The last method we will discuss is inelastic scattering of electrons, called electron energy loss spectroscopy. Often, an instrument we already encountered, namely the TEM, is used to detect these signals. Although electrons with the right wavelength (or momentum) have rather high energies as compared with photons, electrons can be detected with a very good energy resolution making EELS a feasible method. The setup of a TEM with EELS is shown in the slide. The example slide shows that one can obtain the same information from EELS as from optical methods.
The ultimate energy resolution is reached in HREELS (high-resolution electron energy loss spectroscopy). Here, losses of a small fraction of an eV can be detected, because the technique allows to resolve small separations between the elastic peak and the loss features. The setup (slide) consists of a cathode system, a first energy dispersive element (a monochromator), a lens system between the monochromator and the sample, a second lens system between the sample and the analyzer, a further dispersive element (an analyzer) and finally the electron detector. One or

two sequential 127° angle cylindrical sector deflectors fixed at constant pass energy are used as a monochromator. From the broad Maxwell distribution of hot electrons emitted by the cathode, it selects electrons in a narrow energy window (typically 1-10 meV and down to a fraction of a meV in the most advanced systems). The analyzer works in a similar way. A channeltron multiplier is a conventional electron detector. The instrument is very surface sensitive.
The example (slide) shows the determination of the full phonon dispersion for graphene.

Magnetism

In this chapter we will deal with experimental techniques used to measure the magnetic properties of matter. Let us start with a review of the basic properties of magnetically ordered states. The magnetic interactions between the individual moments can produce different types of magnetic ground states, some of which are illustrated on the slide. These include ferromagnets in which all the magnetic moments are in parallel alignment, antiferromagnets in which adjacent magnetic moments lie in anti-parallel alignment, spiral and helical structures in which the direction of the magnetic moment processes around a cone or a circle as one moves from one site to the next, and spin glasses in which the magnetic moments lie in frozen random arrangements.

Ferromagnetism

A ferromagnet has a spontaneous magnetization even in the absence of an applied field. All the magnetic moments lie along a single unique direction. This effect is generally due to exchange interactions (direct exchange, super-exchange, RKKY). For a ferromagnet in an applied magnetic field $\vec{B}$, the appropriate Hamiltonian to solve is:

$$H = -\sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j + g\mu_B \sum_j \vec{S}_j \vec{B}$$

J_{ij}: coupling constant; $\vec{S}_i, \vec{S}_j$: spins at positions i and j; g: g-factor (Landé); μ_B: Bohr magneton

The exchange constants J_{ij} for nearest neighbours have to be positive to ensure ferromagnetic alignment. The first term on the right is the Heisenberg exchange energy, the second term is the Zeeman energy.

The ferromagnetic order evolves spontaneously. The degree of ordering depends on temperature and disappears above the Curie-temperature. The typical magnetization vs. temperature curves resulting from the mean-field model (Weiss model) are shown in the slide. Note that the disappearance of M above T_c is a second order phase transition.

Anti-ferromagnetism

If the exchange interaction is negative ($J < 0$), the molecular field is oriented such that it is favorable for nearest neighbour magnetic moments to lie antiparallel to each other. This is anti-ferromagnetism. Anti-ferromagnetic order disappears above the Néel-temperature.

Susceptibility

The magnetic susceptibility is defined

as $\vec{M} = \chi \vec{H}$. From the Weiss model of magnetism it follows that:

Ferromagnet: $\chi \sim \frac{1}{T - T_C}$ (Curie-Weiss law) $(T \gtrsim T_C)$

Antiferromagnet: $\chi \sim \frac{1}{T + T_N}$

This can be generalized by defining the Weiss temperature Θ leading to

$$\chi \sim \frac{1}{T - \Theta}$$

For a paramagnet, $\Theta = 0$, for a ferromagnet $\Theta = T_C$, and for an antiferromagnet $\Theta = -T_N$. See the slide for a graphical representation. Measuring the dependence of χ on T is therefore an experimental pathway to determine the kind of magnetic ordering and its parameters. For an antiferromagnet, the behaviour of χ also depends on the geometry of the experiment. slide

For a ferromagnet, the formation of magnetic domains leads to the occurrence of hysteresis loops in the $M(H)$ curves (slide).

Magnetooptics

In order to understand how magnetism can change the interaction of light with media, we have to take a look at the behavior of circular polarized light. For chiral objects the response towards left- and right-circular light will be different. (A chiral object is a object that can not be superimposed with its mirror image like the right and the left hand). A difference in the real part of the complex refractive index gives rise to optical activity while a difference in the imaginary part cause circular dichroism. Optical activity means that the speed of propagation is different for left- and right-circular light and has as a consequence, that the plane of polarization of linear polarized light is turned when light shines through a material with optical activity. Circular dichroism is observed in absorbing chiral materials. "Dichroic" means two-colored and is used for any optical phenomenon that affects two colors differently. In the case of circular dichroism, the absorption coefficient is sensitive to the direction of the circular polarization, which implies that if the absorption bands lie in the visible spectral region, the color will be different when viewed with left- or right-circular light.

Experiments

The most obvious experimental technique to try is a conventional measurement of magnetization, i.e. determine the sample's net magnetic moment. This is done using a magnetometer. This is of course only meaningful with samples having a non-zero magnetization. To have a high signal, special constructions are in use. The first to be discussed here is the vibrating sample magnetometer (VSM). The sample is put into a uniform magnetic field in order to magnetize it. The sample is then vibrating sinusoidially, typical by using a piezo-motor. The changing magnetic field nearby the sample induces a voltage in the pick-up coils: $U_{ind} = -N\dot{\Phi} \sim M\dot{V}x$. Typically, the induced signal is detected using a lock-in amplifier taking the mechanical oscillation as a reference signal. By measuring M as a function of external field B or as a function of T, hysteresis curves and magnetization curves can be recorded.

slide

The most sensitive magnetometers are using SQUIDs (superconducting quantum interference devices) as sensors. These are formed by a ring of superconducting material (slide). As the flux through such a ring is quantized in units of $h/2e$.

→ also $\chi(T)$

Optical chirality can be induced by a chiral crystal structure or in non-chiral material by applying a magnetic field. This induces a number of magneto-optical phenomena. In the case of transparent materials, the field induces optical activity and the phenomenon is called either the Faraday-effect or the magneto-optical Kerr effect, depending on whether the rotation of the polarization is observed in transmission or reflection, respectively. [slide] If the medium is absorbing, the field can induce circular dichroism, in which case we have magnetic circular dichroism.

Let us first look at the detection of the magneto-optical Kerr effect (MOKE). (slide). As a light-source, typically a laser is used. The light is polarized and focused on the sample. After reflection, the (now changed) polarization is measured. As the amount of the Kerr-Rotation depends on the magnetization of the sample, this technique can be used for the measurement of hysteresis loops (slide). This technique can also be used to obtain images by forming an image of the sample in polarisation contrast (MOKE microscope) [slide] By this technique, the distribution of magnetic domains can be imaged (slide).

When the external magnetic field is such that in principle a non-integer number of flux quanta has to pass through the loop, a super current is induced which exactly compensates the extra flux. This super current can be read out as a voltage in a ring containing two Josephson junctions. For a typical size of a SQUID, changes in the magnetic field of down to 10^{-15} T can be detected, making the SQUID one of the most sensitive detectors available. In practice, many applications exist where the quantity of interest is first turned in a magnetic signal and then measured using a SQUID

Example: EEG [slide]