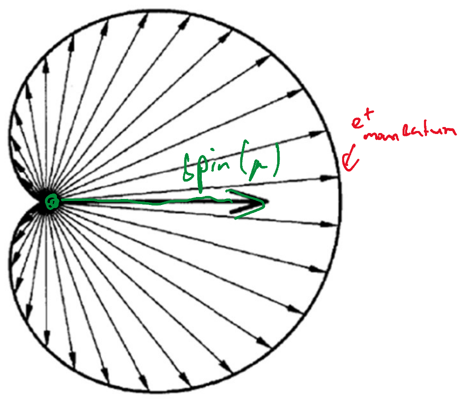


Fig. 3.22 The angular distribution of emitted positrons with respect to the initial muon-spin direction. The expected distribution for the most energetically emitted positrons is shown.

- Positron direction is dominated in one direction due to parity violation of the weak nuclear interaction

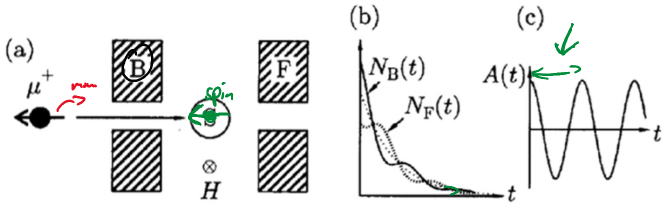
- Positron direction is dominated in one direction due to parity violation of the weak nuclear interaction

spin direction. The expected distribution for the most energetically emitted positrons is shown.

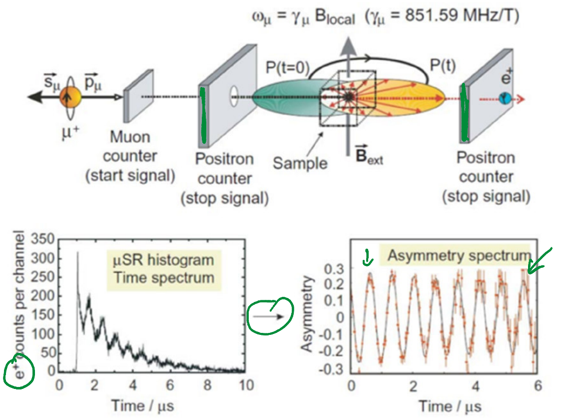
Asymmetry Function

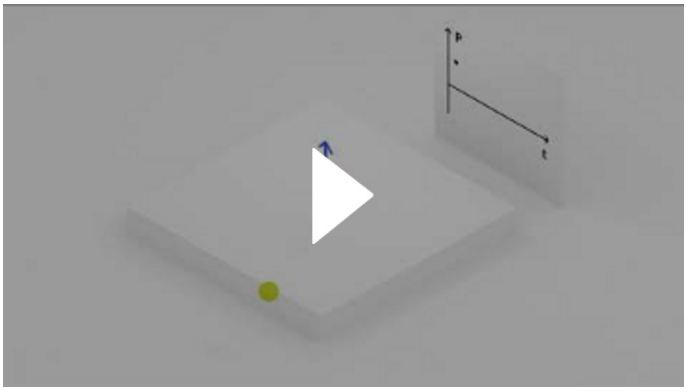
$$A(t) = \frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)}$$

$\omega = \gamma_\mu B$ where $\gamma_\mu = ge/2m_\mu = 2\pi \times 135.5$ MHz T^{-1}

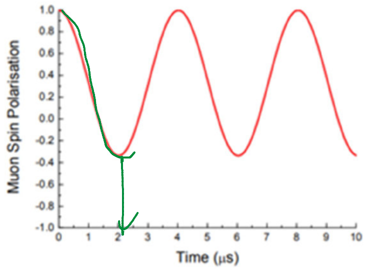


Muons stop uniformly across the sample
→ Volume fraction
Useful for:
- magnetic order is random or of very short range.
- multiphase or incompletely ordered
- No single crystal needed

