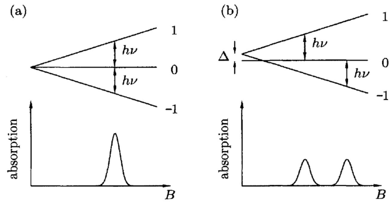
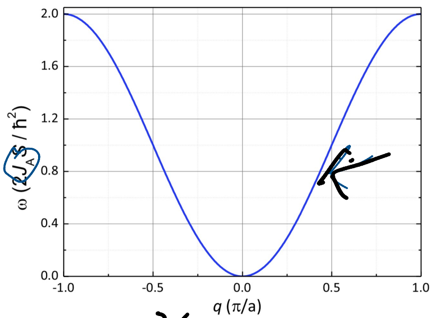
Lecture 28

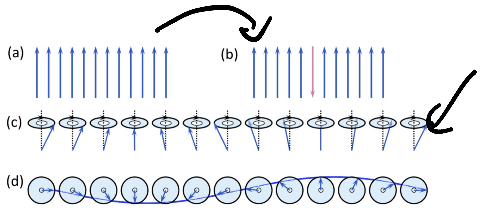
Review

ESR:



Spin waves:

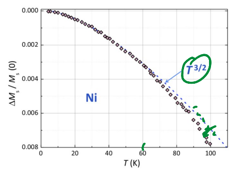




Bloch $T^{3/2}$ - law

$$\frac{\Delta M}{M_S(T=0)} \propto \left(\frac{k_B T}{\mathcal{J}_A\, S/\hbar}\right)^{3/2} \qquad \text{Bloch } T^{3/2} \text{ law}$$

• Describes the LT-dependence of a ferromagnet well



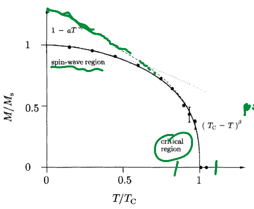


Fig. 6.15 The spontaneous magnetization in a ferromagnet. At low temperatures this can be fitted using the spin-wave model and follows the Bloch $T^{3/2}$ law. Near the critical temperature, the magnetization is proportional to $(T - T_C)^\beta$ where β is a critical exponent. Neither behaviour fits the real data across the whole temperature range. The data are for an organic ferromagnet which has $T_C \approx 0.67$ K for which $\beta \approx 0.36$, appropriate for the three-dimensional Heisenberg model.

Elastic neutron scattering

- neutron is a spin-1/2 particle, no charge
- non-zero magnetic moment.
- produced in great quantities by fission reactions inside the fuel elements of nuclear reactors.
- The beam of neutrons which emerges from a reactor has a spectrum of energies determined by the temperature T of the moderator

↳ slows down your neutrons (H_2O)

$$n(v) \propto v^3 \exp\left(-\frac{\frac{1}{2}m_n v^2}{k_B T}\right),$$

$v^2 \cdot \exp(\ )$ Maxwell

v } emission through a pin hole

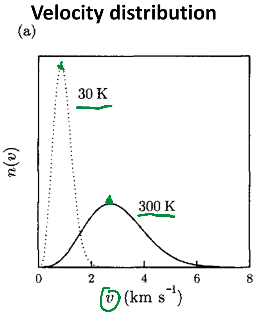
The maximum of this distribution is at

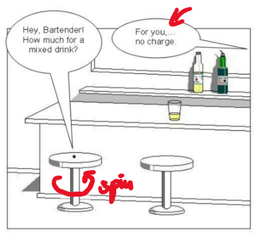
$$v = \sqrt{\frac{3k_B T}{m_n}}$$

The de Broglie wavelength k of a neutron with velocity v is

$$\lambda = \frac{h}{m_n v}.$$

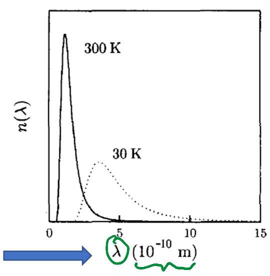
Velocity distribution





A neutron walks into a bar...

wavelength distribution

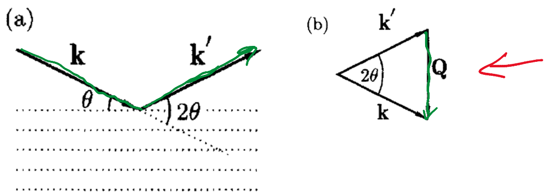


On the order of atomic lattices →

Elastic neutron scattering

Neutrons scatter:
1. with nucleus via the strong nuclear force
2. NOT with electron clouds (no charge)
3. by variations in magnetic field within a crystal via the electromagnetic interaction

