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Progress in Physics (73)

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Introduction

In the 1960s, the high-energy theorist Tony Skyrme was seeking a field theoretical description for the stability of hadrons [1]. By considering a continuous quantum field in the presence of a non-linear excitation, he showed that protons and neutrons could emerge as soliton-like excitations of a spinless pion medium. Skyrme's new concept was that the particle stability could arise by considering the excitation (later dubbed the skyrmion) as a quantized topological de-

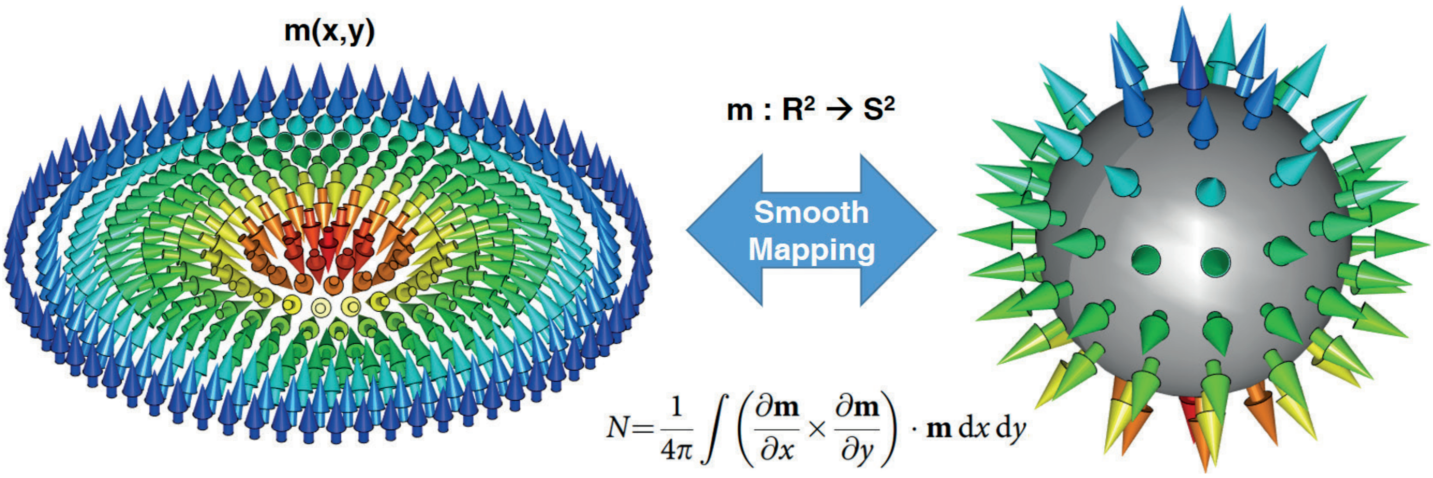

Figure 1: Left shows a schematic visualization of a skyrmion that can be found in magnetic materials, where arrows depict the local direction of the magnetization m. Right shows the result of mapping of the real-space magnetization distribution to an order-parameter space described by the surface of a three-dimensional sphere. The inset integrand provides a convenient means to determine if the real-space magnetization distribution completely wraps the order parameter space, with |N| = Z > 0 describing topological magnetic structures.

fect of the background field. While Skyrme's proposal does not form part of modern mainstream particle physics, his principles nonetheless find traction in various branches of condensed matter physics, ranging from quantum Hall systems, liquid crystals, Bose-Einstein condensates and, as we discuss here, magnetic materials.

In magnetic systems, the skyrmionic excitation can be considered as a topological defect of an otherwise uniform magnetization field. As shown on the left in Figure 1, the skyrmion is visualized in a two-dimensional plane as a point-like region of magnetization reversal at the centre surrounded by a whirl of twisted magnetic spins. Translational invariance is assumed along the third dimension. The topological aspect of the skyrmionic magnetization texture is understood conceptually by examining the mapping of the real-space spin structure to a spherical order parameter space. When the physical space of the magnetization fully wraps the order parameter space at least once - see the right side of Figure 1, the topological winding number is a finite integer and the magnetization texture is described as topologically nontrivial. This condition is never satisfied for topologically trivial magnetization textures such as simple ferromagnets and Néel antiferromagnets, making skyrmions a topologically distinct form of magnetism.

