

X-ray magnetic circular dichroism (XMCD)

Introduction

In X-ray magnetic circular dichroism (XMCD), circular polarized light is used to measure the difference in x-ray absorption. Already in 1975 Stern and Erskine predicted that circular polarized x-rays could be used to get information about the spin-orbit splitting and spin polarization of nickel [1]. In the late 1980s, Gisela Schütz and her colleagues published a study on iron, where the difference in absorption between left and right circular polarized light was investigated [2]. Now days, thanks to the development of synchrotron radiation sources, XMCD is a commonly used technique [3]. XMCD is based upon absorption of core electrons with well defined absorption edges. Consequently, the magnetic properties of different element present in the investigated sample can be separated, which is a big advantage compared to techniques that provide information about the average magnetic properties of a sample. Another advantage is that by measuring the difference in x-ray absorption between left and right polarized light and using the so-called sum-rules, it is possible to get separate quantitative information about the spin magnetic moment and the orbital magnetic moment. [3] Due to the mean free path of the electrons, XMCD is a surface sensitive technique.

Detection principle and sum rules

As mentioned earlier, XMCD is based upon absorption of core electrons. During the excitation, the core level electrons are transferred from the initial ground state to empty or partially filled molecular states. As the lifetime of an empty core hole is very short, the core hole is soon filled by an electron from the valence band during the deexcitation process.

The deexcitation process is either radiative (fluorescence photons are detected) or non-radiative (Auger electrons are detected). In addition to the Auger electrons, photoelectrons and secondary electrons are produced.

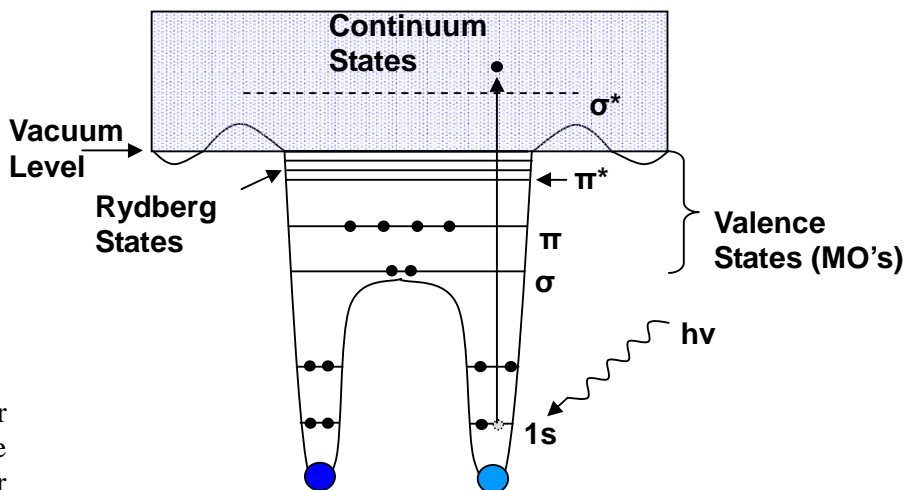


Figure 1. A schematic figure showing the potential of a diatomic molecule. Redrawn from [4]

In XMCD, all electrons from the sample are detected, thus the sample drain current is measured (total electron yield) [3]. The XMCD intensity or the magnetic dichroism effect, is proportional to $\mathbf{M} \cdot \mathbf{P}_c \mathbf{k}$ where $\mathbf{P}_c \mathbf{k}$ is the angular momentum of the photons and \mathbf{M} is the magnetization of the magnetic material investigated. Consequently, the XMCD intensity will be maximized if the magnetization and the direction of the angular momentum of the photons are oriented parallel with each other. The difference in absorption can be detected either by changing the polarization of the light or by changing the direction of the sample magnetization. In order to be able to magnetize the sample along both the easy - and the hard axis, a strong magnetic field is necessary. A superconducting magnet might thus be needed. Often it is interesting to know how much energy

that is required to change the direction magnetization from the easy axes to the hard axes (the magnetic anisotropy energy (MAE)) [3]. The hard axes or the hard direction is the direction in which the ground state energy of the system is highest. Thus, the easy axes or direction is the direction in which the ground state energy of the system is the lowest. Both the spin magnetic moment and the orbital magnetic moment contribute to the total magnetic moment of a material. The spin magnetic moment is due to the magnetic exchange interaction, while the orbital magnetic moment originates from the spin-orbit interaction. For 3d transition metals, the spin magnetic moment is much larger than the orbital magnetic moment. [5] Before a sample experience a magnetic field, the electrons are equally distributed over the orbitals. When a magnetic field is applied, electrons with different spins are energetically separated. Due to the spin-orbit interaction all the orbitals, except the s orbital ($l=0$), will be separated further into more energy levels. To be able to detect magnetic circular dichroism, the measured sample must both have spin-orbit interaction and spin polarization.

