Magnetic Skyrmions

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A magnetic skyrmion is a vortex-like spin whirl, which is 'topologically stable' and has particle-like properties.

Skyrmions, named after the British theorist Tony Skyrme, are topological soliton solutions to nonlinear field models which were introduced in the context of nuclear physics in the 1960s. At their core, skyrmions are topologically stable, vortex-like minimum-energy field configurations, characterised by a topological winding number which can only take integer values. Since then, skyrmions have made their way into many areas of physics, such as liquid crystals and quantum Hall systems, as well as magnetism. This idea, effectively of creating a new type of fundamental particle, has been realised with the discovery of skyrmions in magnetic materials. The confirmation of the existence of skyrmions in chiral magnets and of their self-organisation into a skyrmion lattice has made skyrmion physics arguably the hottest topic in magnetism research at the moment.

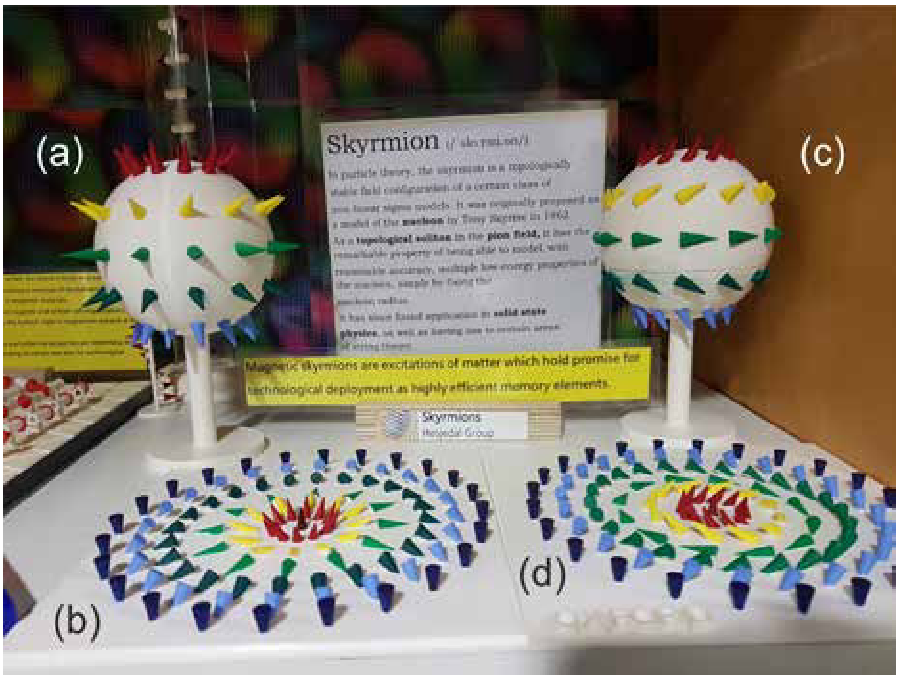

Figure 1: Illustration of the magnetization configurations of non-chiral (left) and chiral (right) skyrmions. The order parameter space objects (the spiky spheres above) can be projected down onto the two-dimensional plane (the swirly disks below) by a stereographic projection, analogously of obtaining a map of Earth on a flat surface. The two configurations can be transformed into each other by changing the helicity angle, which means in this case a 90° rotation about the z-axis (which can be most easily seen in the equatorial plane in which the spikes change from pointing outwards to pointing along the surface).

Magnetic skyrmions are essentially two-dimensional objects, which extend along the applied field direction forming tubes or strings in a real crystal. To understand their special nature better, let's look at a single isolated skyrmion (in two dimensions). Each magnetic spin at a given position in the skyrmion texture is characterised by two angles. By mapping these spins and their orientations onto a sphere in order-parameter space, the topological key property – the so-called winding number – can be easily determined. If each spin direction exists precisely

Technical

What are Skyrmions?

What is usually meant by magnetic order in a common magnetic material is ferromagnetic order, that is, the parallel alignment of the magnetic moments. The responsible microscopic interaction is the direct (or indirect) exchange coupling, which is generally strong and leads to the sizeable magnetic ordering temperatures required for most applications of magnetic materials. The closely related ferri- and antiferro-magnetic orders also rely on these exchange couplings (albeit with the opposite sign of their coupling constants), however, coupling two magnetic sublattices together with their moments pointing in opposite directions.