Thus, in the spirit of Skyrme's original proposal, skyrmions in magnets can be considered as closed, individually countable particle-like states that display a robustness to perturbation due to their distinct topology with the background field. It is these fascinating properties - all rooted in the topology of skyrmions - that make skyrmions not only of fundamental interest, but suitable as robust elements of potential applications such as information carriers or non-volatile storage elements. Accordingly, these reasons motivate the substantial worldwide research effort into skyrmion hosting systems. In Switzerland the National Science Foundation recently funded a network on Nano-Skyrmionics [https://skyrmions.epfl.ch] joining scientists from various institutions. Here, we provide a status report on selected forefront aspects of the research field. This includes identifying fundamentally new topological magnetization configurations, the processes of skyrmion nucleation, manipulation, annihilation and detection with a view to their application as parts of memory devices, and their potential integration in broad-band spin dynamic and logic devices.

Skyrmions in non-centrosymmetric magnets

The twisted magnetization distribution of magnetic skyrmions indicates multiple magnetic interactions are required for their stability. In the late 1980s to the 2000s, pioneering theory showed that the right interaction schemes could be found in magnetic crystals with a strong Heisenberg exchange *J* - which favours a collinear magnetization as for ferromagnetism - and a weaker but competing Dzyaloshinskii-Moriya interaction (DMI), *D* due to spin-orbit coupling that favours a perpendicular spin arrangement [2-5]. Due to the competing effect of the weaker DMI, a gradual twisting of the otherwise collinear magnetization required for skyrmions can be naturally achieved. Moreover, the skyrmion size λ is approximately determined by the ratio $\lambda \sim D/J$, and it typically ranges from 1 to 100 nm. Thus the DMI emerges as the key ingredient for skyrmion formation in the vast majority of the known host systems.

For bulk magnets, the DMI can be introduced into the Hamiltonian when the atomic structure has no inversion symmetry. These noncentrosymmetric crystals can be classified according to their point group symmetries, which in turn dictate the pattern of the allowed DMIs and ultimately the internal magnetization texture of the skyrmion [2,3]. Figure 2 shows schematics of the different types of magnetic skyrmion discovered up to now.

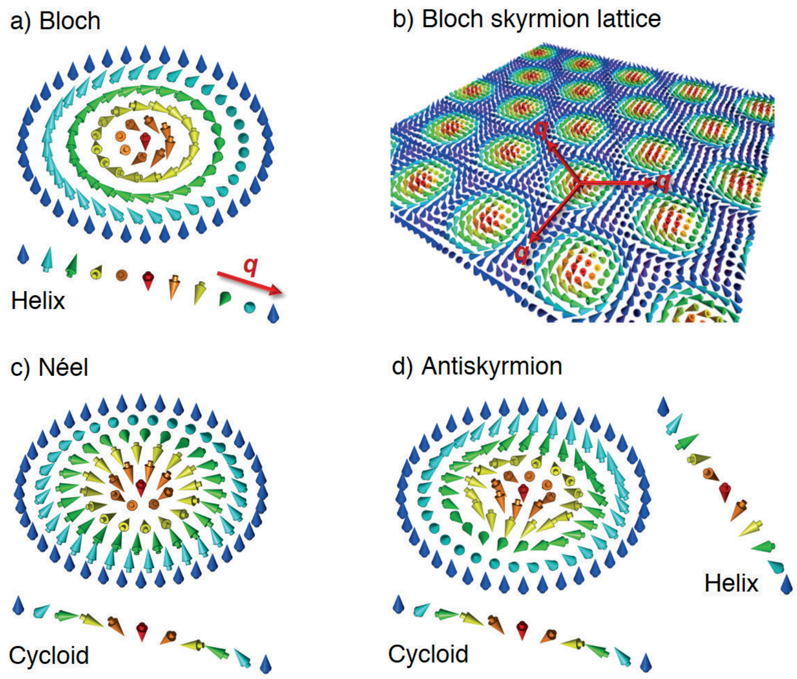

Figure 2: Schematics of the known skyrmion types and a skyrmion lattice. a) Bloch-type skyrmion which has an inherent helix modulation. b) A Bloch-type skyrmion lattice approximately described in terms of three propagation vectors ***q*** *(a so-called triple-q structure). c) Sketch of a Néel-type skyrmion with an inherent cycloid modulation, and d) an Antiskyrmion with inherent helix and cycloid modulations. Panel (b) is © Yoichi Nii.*