→ neutron couples to the magnetic moment of the electrons



Bragg reflections when scattering vector $\vec{Q}$ = reciprocal lattice vector $\vec{G}$

1. nucleus via the strong nuclear force

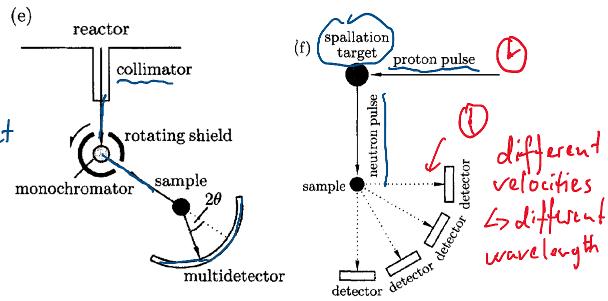
- incident neutron wave produces a spherically symmetric elastically scattered wave
- elastically scattered neutrons can produce strong Bragg reflections

Setups: • reactor (e)

spallation source pulse of neutrons is produced by spallation (f) from a target. proton (high energy) → spallation target

Aufsplitterung

→ Determine neutron energy by time-of-flight measurements



2. Contrast to X-ray and electron scattering:

- Interaction with the nucleus, not the electron cloud

→ Element-sensitive, isotope-sensitive

- highly penetrating probe

• does not damage bio-samples

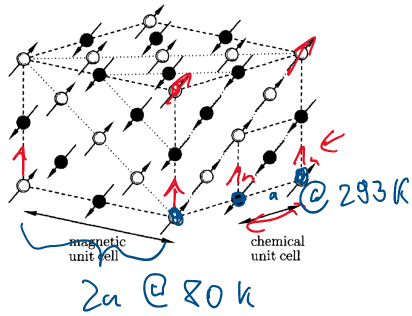
Elastic neutron scattering

3. But Neutron is also magnetic: magnetic scattering.

→ spin-up and spin-down electronic moments 'look' different

Example: magnetic structure of the antiferromagnet MnO. T_N = 116 K

Amplitude of the magnetic Bragg peaks can be used as a measure of the **strength of the magnetic order**, and hence the magnetic order can be followed as a function of temperature.



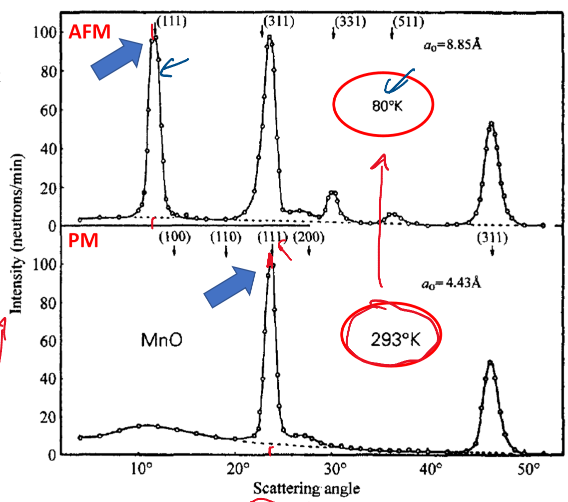
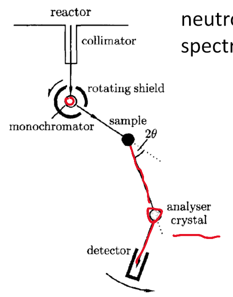


Fig. 5.19 Neutron diffraction patterns for MnO below and above T_N. After C. G. Shull, W. A. Strauser and E. O. Wollan, *Phys. Rev.*, **83**, 333 (1951).

Inelastic neutron scattering



neutron triple-axis spectrometer.

The magnitude of the incident neutron wave vector k is now no longer equal to the magnitude of the scattered neutron wave vector k'.

$$E = \frac{\hbar^2 k^2}{2m_n} \qquad E' = \frac{\hbar^2 k'^2}{2m_n}$$

Conservation of energy and momentum implies that

$$E = E' + \hbar\omega$$ phonon [boring]

$$\mathbf{k} = \mathbf{k}' + \mathbf{q} + \mathbf{G},$$ spin waves (not boring)

- measurement of k, k', E and E' allows a determination of omega and q.