For magnetic materials without an inversion centre, that is, materials for which the (x,y,z) and (-x,-y,-z) are not equivalent, another magnetic interaction emerges which comes from spin-orbit coupling. This interaction prefers to align adjacent spins perpendicular, as was first described by Dzyaloshinskii and Moriya (DM). Combined with the 'normal' exchange interaction, this leads to a twisting of the magnetic moments in a special way, that is, the material exhibits a handedness (chirality) meaning that the twists can go either in one way or the other.

If magnetic moments are arranged in a way that different magnetic interactions compete with each other, exotic phenomena are observed, for example, antiferromagnetically coupled magnetic moments on a triangular lattice show the effect of geometrical frustration. Similarly, for skyrmions to appear, there needs to be just the right balance of energies. First, there is the exchange interaction with aligns the moments in parallel, followed by the DM interaction which leads to a modulation of the magnetic order on longer length scales (for instance, spin spirals).

So magnetic skyrmions are really just a special breed of magnetic texture occurring in a magnetisation field, similar in nature to a vortex. What makes them special are their particle-like properties; they are soliton solutions – a self-reinforcing wave that maintains its shape while it propagates at a constant velocity, like the non-dispersing water waves first observed in 1834 in the Union Canal in Scotland.

once, the skyrmion will have a winding number of 1. Hereby it is not relevant if the spins point all outwards, forming a hairy ball as shown in Figure 1a, or whether the hairy ball is combed (Figure 1c) – the two are said to be topologically equivalent. In contrast, a trivial object with winding number 0 is the ferromagnetic state with all spins aligned; it cannot be transformed into a non-trivial state by smooth transformations (instead, a hole punching or cutting operation would have to be performed, which would not be a smooth transformation). The projection of the hairy ball onto the two-dimensional plane in real-space (Figure 1b) represents a so-called Néel-type skyrmion. This stereographic projection brings the spin at the South Pole to the centre of the vortex, and the spin at the North Pole is mapped onto the boundary. If the hedgehog is combed (such that the spins at the equator are tangential as shown in Figure 1c), the projection will yield a so-called Bloch-type skyrmion (Figure 1d).

One of the key properties of a skyrmion is its non-trivial topological winding number. This means that the shear existence of the magnetic state protects it from decaying since the winding number can only be changed by introducing a singularity in the field (which is forbidden by physics). This so-called topological protection is what makes skyrmion special. However, in real systems, which are not infinitely large, topological protection is not an absolute protection against decay, but just provides a finite energy barrier.

Initially investigated in the framework of mean-field theoretical treatment of easy-axis ferromagnets with chiral spin-orbit interactions by Bogdanov and co-workers in 1989, magnetic skyrmions were first experimentally observed in 2009 by Pfleiderer's group at the TU Munich. Using small angle neutron scattering (SANS), they discovered a hexagonally ordered skyrmion lattice phase in the chiral magnet MnSi (with a lattice constant of ~20 nm). The first real-space observation was achieved by Tokura's group in RIKEN (Japan) using Lorentz transmission electron microscopy in the following year. What makes these materials so special is the lack of inversion symmetry, which results in the appearance of the spin-orbit coupling based Dzyaloshinskii-Moriya interaction (DMI). Whereas the direct and indirect exchange interaction lead to a collinear alignment of magnetic spins, the DMI results in a twisting of neighbouring spins with a preferred rotation sense. This means that there exist left- and right-handed crystals, whereby the chirality is expressed by the sign of the DMI constant.

The magnetic phase diagram of MnSi is rather universal for this class of non-inversion-symmetric chiral magnets (so-called B20 compounds with space group $P2_13$). It is characterised by the helical phase at low applied fields below the ordering temperature, which first transforms into the conical and then the field-polarised phase with increasing field. The skyrmion lattice phase, which requires thermal fluctuations to compete with the conical phase, exists in a small phase pocket just below the transition temperature at finite fields. This is an obvious disadvantage, and novel materials systems and approaches are discussed below, that overcome this limitation.

Skyrmion materials

Magnetic skyrmions were originally discovered in non-centrosymmetric chiral magnets. More recently, thin film heterostructures and superlattices have been engineered to host skyrmions in zero applied field and at room temperature.

