

Foreword

Recent developments in information technology have taken many by surprise. Terabyte storage systems with areal densities pushed to new limits shall soon be finding their way to our doorsteps. Today's research efforts deliver tomorrow's storage systems that rely on magneto-optics and spin electronics. Even though it was not part of a technological roadmap, scientific discoveries of giant-magnetoresistance (GMR) and oscillatory interlayer magnetic-coupling phenomena have been brought to the marketplace as vital products within an extraordinary short 10-year period.

In current longitudinal magnetic recording media, ultra-high-density magnetic recording (40 Gbit/in^2) may prompt spontaneous magnetisation reversal processes when the stored energy per particle starts competing with thermal energy. With the doubling of areal density every 18 months this limit will be reached in 5 years time but it can be postponed by embarking on higher anisotropy media, perpendicular recording and patterned media lithographically predefined by either electron beams, ion beams, standing wave interferometry or self-assembly. However, the search for alternative media is on. Tunnelling magnetoresistance (TMR) in magnetic tunnel junctions has already led to prototypes of novel non-volatile magnetic random access memory (MRAM). Another promising development lies in current-driven magnetic excitation (CDME) with magnetic reversal by means of the exchange field of a steady spin-polarized electric current. Modern information technology is based on the charge and spin of the electrons. Both properties can be exploited simultaneously by introducing magnetic ions in semiconductors, which would enhance device performance and create new functionality. Overcoming the low solubility of magnetic ions by low-temperature molecular beam epitaxial growth, the increased spin-carrier interaction of the ions in GaAs can lead to ferromagnetism and spontaneous spin splitting. Soft magnetic elements have attracted interest because simple geometrical shapes of these materials are characterized by the existence of various stable magnetisation distributions, where sub-micron-size elements show nanosecond-regime reversible state switching. The time-domain structure is critically important due to the need for an increased read - write speed of magnetic information.

Interesting magnetic phenomena are displayed in a wide range of exploratory materials, such as biomagnets, molecular magnets, oxide magnets and soft magnets. Organic magnetic materials possess a number of chemical properties that may provide new processing strategies and new applications, such as electro-optic and opto-magnetic materials. The difficulty of lifting T_c above the liquid helium temperature has recently been overcome by utilizing radicals bearing heavier main group elements (P, S, Se). Among the oxide magnets, mixed-valence manganites are intensively studied. They display unusual properties arising from the competition between spin, lattice and charge degrees of freedom. The ex-

istence of a metal–insulator transition gives rise to colossal magnetoresistance (CMR), usually accompanied by a para-ferromagnetic transition. The formation of dynamic phase segregation as magnetic polarons in the paramagnetic phase is believed to provide the mechanism for carrier localisation.

This myriad of new magnetic phenomena calls for an improved understanding of the microscopic origin. Synchrotron radiation can thereby offer a number of unique advantages. To give just 10 assets of x-ray excitations: (i) Element-specificity can be obtained by tuning the x-rays to the resonance energy of the core-to-valence transition. (ii) With the light interacting only on the orbital part of the wave function, spin and orbital properties can be separated. (iii) Electric dipole (and quadrupole) transitions from the ground state reach only a limited subset of final states, thereby providing a fingerprint for the specific ground state. (iv) The instrumental resolution is of similar order of magnitude as the core hole lifetime (usually a few hundred meV) which allows us to resolve multiplet structure and charge-transfer satellites. (v) X-ray spectroscopy and scattering can be made sensitive to the magnetic moments by using the strong polarisation dependence of the electric dipole and quadrupole transitions. Recent advances in synchrotron radiation devices, such as at the ESRF and elsewhere, have enabled full control over these polarisation properties. On the theoretical side, x-ray transitions involving a deep core state offer the advantage of being more straightforward to calculate than optical transitions. (vi) Mixing between core and valence states can be neglected. (vii) The angular dependent part can be easily separated from the physical part. (viii) The wave function of the core state is well defined, enabling the separation of different interactions, such as spin-orbit and electrostatic interactions. (ix) Summation over the core state obeys the completeness relation. (x) The x-ray transition is much faster than the electronic rearrangement, so that the sudden approximation can be applied.

The effect of magnetic x-ray dichroism (MXD) was discovered at LURE in 1986. X-ray absorption gives the transition probability of an electron from a filled state into a (partly) empty state, where the x-ray polarisation probes the Pauli exclusion principle of the valence states. The sum rule, discovered in 1992, relates the integrated intensity, ρ , of the dichroism spectrum over the x-ray absorption edge with the orbital magnetic moment: $\rho = \sum_m \langle n_m \rangle \equiv \mathbf{L}_z$, where n_m is the occupation number of the magnetic sublevel m in the ground state. MXD has evolved into a powerful standard technique to determine orbital moments, providing insights into the microscopic origin of anisotropic magnetic properties, such as the magnetocrystalline effect, easy direction of magnetisation, magnetostriiction and coercivity.