- Neutrons have energies similar to the energies of atomic and electronic processes, i.e. in the meV to eV range

- magnon energies are typically in the range 1-10 meV

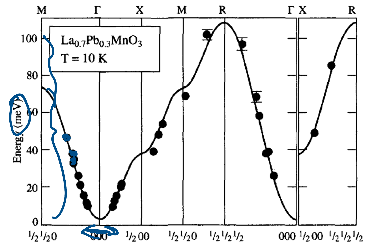
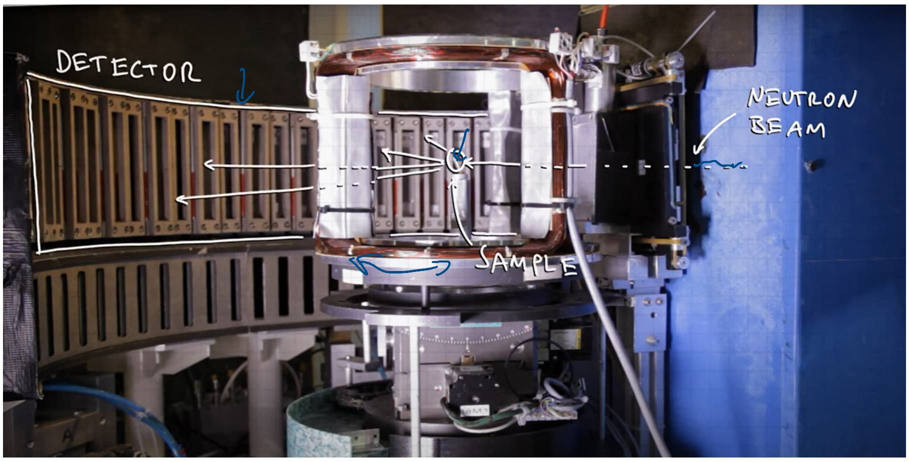
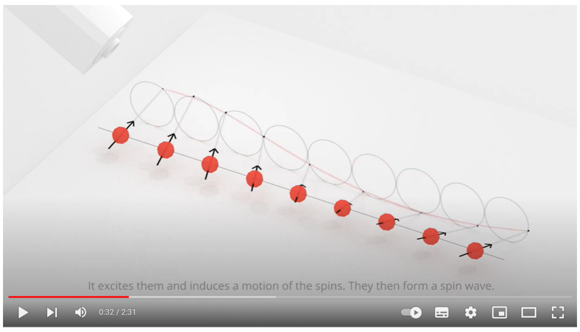


Fig. 6.18 Spin wave dispersion in the ferromagnetic oxide $La_{0.7}Pb_{0.3}MnO_3$ measured at 10 K by inelastic neutron scattering. The horizontal axis corresponds to the magnon wave vector. After Perring *et al.* 1996.

Jülich Centre for Neutron Science



[Quantum Mechanics and Neutron Scattering 2 / 2]



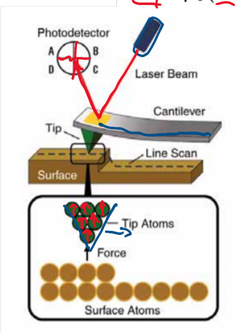
[Neutron Inelastic Scattering] CNRS

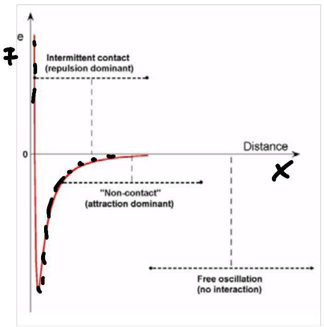
Scanning Probe Methods

Magnetic Force Microscopy

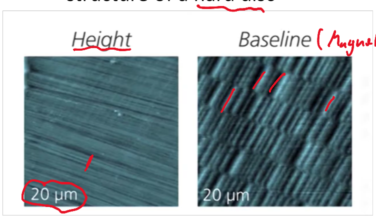
- Atomic Force Microscope: Probes the topography (height) of a surface using the force interaction with a probe tip
- Using a magnetic tip, magnetic signals can also be detected, due to an additional magnetic force

$$\vec{F} = \mu_o(\vec{m} \cdot \nabla)\vec{H}$$

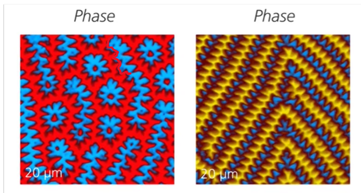




Topography and magnetic structure of a hard disc



Domain structure
Yttrium Iron Garnet (YIG) film



Images of magnetic structures of Yttrium Iron Garnet film. Magnetic force microscopy.