The Bloch-type skyrmion shown in Figure 2a is the most common found in the bulk, in particular in crystals described by chiral point groups. Indeed, the Bloch skyrmion was the first type to be discovered in 2009, being shown by small-angle neutron scattering (SANS) to form a hexagonal skyrmion lattice in the then-mysterious *A*-phase of the *B*20 chiral cubic magnet MnSi with spacegroup $P2_13$ [6]. This system was already well-known for its helix ground state (lower part of Figure 2a) described by one propagation vector ***q***, and which onsets immediately on cooling below the critical temperature T_c = 29 K. The SANS experiment showed the *A*-phase in MnSi - which it turns out is archetypal for many skyrmion materials by being thermodynamically stable just a few Kelvin below T_c and in a small magnetic field - to be a skyrmion lattice phase. Here the skyrmion lattice can be described approximately by a superposition of three helices to form a so-called triple-***q*** structure (Figure 2b). Shortly afterwards in 2010 [7], the hexagonal skyrmion lattice structure was confirmed by real-space Lorentz transmission electron microscopy (LTEM) studies of $Fe_{0.5}Co_{0.5}Si$, another *B*20, $P2_13$ system. In this study isolated skyrmions were also observed directly, emphasizing their inherently particulate nature.

Over the last decade, the types of magnetic crystal found to host skyrmions has diversified far beyond *B*20 compounds. In 2012, the $P2_13$ system Cu_2OSeO_3 was discovered to display an *A*-phase that hosts Bloch skyrmions below $T_c = 57$ K [8]. Unlike the *B*20s which are generally metallic or semiconducting, Cu_2OSeO_3 is an oxide insulator with pronounced magnetoelectric coupling and suppressed spin wave damping. These latter properties offer unique perspectives for control of the static and dynamic properties of skyrmions in insulators in contrast to metallic systems. Later in 2015, Bloch skyrmion lattice phases were discovered for the first time to be thermodynamically stable at room temperature in the itinerant $Co_8Zn_8Mn_4$ alloy with chiral cubic spacegroup $P4_132$ or $P4_332$ [9,10]. By tuning the composition of the Co-Zn-Mn alloy the temperature range of thermodynamic skyrmion phase stability can be shifted either well above or well below room temperature. Notably, in $Co_9Zn_9Mn_2$ metastable skyrmion states have been realized at room temperature and zero magnetic field [11].

Also in 2015, the Néel-type skyrmion lattice (Figure 2c) was discovered in the polar semiconducting spinel GaV_4S_8 with spacegroup *R*3m [12]. The Néel-type skyrmion lattice form can be described as a superposition of three cycloidal modulations. Finally in 2017, a novel 'antiskyrmion' texture (Figure 2d) was discovered by LTEM at room temperature in a Heusler alloy $Mn_{1.4}Pt_{0.9}Pd_{0.1}Sn$, spacegroup $I\bar{4}2m$ [13]. In this system the complex DMI pattern leads to an internal magnetization texture with inherent cycloid and helix modulations.

As introduced here, a variety of non-centrosymmetric magnets have been discovered to host various types of skyrmionic spin textures, including some at room temperature. Nonetheless, current efforts in materials discovery continue unabated, aiming at diversifying further the classes of known topological spin textures and host systems. From a fundamental perspective, the motivation is to expand the number of skyrmion phases and hence platforms for exploring the fundamental physics of topologically non-trivial magnetism, in either thermodynamic equilibrium phases or far-from-equilibrium metastable states. From an applications perspective, the achievement of skyrmions with new internal magnetization textures, particularly at room temperature and across metallic and insulating systems, promises versatile and distinct functionalities. In addition to the bulk noncentrosymmetric magnet skyrmion systems mentioned above, skyrmions can be realized in fabricated magnetic multilayers, which will be described later in this article.

Skyrmion creation and manipulation in thin plates of non-centrosymmetric magnets

In bulk skyrmion hosting materials, the underlying magnetic state is not a ferromagnetic state, but a modulated helical

How to measure skyrmions

There exist several experimental methods with which skyrmions can be detected.

Small angle neutron scattering (SANS): Just like X-ray diffraction can be used to measure crystalline structures, neutron scattering can be used to measure magnetic structures in accordance with Bragg's law $n\lambda = d \sin(\theta)$. A triangular lattice of skyrmions gives rise to a characteristic 6-fold pattern of Bragg peaks on the neutron detector, as illustrated in figure A1. SANS was used to identify skyrmions first in MnSi [6], and subsequently in a growing number of skyrmion hosting materials.