When first discovered in 2009, there were only few materials related to MnSi in which magnetic skyrmions were predicted to exist. Among these B20 compounds, FeGe took a special place since its transition temperature is close to room temperature and therefore potentially interesting for applications. In 2015, Tokura's group in RIKEN found with CoZnMn a system in which the transition temperature is above room temperature. A completely different approach was taken by making use of interfacial DMI effects in thin film heterostructures, e.g., Ru/Co or Pt/Co multilayers. These systems have inherently larger transition temperatures, however, this comes at a price. When looking at the skyrmion size, most of these multilayer systems

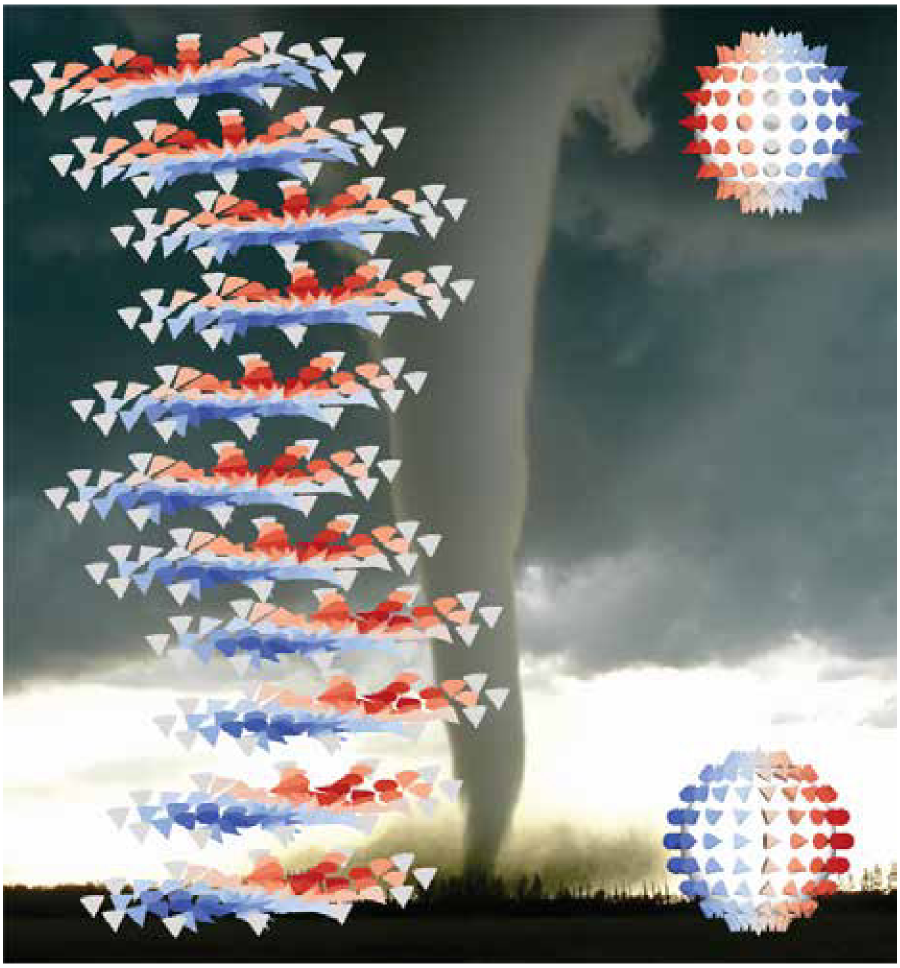

Figure 2: Magnetic tomography has been used to reconstruct the tornado-like 3D magnetic skyrmion structure.

have skyrmion measuring 100's of nm, compared to 18 and 70 nm in MnSi and FeGe, respectively.

Emergent electrodynamics

Electric transport in skyrmion systems is governed by their non-trivial topology, giving rise to emergent electrodynamic effects, such as the topological Hall effect.