Scanning Probe Methods

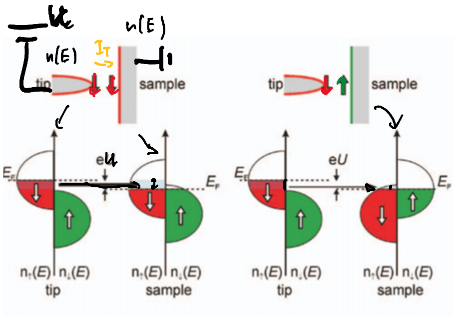
Spin-polarized scanning tunneling microscopy

Spin-dependent conductance of a ferromagnet-tunnelbarrier-ferromagnet interface

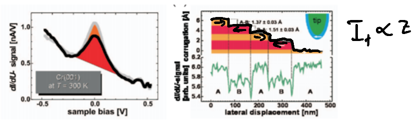
$$G_{\uparrow\uparrow} = G_{\mathrm{fbf'}}(1 + P_{\mathrm{fb}}P_{\mathrm{f'b}}),$$

$$G_{\uparrow\downarrow} = G_{\mathrm{fbf'}}(1 - P_{\mathrm{fb}}P_{\mathrm{f'b}}).$$

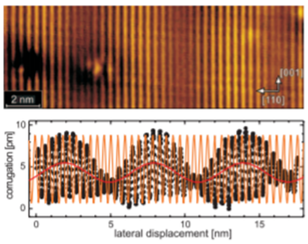
$$\frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\uparrow} + G_{\uparrow\downarrow}} = P_{\mathrm{fb}}P_{\mathrm{f'b}} =: P_{\mathrm{fbf'}}$$

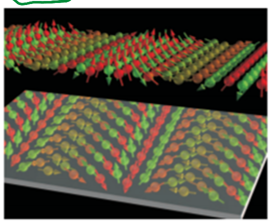


Fe-coated W tip above differently magnetized terraces of an antiferromagnetic Cr001 surface



Spin spiral state: Mn grown on a W(110) substrate





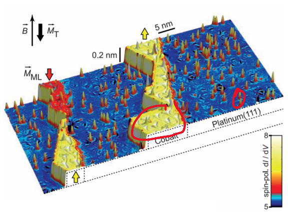
Roland Wiesendanger: Spin mapping at the nanoscale and atomic scale, Rev. Mod. Phys. 81 (2009)

Scanning Probe Methods

Spin-polarized scanning tunneling microscopy

Revealing Magnetic Interactions from Single-Atom Magnetization Curves

Focko Meier,* Lihui Zhou, Jens Wiebe,† Roland Wiesendanger



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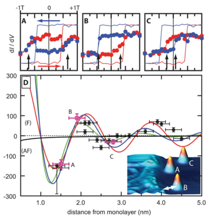
SCIENCE VOL 320 4 APRIL 2008



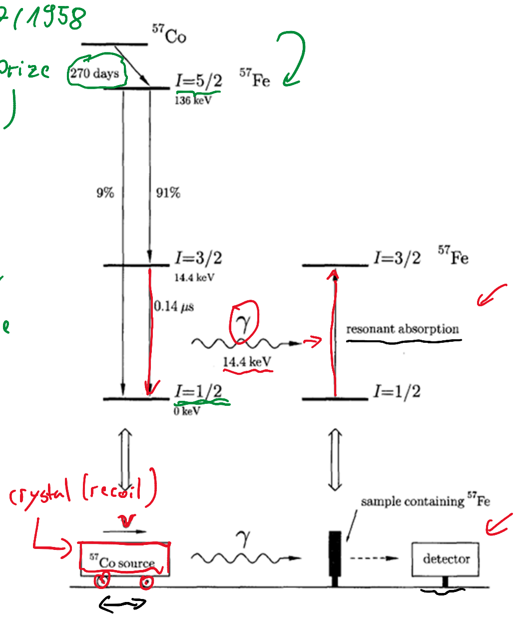
Mößbauer Spectroscopy

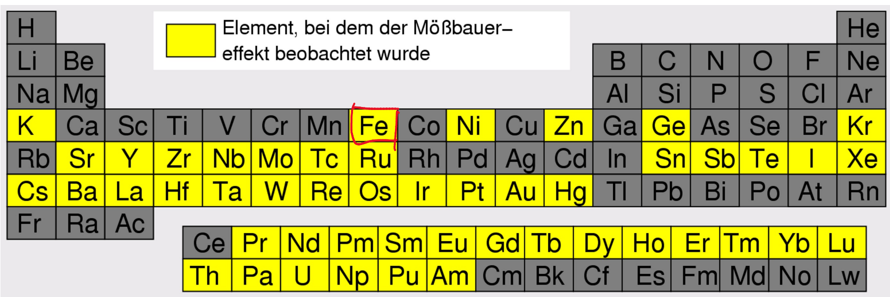
Rudolf Mößbauer 1957/1958 (Nobel prize 1961)