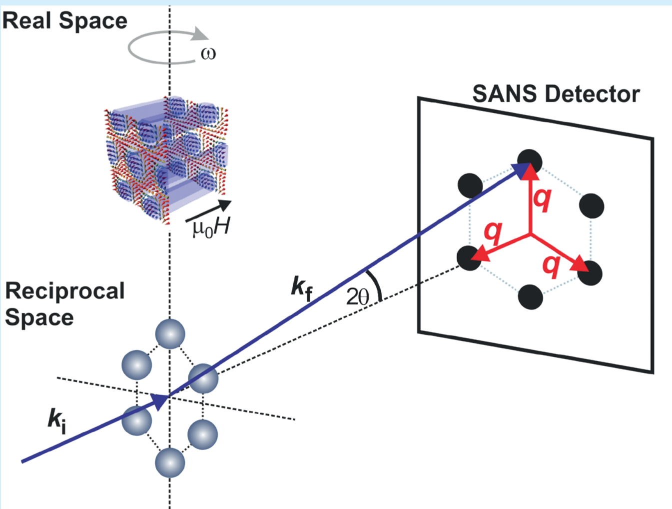

*Figure A1: Schematic showing how neutrons diffracting off the two-dimensional hexagonal skyrmion lattice in real-space, results in a six-fold ('triple-**q**') skyrmion lattice diffraction pattern on the SANS detector. To observe the hexagonal pattern, the magnetic field, which defines the direction of the skyrmions, is aligned approximately with the neutron beam wavevector $\mathbf{k}_i$.*

Magnetic contrast, Lorentz, transmission electron microscopy (LTEM): In a transmission electron microscope, electrons travel through a thin (few hundred nm) sample. The in-plane component of a magnetization pattern deflects the electrons perpendicular to the magnetization direction - this is known as the Lorentz force. Since

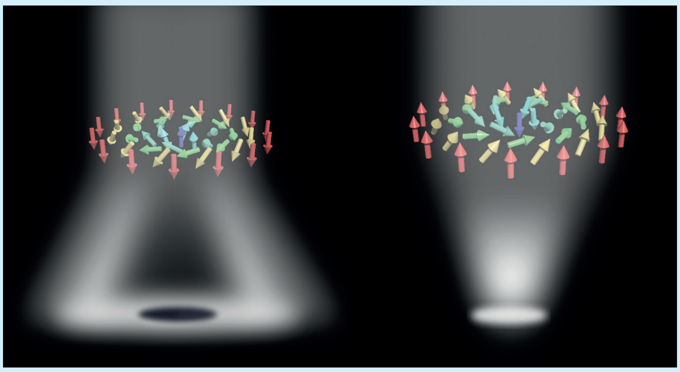

Figure A2: Illustration of how the circulating in-plane magnetization component of a skyrmion respectively focuses or defocuses the electron beam depending on the sense of rotation (chirality) of the skyrmion. (In detail, because an electron microscope employs focusing optics, the effect of the skyrmion is to change the effective focal length for magnetic contrast.)

the in-plane component of the skyrmion has the magnetization circling in a ring around its center, a skyrmion will act as a focusing or defocusing lens for the electrons. Hence, LTEM images skyrmions as well defined dots in the image. This special phenomenon makes real-space studies of skyrmions a very powerful and exciting field of research.

Topological Hall effect (THE): When current carrying electrons flow through a material in presence of a magnetic field, the Lorentz force bends their trajectory leading to a transverse potential - a phenomenon known as the Hall effect. (Some two-dimensional electron systems exhibit a special quantum Hall effect, which was the topic of the 1985 and 1998 Nobel prizes in physics, and in 2019 was used for redefining the international system of units [14]). In ferromagnetic materials, the external magnetic field is amplified by the local magnetization leading to a much stronger anomalous Hall effect, which is proportional to the magnetization of the sample. The special topological nature of the skyrmion spin texture leads to a different topological Hall effect. Therefore, the possible existence of skyrmions can be inferred by comparing measurements of Hall effect and magnetization as a function of magnetic field. Since such measurements are easier and cheaper than neutron scattering (which requires large samples) or electron microscopy (which require micro-fabrication of the sample), topological Hall effect often gives the first hint of skyrmions in a new material.