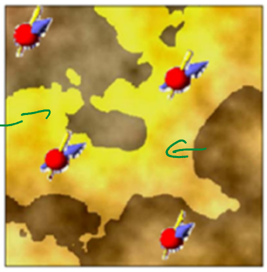


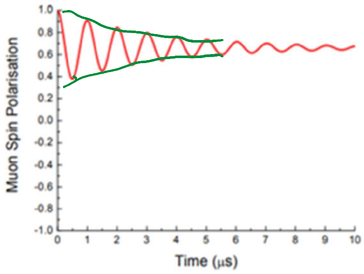


Homogeneous:



Inhomogeneous:





Amplitude a = Magnetic volume fraction
Frequency ω = Local field, size of magnetic moments
Damping λ, σ = inhomogeneity of magnetic regions

Further methods

X-Ray methods

XMCD
(X-Ray Magnetic circulator dichroism)

Optical Methods

Magneto-optic Kerr effect
Changes in polarization and reflected intensity to light reflected from a magnetized surface

Electronic Methods

Lorentz microscopy

Transport Methods

Hall Probes
Magnetoresistance measurements

NV centers and NV magnetometry

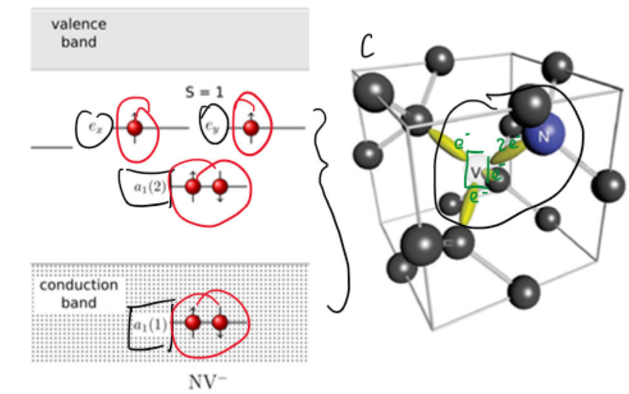
Nitrogen vacancy (NV) center in diamond

- substitutional **nitrogen** and a nearest neighbor **lattice vacancy**

- pointdefect, C_{3v} symmetry

- S = 1 (when negatively charged)

NV^0: $5e^-$
NV^-: $6e^-$



ground-state spin Hamiltonian:

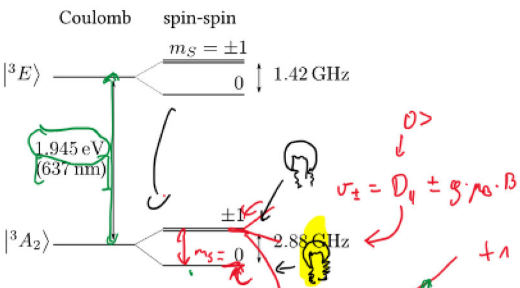
axial $\mathcal{H}_{\|}$

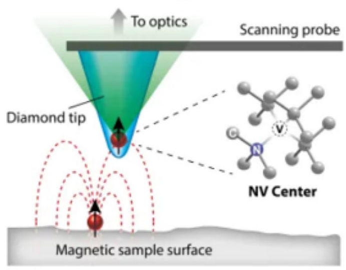
$$\mathcal{H} = hD_{\|}S_z^2 + g\mu_B B_{NV} S_z$$

$$\nu_{\pm} = D_{\|} \pm \frac{g\mu_B}{h} B_{NV}$$

S = 1 $m_s = -1; 0; +1$

NV centers and NV magnetometry





Spin readout

- spin detection via **fluorescence intensity**
  - $m_s = 0$ → bright
  - $m_s = \pm 1$ → dark
  - contrast up to **30%**, for GS and ES
- opticall detected magnetic resonance (**ODMR**)