- Also magnetic resonance technique, but a little bit different
- Recoil-free absorption of gamma rays emitted by one nucleus that is absorbed by a sample containig the same isotope
- Ingredients: a source of 57Co → 57Fe(I=5/2)
  - → decays to excited 57Fe (I=3/2)
  - → decays to 57Fe (I=1/2)

  γ-ray cascade
- Emits a 14.4 keV gamma ray (f = 3.5 x 10^18 Hz)
- To sweep frequency the Doppler effect is used (v = 1 mm/s corresponds to 12 MHz)
- Use 57Fe in the sample as a resonant absorber
- Other elements are also possible, but not all

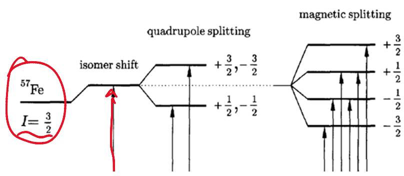
  (^{119}Sn, ^{127}I ...)





Mößbauer Spectroscopy

What can we measure with this?



1. **Isomer shift** (Comparable to Fermi contact basically)
   → shift of the resonant absorption due to differences

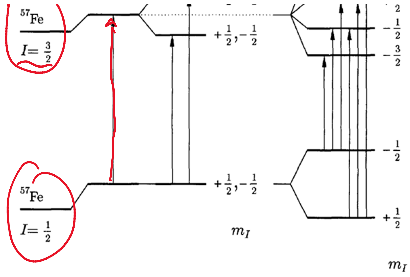
What can we measure with this?

1. **Isomer shift** (Comparable to Fermi contact basically)
   → shift of the resonant absorption due to differences in charge and Coulomb interaction (Oxidation state, valency, electron shielding)

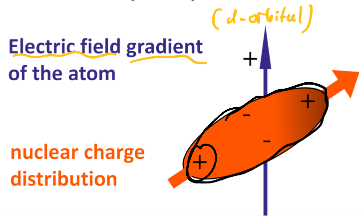
2. Nuclear **Quadrupole splitting** $H_{NQI} = P \cdot I_z^2$

Coupling of the nuclear quadrupole moment to the charge gradient (e.g. d-orbitals)
(Oxidation State, Spin state, site symmetry and arrangement of ligands)

3. **"Local" magnetic field**
   - Exchange interaction
   - Hyperfine interaction



Nuclear quadrupole interaction



Mößbauer Spectroscopy

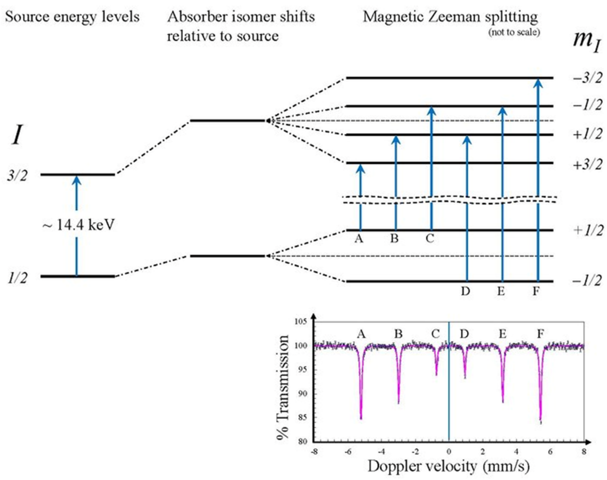
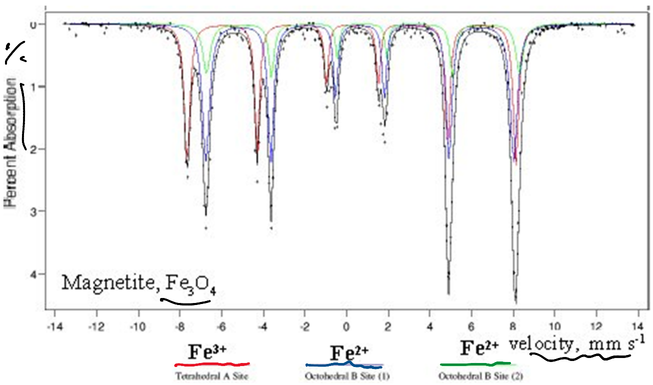


Fig. 4: Mossbauer spectrum and diagram illustrating magnetic Zeeman splitting in 57Fe.

Mößbauer Spectroscopy



Magnetite (Ferrimagnet)