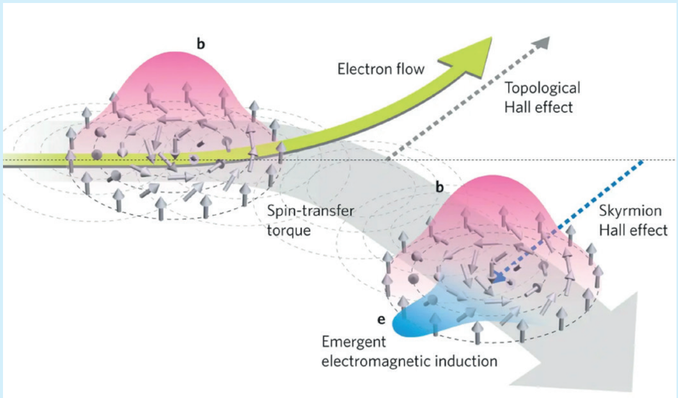

Figure A3: Schematic of the topological Hall effect, adapted from [15].

Broadband microwave spectroscopy on collective spin excitations: Wave-impedance matched transmission lines or coplanar waveguides optimized on dielectric substrates (Fig. A4) are widely exploited to investigate collective spin excitations in skyrmions crystals. Using for instance the output port of a vector network analyzer (VNA) one applies a frequency-tunable microwave current to the metallic leads which generates a microwave magnetic field at the position of the skyrmion-hosting magnetic material. Thereby the non-collinear spin structure experiences a torque and undergoes spin-precessional motion. Via the time-dependent magnetic flux density and Henry-Faraday's induction law the precessing spins induce a microwave signal in the metallic conductor whose phase and amplitude are analyzed in the detector input of the VNA. Such broadband microwave spectroscopy setups have allowed for the resonant excitation and detection of the magnetization dynamics in skyrmion crystals and further collinear and non-collinear spin structures. Several theoretical and experimental groups showed independently that periodic lattices of skyrmions exhibit a characteristic set of eigenmodes. Their field dependencies and polarization characteristics nowadays serve as a fingerprint of a skyrmion phase which can be tested inductively and non-invasively without attaching e.g. electric leads.

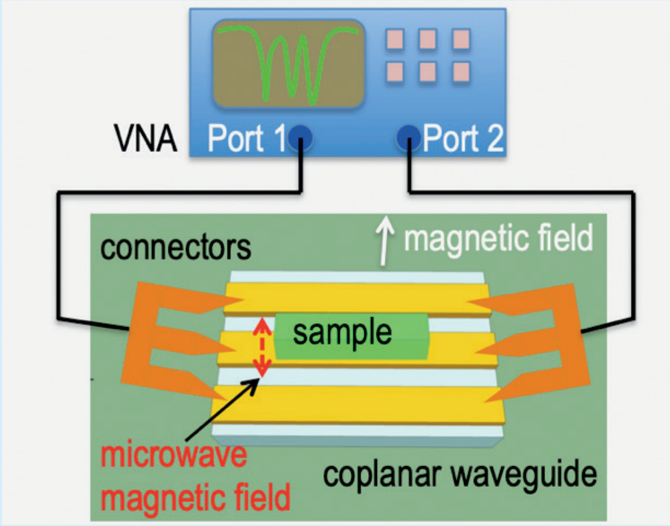

Figure A4: The spin structure of a magnetic sample is excited using a microwave current applied to a coplanar waveguide.

Scanning transmission x-ray microscopy (STXM): High resolution imaging gives an important insight into the physics of skyrmion systems. STXMs are synchrotron based instruments working in the soft x-ray range (typically 200 - 2000 eV) covering the L-edges of the transition metals and the M-edges of the rare earth elements. The spatial information is obtained by focusing an x-ray beam using Fresnel zone plates to a spot of typical 20 - 30 nm and raster scanning the sample through this spot. The transmitted intensity is recorded to generate an image [16]. In addition x-ray magnetic circular dichroism provides element specific magnetic contrast, as the x-ray absorption depends on the relative orientation of the magnetization with respect to the polarization vector, if the photon energy is tuned to the respective absorption edge of the magnetic element of interest. Figure A5 shows a sketch of a STXM and an example image of skyrmions.

