Skyrmions getting an X-ray

Dr Shilei Zhang & Prof Thorsten Hesjedal, University of Oxford; Prof Gerrit van der Laan, Diamond Light Source

A team of researchers, led by Dr Shilei Zhang and Prof Thorsten Hesjedal at Oxford and Prof Gerrit van der Laan at Diamond Light Source, have used the energy-dependence of resonant elastic X-ray scattering (REXS) on beamline I10 at Diamond Light Source (Didcot) to measure the microscopic depth dependence of 'skyrmion tornados' in the non-centrosymmetric material Cu_2OSeO_3. In their work they reveal a continuous change from Néel-type winding at the surface to Bloch-type winding in the bulk with increasing depth. This not only demonstrates the power of REXS for microscopic studies of surface-induced reconstructions of magnetic order, but also reveals the hidden energetics that makes magnetic skyrmions such a stable state – a crucial finding for skyrmion device engineering.

The three dimensional structure of skyrmions near the surface is the magnetic nanoscale version of a tornado. Just like a tornado, skyrmions can move, deform, and interact with their environment without breaking up. This makes them ideal for use as information carriers for memory and logic devices. The stability of a tornado is however not only due to the twisting, but also resulting from its three dimensional structure. Such a 3D structure was also found in magnetic skyrmions, guaranteeing their topological stability. Before the team's challenging study, skyrmions had been almost exclusively treated as two-dimensional objects.

In experimental studies, two flavours of skyrmion had been observed – so-called Bloch-type and Néel-type skyrmions (with the nomenclature based on the type of domain wall their cross-section resembles). Whereas Néel-type skyrmions have no chirality, Bloch-type skyrmions can be right- or left-handed. The study by Zhang et al. found that these commonly known skyrmions are just the tip of the iceberg; in fact, the physical quantity 'chirality' is indeed insufficient to describe a skyrmion. Instead, they introduce the helicity angle χ which is a continuously varying property, whereby the Bloch- ($\chi = \pm 90°$) and the Néel-type ($\chi = 0°, 180°$) skyrmion are simply the extreme cases of all possible skyrmion textures.

The key breakthrough to filling this concept with life was the first measurement of the helicity angle. By using circular dichroism (CD) in a resonant elastic X-ray scattering (REXS) experiment (CD-REXS), the team was able to unambiguously determine the helicity angle of a skyrmion texture. REXS on a hexagonally ordered skyrmion lattice gives six diffraction peaks. The breakthrough idea was then to make use of circular dichroism, i.e., the difference between the intensities obtained using left- and right-circularly polarised incident light, which is known to be sensitive to chirality. In CD-REXS, the dichroic diffraction pattern is characteristic for a given helicity angle.

Depth-dependent 3D mapping of magnetic structures

With the new CD-REXS technique demonstrated and established, the team systematically explored the missing information in the third dimension, expecting a Bloch-type skyrmion throughout the material for the investigated material Cu_2OSeO_3. To access the third dimension they made use of the finite penetration depth of soft x-rays. Depending on the wavelength of the incident x-rays, it is possible to probe more or less deeply. Right at the 2*p* absorption edge of a 3*d* transition metal, the soft x-rays are particularly surface-sensitive as the absorption is large, whereas away from the absorption maximum, increasingly deeper layers are probed as well. In CD-REXS experiment, the helicity angle can therefore be measured as a function of depth. Most remarkably, analogous to a tornado structure, the magnetisation flux spirals around the skyrmion tube.

Next steps

The team's study reveals a stunning influence of the surface, which highlights the shortcomings of established theoretical models. A deeper understanding of the underlying physics is crucial for future device applications as they are tied to surfaces (and thin films). Their study also suggests the helicity angle as a new degree of freedom for magnetic skyrmions, which may be used to encode information in magnetic memory applications in the future.

This work was supported by EPSRC through the UK Skyrmion Project grant *Skyrmionics: From Magnetic Excitations to Functioning Low-Energy Devices*, EP/N032128/1, and Diamond Light Source.

For more information on:

The three-dimensional exploration of the skyrmion lattice state:

- S L Zhang, G van der Laan, W W Wang, A A Haghighirad, and T Hesjedal, *Direct Observation of Twisted Surface Skyrmions in Bulk Crystals*, Phys Rev Lett 120, 227202 (2018)
- S L Zhang, G van der Laan, J Müller, L Heinen, M Garst, A Bauer, H Berger, C Pfleiderer, and T Hesjedal, *Reciprocal space tomography of 3D skyrmion lattice order in a chiral magnet*, PNAS 115, 6386-6391 (2018)

The method for the direct determination of the properties of spiral spin structures:

- S L Zhang, G van der Laan, and T Hesjedal, *Direct experimental determination of spiral spin structures via the dichroism extinction effect in resonant elastic soft x-ray scattering*, Phys Rev B 96, 094401 (2017)