A surprising twist on skyrmions

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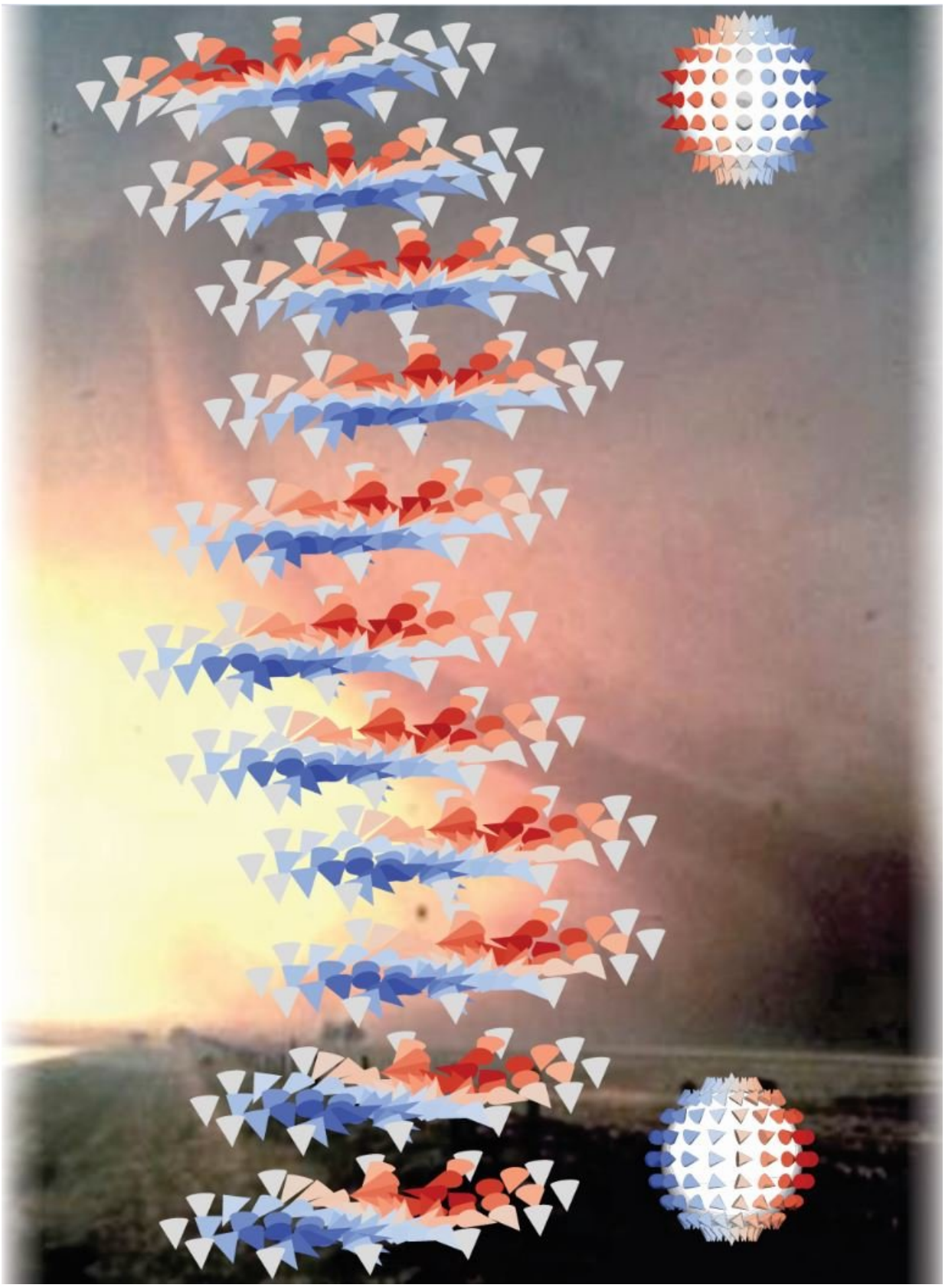

Credit: Diamond Light Source

Vortex structures are common in nature, reaching from swirls in our morning coffee to spiral galaxies in the universe. Vortices are been best known from fluid dynamics. Take the example of a tornado. Air circulates around an axis, forming a swirl, and once formed, the twisted air parcels can move, deform, and interact with their environment without disintegrating. A skyrmion is the magnetic version of a tornado which is obtained by replacing the air parcels that make up the tornado by magnetic spins, and by scaling the system down to the nanometre scale. Once formed, the ensemble of twisted spins can also move, deform, and interact with their environment without breaking up – the ideal property for information carriers for memory and logic devices.