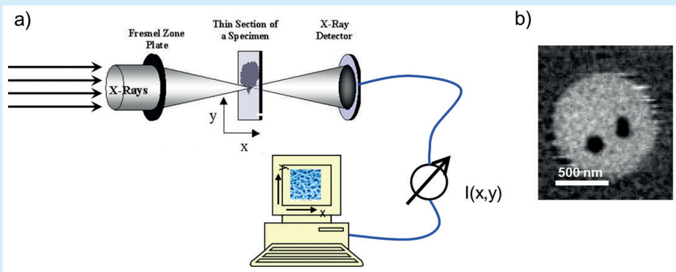

Figure A5: a) Sketch of a scanning transmission x-ray microscope (STXM). b) Example of a magnetic image of two skyrmions in a disk of a magnetic multilayer, the grey level corresponds to out-of plane component of the magnetization (m_z).

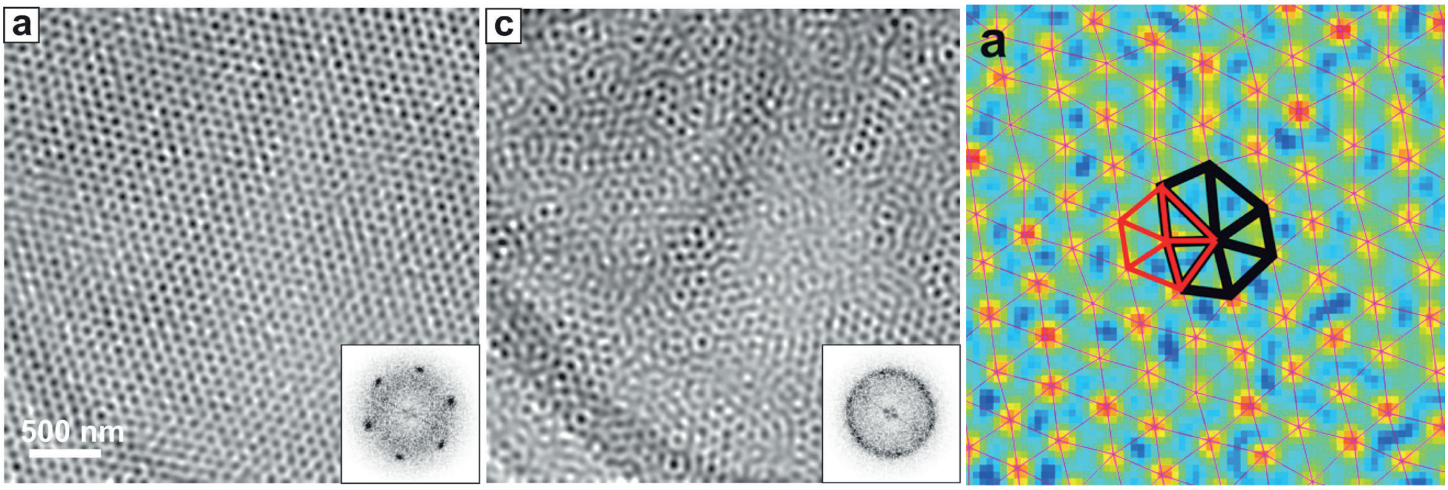

Figure 3: (left and middle) Skyrmion solid and skyrmion liquid imaged with magnetic contrast electron microscopy LTEM, from [17], (right) 5-7 defect from [18].

or cycloidal structure with a well defined periodicity $\lambda \sim D/J$. Therefore, the skyrmions are strongly bound in a triangular lattice with distance λ, and it is difficult to observe isolated skyrmions. One might therefore speculate whether these magnetic textures are best described as ordering of topologically protected skyrmion particles or simply as a magnetic structure composed of 3 superposed helical modulations. Studies of defects and dynamics of the magnetization pattern partly answers this question. Defects and dynamics in a 3q structure would involve fluctuations in the direction, periodicity and relative phases of the 3 propagating helices. However, what is observed experimentally is that the skyrmions remain well defined and move around like particles even when the lattice is disordered into a skyrmion liquid [17]. Thus, defects in the magnetization pattern are limited to well defined defects of the triangular lattice. These observations on the one hand demonstrate that the skyrmions are topologically protected as emergent particles, but on the other hand imply that also the lattice of skyrmions exhibits topologically defined dynamics. The 2016 Nobel prize in physics was awarded to Kosterlitz, Thouless and Haldane for introducing topological concepts to condensed matter physics. Specifically, Kosterlitz and Thouless discovered that in 2D the phase transition between a solid and a liquid is topological in nature and is characterized by the formation and eventual unbinding of defect pairs. In the triangular lattice where every site should have 6 neighbours, the defect pair has respectively 5 and 7 neighbours. Phase transitions involving atoms or molecules are difficult to image directly due to the required spatial and temporal resolution.With the ability of electron microscopy to image and record movies of large areas with up to 10^5 skyrmions, skyrmions have surprisingly emerged as a new platform for experimental real-space studies of such 2D topological phase transitions.