The special structure of a skyrmion not only leads to particle-like behaviour but also to very special electrical transport properties. Following an electron that moves through a skyrmion, whereby its spin aligns adiabatically with the local magnetisation, it picks up a Berry phase. Alternatively, this Berry phase can be seen as coming from an emergent magnetic field whereby its magnetic flux is directly connected to the topological winding number. For MnSi with its relative large skyrmion diameter, the effective field is as large as 13.6 T, and it will be even larger for smaller skyrmions. This additional magnetic field will lead to an additional Hall deflection in a transport experiment, the so-called topological Hall effect (THE). This THE is a hallmark of the topological properties of magnetic system, however, on its own, it is insufficient as a proof of the existence of skyrmions. The deflection of an electron traversing a skyrmion also means that the skyrmion will be subject to a momentum transfer by the electron. This momentum transfer is very efficient and Pfleiderer et al. measured extremely small current densities required to move a skyrmion; in fact, they are more than five orders of magnitude smaller than those needed to move a conventional domain wall.

Components for skyrmion devices

To build a future skyrmion-based device requires a couple of key components. There are elements for creating and erasing skyrmions, structures for transporting skyrmions, and also skyrmion detection systems needed. All of these have been independently demonstrated.

The creation (and annihilation) of skyrmions stands at the beginning of a device structure for logic or information storage applications. The simplest way to create skyrmions in B20 systems is to apply the correct magnetic field at a temperature close to the transition temperature. In multilayer systems, a multitude of different techniques has been demonstrated experimentally or in simulations, such as the generation by spin torques (using nano-contacts) or the use of electric fields (via strain) to name a few. The controlled translation of skyrmions, which would e.g. be required for a racetrack-type device, was accomplished using magnetic field gradients, electric fields, magnons, temperature gradients, or spin torques. For the detection of skyrmions, a mechanism has to be found that is selective to the special spin texture, and in principle able to distinguish it from a trivial spin vortex. The THE is one of these effects that is rather straightforward to implement in a device.

Future directions and possible technological applications

Skyrmions, in which magnetic information can be encoded robustly, have the potential to revolutionise data storage. Owing to the 100,000 times lower energy needed to manipulate skyrmionic information on the nanometre scale, efficient devices are within reach.

Magnetic skyrmions have the potential to make it into consumer electronic goods, promising more robust magnetic bits and higher storage densities at lower costs and energy consumption. On the way to success lie a number of challenges in terms of materials science, skyrmion physics, and device engineering. For example, for building a skyrmion racetrack structure, in which bits are represented by the presence or absence of a skyrmion, elements for the controlled creation and annihilation of individual skyrmions, their controlled manipulation (while keeping their distance), and a non-destructive detection mechanism are required. One example of the challenges is the translation of skyrmions. What makes the detection in principle easy is the presence of the THE, however, this also means that the skyrmions do not travel along a straight line. This issue has been addressed by either engineering heterostructures consisting of two halves with opposite THE, overall compensating the effect, using a different type of skyrmion that lives in an antiferromagnetic material, or by simply guiding skyrmions in patterned waveguides.

However, racetrack-type devices are not necessarily the arena in which skyrmions can unfold their full potential. Unconventional (beyond the von Neumann) computing architectures, such as stochastic computing, are an area where skyrmions in the form of reshufflers could excel. Other fields are neural networks and neuromorphic computing. While it is difficult to predict their future, skyrmions have certainly changed our way to look at magnetic textures and opened up exciting research avenues.

UK Magnetics Society Student Bursary Scheme

The Society has Student Bursaries of £300 or £500 available to assist postgraduate students of member organisations to attend conferences of international standing in the UK or overseas, in subject areas which reflect the interests of the UK Magnetics Society membership. The award of a bursary is intended to acknowledge the student's contribution to the magnetics community and act as a catalyst for attracting additional support.

The Dennis Hadfield Memorial Prize, awarded to the best student conference report to appear in MagNews each year, was instigated following the death of Dennis in 1999 Dennis was a founding member of what was originally called the UK Magnetics Club (now the UK Magnetics Society) in 1986.

This followed an Overseas Scientific and Technical Experts Mission (OSTEM) to the USA to look at the state of the permanent magnets industry One of the recommendations of the OSTEM report was to set up a UK magnetics club and this idea came from Dennis. Through his contacts he managed to secure a DTI grant to enable the club to be established and from its inception it had a strong industrial/academic flavour which continues to this day.

The great success of the Society will be a lasting testimony to the vision of Dennis and to the foundations he laid down as its first chairman.

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:

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