MAGNETIC SCATTERING: X-RAYS AND NEUTRONS

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Magnetism is a huge field of science, ranging from fundamental science (basic interactions and phenomena) to technological applications (devices and machines). Methods of the investigation of magnetic properties involve bulk measurements (static and dynamic magnetic susceptibilities, magnetisation, torque, …) and microscopic probes (resonance, microscopy, imaging, scattering methods). Scattering methods occupy an outstanding position, because they allow the observation of magnetic properties with atomic spatial resolution and adjustable time ranges. In a simple approximation, the quantities observed in scattering experiments represent Fourier transforms (in Q and ω space) of correlations between moments. With these data at hand, it is possible to determine the symmetry and the arrangement of magnetic moments in solids (diffraction experiments) and the strength of couplings (by observing collective and local magnetic excitations), and to access the origin of magnetic moments (symmetry of the electrons contributing to the magnetisation).

Radiations such as photon beams, neutron beams or even beams of polarised nuclei do indeed qualify as probes for magnetic scattering experiments because they are sensitive to magnetisation densities with the appropriate wavelength or energy. In the following we shall concentrate on the use of photons and neutrons to study magnetic properties of solids.

Historically, photons in the visible range were the first to be used to detect magnetic properties (magneto-optics effects) but not in scattering experiments. In the late 1940’s the first magnetic scattering experiments were conducted with neutrons taking advantage of their sensitivity to magnetic moments arising their spin 1/2. Since then, the neutron scattering has evolved, improved and flourished leading to new approaches to the study of magnetism (determination of magnetic structures and observation of magnetic fluctuations). An extraordinary wealth of information has been discovered through neutron scattering experiments; in particular, all we know about magnetic structures comes from neutron experiments.

However, neutron scattering experiments are intensity limited: magnetic imaging of an isolated nano-device would be impossible with neutrons. Luckily, an alternative method has been discovered: it was shown experimentally some 30 years ago that x-rays could be used to detect magnetic properties through scattering measurements. Since then the advent of synchrotron sources has led to new developments in the field (polarised x-rays spectroscopy, x-ray resonant scattering) which have boosted the study of magnetism with x-rays.

The brief reminder of the theoretical aspects of magnetic neutron and x-ray scattering methods will provide and discuss important orders of magnitude: scattering amplitudes, comparisons between magnetic and non-magnetic scattering amplitudes, sensitivity to orbital moment, effect of resonant scattering.

The main properties and characteristics of these methods have consequences on the choice of the appropriate probe to be used in experiments. As mentioned above, magnetic imaging is restricted to x-rays, while the determination of the magnetic moments in materials is the realm of magnetic diffraction. Neutron powder diffraction is still a very popular technique to determine magnetic structures. Moreover, neutron diffraction methods are the only technique allowing the measurement of the spatial extent of magnetisation densities at the atomic scale with full three-dimensional resolution.

X-rays play a key role in two distinct cases: separation of spin and orbital moment, and chemical or electronic sensitivity. In the non-resonant regime, scattering of x-rays by spin moments, <S>, rotates the polarisation differently compared to what is expected from orbital moments <L>. This property allows the experimental separation of <L> and <S> in diffraction experiments; such separation is not readily feasible with neutrons, because neutrons probe the total magnetization <L>+2<S>.
The resonance in x-ray scattering occurs when the incident photon energy is tuned near absorption edges. The x-ray scattering amplitude, which includes all possible transitions within the scattering object, contains important contributions from possible transitions of core electrons into available unoccupied states; the probability for such transitions depends on the relative orientation of the x-ray polarisation (the incident electric field) and the local quantization axis (for the electronic wave functions) which can be due to the local magnetization or any symmetry breaking field: this leads to the magnetic sensitivity of resonant x-ray scattering. Resonant magnetic scattering amplitudes can be extremely large, much larger than conventional magnetic scattering, which allows the observation of minute magnetic signals either from small magnetic moments or from tiny samples. Resonant effects have also opened up other new fields of research because the resonant energies are characteristic energies of electronic shells of chemical elements and valence states: by setting the photon energy at the edge corresponding to a given element in a given valence state, experimentalists are probing the magnetisation carried by a given electronic shell of this type of element. The response is element specific, valance state specific and electronic shell sensitive. Such properties remain unmatched by neutron methods and are extremely useful when dealing with multi-component magnetic systems.

Neutrons can be described as being magnetic, while x-rays are more electronic. However, both radiations are powerful complementary magnetic probes. They can, and should be used to extract the maximum information; examples will be given to illustrate the complementarity of the methods. Instrumentation details should also be considered when optimizing experiments (instrument resolution effects, sample environment, …).

All the above considerations apply to elastic scattering or diffraction. The case of inelastic scattering is to be treated separately. Indeed, the dynamics of magnetic moments and fluctuations of spins can be observed by inelastic neutron scattering only. The non-resonant x-ray scattering amplitude is just too weak to allow the observation of such inelastic process even on powerful synchrotron machines, and the resonant inelastic scattering is dominated by electronic excitations. Nevertheless, the respective time scales of neutrons and x-rays in diffraction experiments must be taken into account: x-rays probe and integrate much faster phenomena than neutrons.

In conclusion, there exist well-defined domains of excellence for neutron and synchrotron x-rays. The neutron interactions appear as more magnetic, to be used for magnetic structure determination and observation of dynamics or fluctuations of magnetic moments. Synchrotron x-rays should be used for imaging, studies of nano-objects, studies about the origin of magnetic moments (sensitivity to electronic shells and chemical elements). Needless to be said, when looking for the unexpected, the strengths of the two probes such as neutrons and synchrotron x-rays are to exploited.