Studies of skyrmion dynamics are not limited to studying intrinsic fluctuations. Many studies have explored driving and controlling the skyrmions. In MnSi it was found that skyrmions can be driven by current densities as low as 1 μA/μm^2, which is 5 orders of magnitude less than for magnetic domain walls [19]. The phenomenon was explained through spin-transfer-torque by the polarized electron flow and a quantitative theory was developed [20,21]. The rather low pinning of skyrmions was investigated both with resistance noise spectroscopy [22], where the washboard effect frequency of the regular skyrmion lattice sliding past fixed pinning centres allowed extracting skyrmion drift velocities of 1 - 100 μm/s, and with in-situ SANS [23], which revealed increased pinning at the edges of the material, leading to hydrodynamic-like flow of skyrmions.

Part of the rapidly growing interest in magnetic skyrmions is driven by the potential of information storage. To this end controlled creation of skyrmions is required. It has been proposed theoretically that driving a current past a notch constriction can generate individual skyrmions from a uniformly magnetized state [24], and demonstrating experiments are ongoing. Several other mechanisms have been proposed [25], some of which have been realized experimentally for bulk systems, including use of electric fields in the insulating skyrmion hosting material Cu_2OSeO_3 [26] and laser pulses in the near-room-temperature skyrmion hosting compound FeGe [27]. So far skyrmion creation in bulk materials has mainly resulted in transition to the skyrmion lattice state rather than controlled creation of single or few skyrmions. In this respect, efforts in multilayer magnetic films have progressed further as will be discussed later in this article.

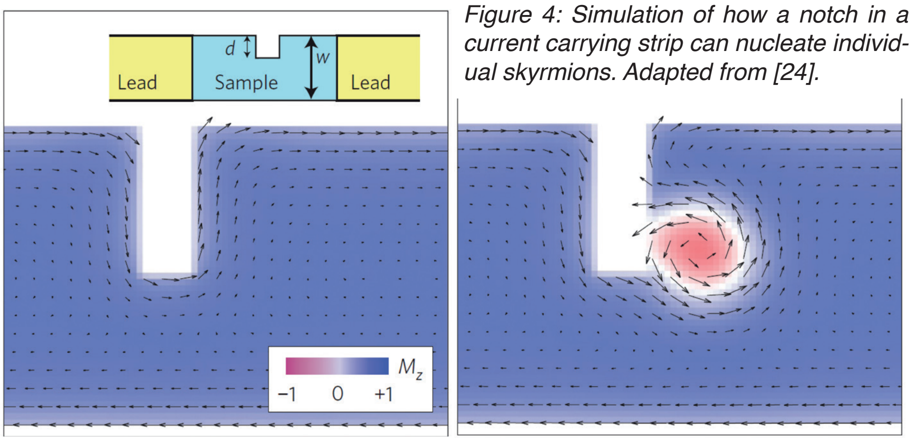

Figure 4: Simulation of how a notch in a current carrying strip can nucleate individual skyrmions. Adapted from [24].

Collective excitations of magnetic skyrmions

Soon after the discovery of its surprising quasistatic properties a pioneering micromagnetic simulation study performed by M.

Mochizuki showed that a skyrmion crystal exhibited characteristic dynamic excitations [28]. The three collective spin excitations were classified concerning their peculiar spin-precessional motion and named correspondingly as breathing, clockwise and counterclockwise rotational modes. Mounting the chiral ferrimagnetic insulator Cu_2OSeO_3 on a conventional microwave antenna and performing broadband microwave spectroscopy at cryogenic temperatures Y. Onose *et al.* indeed observed magnetic resonance phenomena consistent with the predicted polarization characteristics and character of spin-precessional motion in a skyrmion lattice [29]. Several other groups performed similar microwave experiments afterwards and evidenced that the three modes represented a universal feature, no matter whether the skyrmion crystals appeared in metallic, semiconducting or insulating magnetic materials. Still their exact resonance frequencies varied from material to material between roughly about 1 and a few 10 GHz. These observations were in agreement with a recently developed theory which also considered the specific shapes of the magnets [30]. The characteristic set of field-tunable resonances in the few GHz frequency regime stimulated the broader interest in skyrmion-hosting materials concerning the exploration of their novel functionalities for signal processing at microwave frequencies which are relevant for information technologies and mobile communication.