When the photon is absorbed by the electron, its angular momentum is transferred to the photoelectron. As the change in angular momentum of the photon during the interaction with the electron must be conserved, not all electron transitions between the orbitals are allowed. All transitions between orbitals follow the so called selection rules, which states that the only transitions allowed are the ones in which $\Delta l = \pm 1$. The electrons are also not allowed to change their spin during the transition. When right polarized light is used ($\hbar = +1$), transitions corresponding to $\Delta l = 1$ is allowed. When left polarized light is used, only transitions corresponding to $\Delta l = -1$ are allowed. As can be seen in Figure 2, difference in absorption can be investigated either by changing the polarization of the light or by changing the direction of the sample.

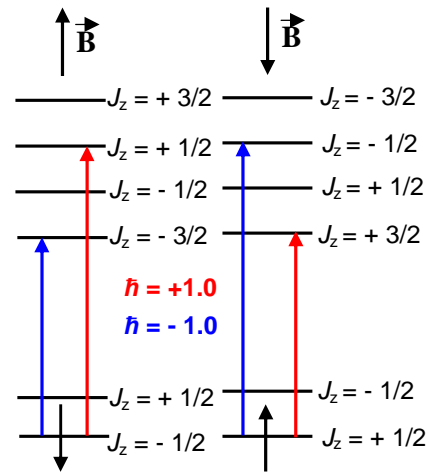


Figure 2. Examples of allowed transitions between the s and p orbital.

As mentioned earlier, it is possible to use so called sum-rules to get quantitative information about the spin magnetic moment and the orbital magnetic moment. If the difference in intensity between left and right circular polarized light for the first peak in Figure 3 is assigned as A and the difference in intensity between left and right circular polarized light for the second peak as B. Then, according to the sum rules, $A+B$ is proportional to the orbital magnetic moment. The spin magnetic moment is proportional to $A-2B$.

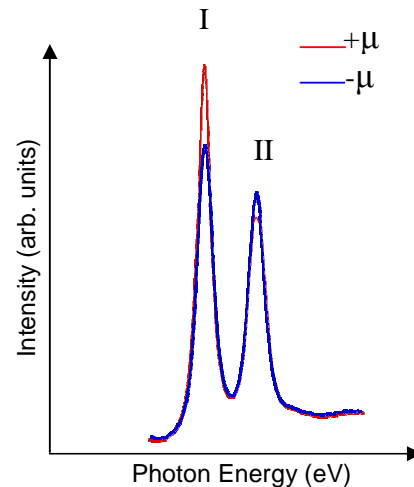


Figure 3. A schematic example of a normalized XMCD spectrum.

Examples of XMCD experimental results

Due to the surface sensitivity of XMCD, this is a good technique to study the magnetic properties at an atomic level. This has been done on Fe nanoparticles capped with a 25 Å thick layer of Al, Pt or Pd. The results revealed that there were a large difference between the magnetic properties of Fe depending on which capping that was used. There was a decrease in the total magnetic moment of Fe for all the capping but the largest change in the magnetic properties of Fe was when the Al capping was used. Consequently, the magnetic properties of atoms at an interface are greatly influence by the closest environment [6]. In another recent published article, the magnetic properties of CoPt nanoparticles were investigated. It was shown that compared to earlier published results of Co bulk sample, the CoPt nanoparticles showed an increase in the spin magnetic moment, thus Pt influenced the magnetic properties of Co [7]. Contrary, a study of FePt nanoparticles showed a decrease in the effective spin magnetic moment at both the Fe sites and the Pt sites. According to the article, the effective spin magnetic moment of a bulk material is $(2.92 \pm 0.29)\mu_B$ at the Fe sites. For nanoparticles composed of 50% Fe and 50% Pt and a diameter of 6.3 nm, the effective spin magnetic moment was $(2.28 \pm 0.25)\mu_B$ at the Fe sites, thus a decrease with approximately 20%. With smaller particles, the effective spin magnetic moment decreased even further. For particles with a diameter of 4.4 nm, composed of 56% Fe and 44%Pt there was a decrease in the effective spin magnetic moment with approximately 27%. For particles with a diameter of 3.4nm (48% Fe), the effective spin magnetic moment at the Fe sites decreased even further compared to the bulk material. [8]

References

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