The charge-conjugated companion of x-ray absorption is the transition of a hole from an empty state into a (partly) filled state, like that which occurs in x-ray photoemission or fluorescence. This implies that sum rules also hold for valence photoemission, while for core-level photoemission the dichroism of each magnetic sublevel is directly proportional to its orbital moment expectation value. Magnetic dichroism in photoemission is a powerful probe to measure different kinds of correlations between the angular moments of core and valence

electrons. Chirality is not only introduced through the helicity vector of the light but also by the experimental geometry spanned by the directions of light polarisation, sample magnetisation and photoemission detection. In angle-integrated photoemission, odd magnetic moments can only be measured with circularly polarized light; however, the interference term between the $l \pm 1$ emission channels means that these moments can also be measured at a restricted detection angle using linearly polarized light. Apart from a different surface sensitivity, core-level photoemission differs from x-ray absorption in the way the core hole is screened. The photoelectron leaves the atom behind in either a screened or an unscreened state, which enables the study of electronic relaxation processes. MCD in photoemission is still poorly understood mainly because many-body effects have to be taken explicitly into account. Second-order processes, such as x-ray fluorescence, resonant photoemission and resonant scattering, can be used to study forbidden optical transitions, such as $d-d$ and spin-flip transitions, which are allowed due to interactions in the intermediate state.

Periodic structures can be solved by x-ray scattering. “Forbidden reflections” show up if the scattering amplitudes of equivalent sites become different. Such differences are most pronounced in the case of “anomalous diffraction” where virtual excitations to the valence states impose the symmetry properties of the electronic and magnetic structure of the material. For instance, antiferromagnetic ordering induces a superlattice with half the size of the charge distribution. This principle can be extended to study domain structures using the wavelength of the transition-metal $L_{2,3}$ or lanthanide $M_{4,5}$ excitations, which has the proper length scale to map the magnetic periodicities in reciprocal space by scanning the Bragg angle. Magnetic sensitivity can hereby be obtained by using the equivalent of either the Faraday rotation of linear polarized light or the Kerr effect of elliptically polarized light in the x-ray region. The method is ideally suited to study magnetic closure domains, patterned structures, (anti)ferromagnetic coupling, i.e. in GMR and CMR devices, and interlayer magnetic roughness (diffuse scattering).

The Lecture Notes of the successive Spring Schools on “Synchrotron Radiation and Magnetism” held at Mittelwihr (1989, 1996, 2000) capture the spirit of this rapidly developing research area. For instance, the effect of x-ray natural circular dichroism (XNCD), predicted in 1989, has very recently been detected unambiguously, offering an element-specific way to access the absolute configuration of chiral centers in inorganic and organometallic materials. Such developments have been possible thanks to exotic insertion devices for synchrotron radiation and the availability of crystal phase plates which extend the range of circular polarimetry up to hard x-rays. In the above, I have only been able to give a glimpse of the synergy between magnetism and synchrotron radiation. To find out more I invite everyone to read the Lecture Notes, which give an excellent presentation of the developments.

Editorial

The third school on “Magnetism and Synchrotron Radiation” was held in the midst of the vineyards of Mittelwihr in Alsace, 9–14, April 2000. As usual, the school was followed by a workshop in which world specialists presented recent developments. About a hundred participant took part, with the stimulating prospect that SOLEIL, a third-generation machine, would be built.

Mittelwihr I took place in March 1989 shortly after the first experiments on x-ray magnetic dichroism. It coincided with the commissioning of an asymmetric wiggler to produce elliptically polarized light in the straight section of SuperACO at LURE. The wiggler was to feed SU22 and SU23, two new beam lines.

Mittelwihr II took place in April 1996¹ and just a few months after Carra, Thole, van der Laan, and Altarelli discovered the new famous sum rules applicable to magnetic spectroscopies. This school took place while there was an expectation that the construction of SOLEIL was imminent. It turned out that the synchrotron radiation community had to exercise considerable patience before such an announcement was finally made (September 2000).

This book brings together the main lectures that were taught at **Mittelwihr III** along with some more narrowly focused contributions from the workshop. As in the previous volumes covering Mittelwihr I and II the reader will find three introductory chapters on the three main topics covered by the schools: (i) synchrotron radiation (x-ray source and polarisation), (ii) magnetic properties, and (iii) magnetic spectroscopies using x-rays. These are followed by several lectures dealing with current topics in spectroscopy: magnetic x-ray absorption and resonant or non-resonant photoemission. Then, concerning magnetism: the molecular magnetism, the dynamics of micromagnetism, and the magnetism of layered structures using magneto-optical effects. The reader will also find a chapter dedicated to the expanding field of nanomagnetism. This monograph also deals with emerging experimental techniques, such as spin-resolved circularly polarised resonant photoemission, magnetic x-ray spectroscopy at low temperatures or high pressures and x-ray resonant Raman spectroscopy. Finally, the reader will also find information covering other experimental techniques for studying magnetism, such as Mössbauer spectroscopy, neutron scattering or diffraction, and nuclear magnetic resonance.

¹ E. Beaurepaire, B. Carrière, J.-P. Kappler: *Magnetism and Synchrotron Radiation* (Editions de Physique, Les Ulis 1997)

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