As an example for magnetic circular dichroism, we will take a look at XMCD (x-ray magnetic circular dichroism). This technique is closely related to x-ray absorption spectroscopy discussed earlier. It has the advantages that it can distinguish the magnetic contributions from different elements and that it is very sensitive. XMCD is the difference for a magnetic material between the absorption of left and right circular polarized x-rays. [Slide] In x-ray absorption, the atom absorbs a photon, giving rise to the transition of a core electron to an empty state above the Fermi level. The absorption edges have energies which are characteristic for each element. Due to the dipole selection rules for the absorption of a photon, the intensities of the absorption lines differ for the two polarizations in the presence of a magnetic field. Using the appropriate sum rules the magnetic moment per atom can be determined and one can even distinguish between orbital and spin momentum. (slide). As this technique needs a tunable x-ray, it can only be carried out at a synchrotron.

techniques based on the detection of electrons (LEEM, photoemission) can be turned into methods sensitive to magnetism by measuring the spin of the detected electrons. A device used to detect the spin is the Mott-detector (Mott-polarimeter). This device is based on the spin dependence of the scattering cross section for electrons with atoms.

As the scatter, an atom with a high nuclear charge is used (e.g. gold). The scattering electron penetrates deep into the Coulomb field of the atom. In the rest frame of the electron, the atom moves towards the electron (slide). When the electron is inside the atom, the atomic charge is dominated by the positive nuclear charge. In the rest frame of the electron, the moving electric field generates a magnetic field with circular field lines. The magnetic field is inhomogeneous, it becomes weaker as the distance to the atomic nucleus increases. The large magnetic field gradient exercizes a sizeable force on the magnetic moment of the electron. This force is superimposed onto the Coulomb force acting on the charge of the electron. If the magnetic moment is up and if the electron passes on the righ side of the atom, magnetic field and magnetic moment are parallel and the force pushes the electron towards increasing field, i.e. to the left. if the electron passes on the left side of the atom, magnetic field and magnetic moment are antiparallel and the force pushes the electron towards the weaker field, i.e. to the left as well. Altogether, an electron with magnetic moment up wrt the scattering plane is preferentially scattered to the left, and an electron with magnetic moment down is preferentially scattered to the right. By detecting the intensities of the electron beam on both sides after the scattering, the spin direction can be determined slide.

The next slide shows a setup for spin-resolved ARPES. First, the photoelectrons are sorted according to energy and angle as we have learned before. In an additional step, the 3D orientation of the spin is detected using two Mott polarimeters. The slide shows as an example the spin resolved Fermi-surface of Ni.

Magnetic resonance techniques

The next techniques we will discuss are able to determine the response of an individual magnetic moment to the local environment it is sitting in. This environment is determined by the crystal field, spin-orbit coupling, and hyperfine interactions (see below). The experimental technique is based on resonant transitions between Zeeman-split states.

Nuclear magnetic resonance (NMR)

For an NMR experiment, one needs a nucleus with a non-zero spin (^1H, ^2H, ^{13}C). In a simple NMR experiment $\boxed{\text{slide}}$, a sample is placed inside a coil which is mounted between the pole pieces of a magnet. The magnet produces a magnetic field $\vec{B}_0$ along the z-direction. The z-component m_I of the angular momentum of the nucleus I can only take integral values between $-I$ and I. The energy E of the nucleus with magnetic moment $\vec{\mu}$ in the field $\vec{B}_0$ is then:

$$E = -\vec{\mu}\,\vec{B}_0$$

$$= -\underset{\text{g-factor of nucleus}}{g_N}\,\overset{\text{nuclear magneton}}{\mu_N}\, m_I\, B_0$$

This corresponds to a ladder of $2I+1$ equally spaced energy levels with a mutual separation of $g_N \mu_N B_0$ as illustrated in the slide for the case $I = 3/2$. For usual fields in the range of 1 T the energy separation corresponds to photons in the radio frequency regime. Therefore, transitions between adjacent pairs of levels can be exited by a radio frequency (RF) field, which is the basis of NMR. In the sketch of the NMR setup, this RF field is provided by the coil around the sample. Only transitions where the <u>dipole selection rule</u> $\boxed{\Delta m_I = \pm 1}$ is obeyed are possible, which implies that only transitions between adjacent states may occur.

In the most common experimental setup, the RF coil is part of a tuned circuit with a large Q factor. The (quasi-) static field B_0 is ramped up, and when the energy separation matches the frequency of the loop, energy is lost which yields the measurable signal (at the position of nuclear magnetic resonance). The resonance frequency is given by

$$\nu = \frac{\omega}{2\pi} = \frac{\Delta E}{2\pi\hbar} = \frac{g_N \mu_N B_0}{2\pi\hbar}$$

The NMR frequency can be slightly shifted depending on the chemical environment of the nucleus (chemical shift), as the electrons orbiting the nucleus slightly shield it from the applied field. (This chemical sensitivity is the reason for the application of NMR in medical imaging). It can be also changed by nuclear <u>spin-spin coupling</u> mediated by the electrons, therefore containing information about the magnetic environment of the nucleus.

<u>Electron spin resonance</u>

One can perform the analogous experiment to NMR with electrons (electron spin resonance - ESR). As the magnetic moment of the electron is higher than the one of the nucleus, the resonance for typical magnetic fields is in the microwave regime. The technique is therefore based on waveguides and cavities slide. Again, the behaviour of the microwave circuit changes significantly when it is operated at a resonance frequency of the sample. ESR allows to detect the local crystal field. This will be explained using an atom in an octahedral environment, a situation found for the metal ion in a perowskite, which is the crystal structure of many transition metal oxides slide. The crystal field in this case arises mainly from electrostatic repulsion from the negatively charged electrons in the oxygen orbitals. The outermost orbitals of the metal are the d-orbitals slide. Close inspection reveals that the d-orbitals fall in two groups: The t_{2g}-orbitals which point between the axes (d_{xy}, d_{xz}, d_{yz}) and the eg-orbitals which point along these axes (d_{z^2}, $d_{x^2-y^2}$). As the overlap of the eg-orbitals with the oxygens is stronger, they will be shifted up in energy slide. This is the crystal-field-splitting.

The consequence of crystal-field-splitting for the ESR signal is shown on the slide: It leads to a splitting of the absorption lines. This ca be used to evaluate the strength of the crystal field and the occupation of the d-orbitals