Surface magnons by EELS

J. Kirschner

Max-Planck-Institut für Mikrostrukturphysik
Weinberg 2
06120 Halle

Magnons are quantized collective excitations in ferromagnets or antiferromagnets. In energy they range from the meV range to the eV range, in momentum from zero, the zone center, to the zone boundary (up to $2A^{-1}$). Their lifetimes range from a couple of ten femtoseconds to tens of microseconds, depending on damping. Each magnon carries a magnetic moment of two Bohr magnetons, and thus has the statistical properties of a Boson. Low energy magnons are easily excited by phonon-magnon interaction, i. e. by temperature. If sufficient magnons are excited, the global magnetic moment of a body decreases substantially. Therefore magnons play an important role for the magnitude of the Curie temperature, i. e. the the ferromagnetic vs paramagnetic transition.

The detailed description of the physical nature of these collective magnetic excitations cannot be cast into one single picture because of the many orders of magnitude of dynamic range in energy, momentum, and lifetime. In the limit of long wavelength, low energy, and long lifetime the usual semiclassical picture of precessing (classical) spins has proven useful. In this case, each spin is only slightly tilted out of its direction along the magnetic easy axis. Thus, the reduction of the magnetic moment by 2 Bohr magnetons occurs by the concerted action of many thousands or millions of localized spins, depending on the wavelength. This picture relies on classical spins, because they may adapt any spin orientation continuously, as opposed to the quantum spins being quantized in direction. These “spin waves” are damped by collisions with phonons, other magnons, electrons, lattice deformations and impurities, but they are usually long-lived. At the other extreme of the magnon spectrum we have magnons of high energy, short wavelength, and short lifetime. Their wavevectors are close the zone boundary, energies may go up to nearby 1 eV and their lifetime may be as short as femtoseconds (as compared to micro- and milliseconds for spin waves). For their physical description a spin density fluctuation model seems much more appropriate, which considers local fluctuations of the magnetic moment, both in direction and magnitude, (with spin waves the magnitude is assumed to be constant), as well in space as in time. In this picture a magnon may be viewed as a “magnetic exciton” of the spin density which moves, while oscillating, slowly through the lattice or may be localized at lattice sites. These high energy magnons are usually short-lived, because of their strong interaction with single electron-hole excitations, called Stoner excitation. A Stoner excitation consists of an electron in an empty band, a hole in a filled band, with opposite spins of the quasiparticle (adding up to two Bohr magnetons!). Electron and hole may have different wavevectors, i. e. they reside at different locations in the Brillouin zone, and the wavevector of the Stoner excitation is the vectorial sum of the individual wavevectors. High energy magnons couple strongly with Stoner excitations because of their similarity in energy, wavevector and spin character. This relationship is so intimate that magnons may even be described as a coherent superposition of Stoner excitations. It has been proven that this concept holds not only for the high energy, short wavelength magnons, but also for the low energy, long wavelength modes. The long lifetime of the latter is understandable because for electrons and holes very close to the Fermi-energy (i. e. low energy Stoner excitation) the available phase space for the deexcitation shrinks with decreasing energy.

For the observation of magnons a number of techniques have been developed, to which we added spin-polarized electron energy-loss spectroscopy. The oldest and time-honoured technique is ferromagnetic resonance: an external field holds the spins aligned while a radiofrequency wave (more precisely its magnetic vector) seeks to disturb them. When a resonance conditions is met, i. e. when spin waves are created, the spins start to precess and absorb energy from the RF wave. This absorption can be measured very sensitively. This technique has been pushed to atomic monolayer sensitivity (if the total amount of magnetic material is sufficient e. g. 1 cm^2 monolayer Fe on a non-magnetic substrate). We note that the basic coupling mechanism is the interaction of the magnetic moment of the electron with a magnetic field. Another very sensitive and useful technique is the inelastic scattering of photons, usually called “Brillouin light scattering”, which is a misnomer. The photon, as Boson, couples to the orbital moment of an electron and this couples to the magnetic moment via spin-orbit interaction. The coupling is most efficient if the photon wavelength matches that of the spin wave. This means in practice a wavelength of order 1µm since lasers efficiently work in this range. Magnons of this wavelength have typically low energy at near-zero wavevector.

Another excellent tool for magnon spectroscopy is the scattering of thermal neutron beams from reactors or spallation sources. The coupling mechanism in this case is the interaction of the magnetic moment of a neutron with the oscillating magnetic field of a spin wave. Because of the high momentum of the neutron magnons with wavevector way out into the Brillouin zone may be probed, and in fact we owe most of our knowledge about medium to high energy magnons in the bulk to polarized neutron scattering. The neutrons' weak interaction with matter makes the scattering analysis simple, but the scattering cross section very small. Thus, large amounts of material is needed as well as sophisticated detectors. By way of contrast electrons interact strongly with matter. This gives very good sensitivity but complicates the analysis considerably. As compared to neutrons, up to ten orders of magnitude less material is needed for a magnon spectrum in a give period of time. This makes the technique sensitive to surfaces and nanostructures. The history of spin-polarized electron energy loss spectroscopy (SPEELS) has been a 25 years history of trial and error until in 1999 the proof of principle of this technique was given: A spin-polarized electron with (quantum) spin antiparallel to the majority spin orientation may create a magnon by exchanging with another electron in the surface with parallel (majority) spin, coming out with somewhat smaller energy: the energy difference equals the magnon energy. The interaction is of the exchange type, i. e. electrostatic, no magnetic interaction is involved. This is puzzling, but this is the origin of the extraordinary sensitivity of SPEELS.

We will give examples of surface magnons of ferromagnetic epitaxial films, discuss the depth sensitivity, the dispersion relation (is the symmetry given by the surface Brillouin zone or by the projection of the bulk Brillouin zone onto the surface?). By experimental analysis of the lifetime and the group relocity of the high energy magnons we find that we probe collective magnetic excitations on a linear phase space scale of some 10 yoktom-sec. (yokto $\triangleq 10^{-24}$)