What makes a tornado stable is not only coming from its twist, but also due to its three-dimensional properties, i.e., the wind current has extra twist along the column of turbulent flow. This leads to a tight bundling of the vortex sheets at different heights along the tornado column. Similarly, such a 3-D structure can also occur in magnetic skyrmions, guaranteeing their topological stability. Up to now, skyrmions have been most commonly treated as two-dimensional objects, and their exciting tornado-like structure remained unexplored. In fact, the 3-D characterization of magnetic structures is a rather challenging task. A team of researchers, led by the University of Oxford and Diamond Light Source, have used the energy-dependence of resonant elastic X-ray scattering (REXS) on beamline I10 at Diamond to measure the microscopic depth dependence of 'skyrmion tornados' in Cu_2OSeO_3. In their work, published in *Proceedings of the National Academy of Sciences*, 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.

Dichroism Extinction Rule

In most cases, a 2-D skyrmion is a chiral object, i.e., its mirror image is not identical to itself. One can use left- or right-handedness to describe such symmetry breaking. However, if one takes a closer look at a skyrmion vortex (see movie), one may raise the question: How chiral is a skyrmion? Indeed, starting from a hedgehog swirl structure that does not carry chirality, one can twist the skyrmion to make it appear convergent. Further twisting makes it appear divergent, until the chirality finally flips. This implies that the physical quantity 'chirality' is indeed insufficient to describe a skyrmion, and is in fact just a subset of a broader concept, the helicity angle χ. So far, only the two extreme cases, the Bloch- ($\chi = \pm 90°$) and the Néel-type ($\chi = 0°, 180°$) skyrmion had been experimentally identified.

The crucial experimental challenge was how to measure the helicity angle? The team demonstrated that the exact value of the helicity angle can be unambiguously determined making use of circular dichroism (CD) in a resonant elastic X-ray scattering (REXS) experiment (CD-REXS). The hexagonally long-range ordered skyrmion lattice phase gives rise to the six-fold-symmetric diffraction pattern. Circular dichroism, the difference between the intensities obtained using left- and right-circularly polarised incident light, is known to be sensitive to the chirality of a material. They use the CD of the diffraction intensities from all six magnetic skyrmion lattice peaks, which effectively gives the dichroic information in reciprocal space. This way, each helicity angle corresponds to a characteristic CD-REXS pattern, as shown in the movie. This novel method, published in *Physical Review Letters*, makes

use of the dichroism extinction rule, a general measurement principle that was developed by the same group (highlighted in 2017).

Depth-dependent REXS – The gateway to 3-D mapping of magnetic structures

While the team has found a way to measure the internal structure of a 2-D skyrmion vortex, the structural information about the third dimension, i.e., the structure along the tornado column was missing. Commonly, soft X-rays probe down to a finite depth below the surface, while averaging the signal. Intriguingly, by tuning the wavelength of the incident X-rays, it is possible to systematically vary the probing depth to perform a quasi-tomographic mapping of the magnetic state. At the 2p absorption edge of a 3d 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 a CD-REXS experiment, the spectroscopic measurement therefore provides a strategy to obtain the helicity angle as a function of depth in a three-dimensional skyrmion crystal. Eventually, a clear 3-D skyrmion structure can be reconstructed. Strikingly, very much like the tornado structure, an extra twist, i.e., the magnetisation flux line that spirals around the skyrmion tube is unambiguously identified.

These findings not only highlight the structural beauty of magnetic skyrmions, but also reveal the underlying physical mechanisms that stabilises magnetic skyrmions – the experimental evidence that skyrmion scientists have been looking for, for years. The large discrepancy between the reconstructed experimental model and theoretical predictions suggest much deeper physics to be explored. According to Dr. Zhang, the team leader, "This finding reveals that the helicity angle is a new degree of freedom for magnetic skyrmions, which can take arbitrary values." Following this idea, he sees that the manipulation of

this materials parameter may allow for a new state variable for magnetic memory applications in the future.

More information: Shilei Zhang et al. Reciprocal space tomography of 3D skyrmion lattice order in a chiral magnet, *Proceedings of the National Academy of Sciences* (2018). DOI: 10.1073/pnas.1803367115

S. L. Zhang et al. Direct Observation of Twisted Surface skyrmions in Bulk Crystals, *Physical Review Letters* (2018). DOI: 10.1103/PhysRevLett.120.227202

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