Skyrmions in magnetic multilayers

Magnetic multilayer stacks (MML) were long used to provide systems with a perpendicular magnetic anisotropy (PMA) and they are used e.g. to study magnetic bubbles. By introducing asymmetries around the magnetic layers by choosing different non-magnetic heavy metal layers an asymmetric exchange, the DMI is introduced into these systems, providing the necessary requirements for stabilizing skyrmions. Here, the DMI is an interface effect, strongly depending on the materials combination selected. One example of the experimental realization of these stacks are Co/Pt/Ir, shown in Figure 5. The strength of this effect depends on the materials used in these multilayer stacks, illustrated in Figure 6. This explains why one of the routinely used material systems Co/Pt/Ir shows a large DMI. The different signs of the two interfaces, the Co/Pt and the Co/Ir interface add up in absolute value, as they sit on opposite sides of the film, resulting in an inversion of the sign for one of them.

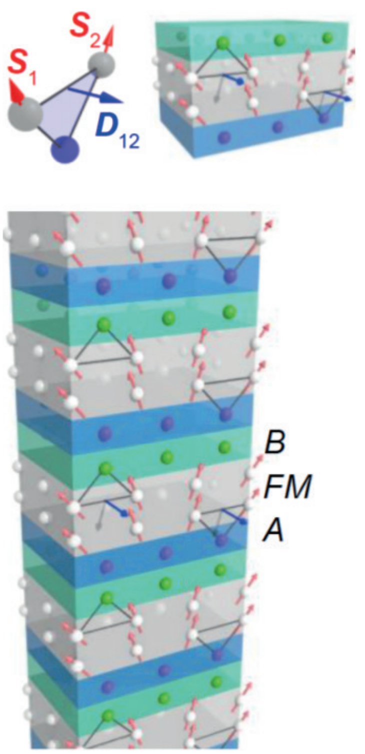

Figure 5: Interfacial Dzyaloshinskii-Moriya interaction (DMI) in asymmetric magnetic multilayers. The DMI for two magnetic atoms (gray spheres) close to an atom with large spin-orbit coupling (blue sphere). Zoom on a single trilayer composed of a magnetic layer (FM, gray) sandwiched between two different heavy metals A (blue) and B (green) that induce the same chirality (same orientation of D) when A is below and B above the magnetic layer, and finally on an asymmetric multilayer made of several repetition of the trilayer. (Figure adapted from [31])

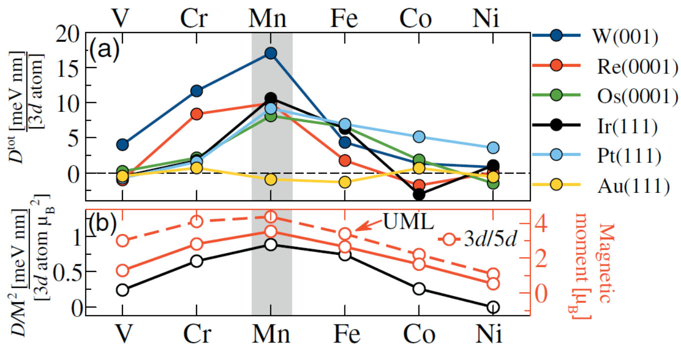

Figure 6: Strength of the DMI for different material combinations, derived from first-principle calculations. (Figure taken from [32], with permission from APS). Strength and sign of the Dzyaloshinskii-Moriya interaction D^{tot} in 3d TM monolayers on 5d substrates calculated around their magnetic ground. A positive sign of D^{tot} indicates a left-rotational sense or "left chirality".

For various applications, MML based skyrmion systems are very promising, as they allow to tune the properties to the actual needs. Important features are stability at room temperature and at zero field. Current research is focusing on various aspects, which are important for applications, e.g. the defined creation, manipulation and detection of skyrmions. For the creation in a confined region, current induced nucleation processes, as shown in Figure 7, are very promising.

Towards applications these Skyrmions have to be manipulated and detected. For the manipulation, e.g. shifting skryrmions through structures, current driven processes are very good candidates, as they are well compatible with existing electronic concepts. One example is presented in e.g. [34], where skyrmion velocities of several ten meters per second were archived. Finally the presence of skyrmions has to be detected, e.g. for reading out a logic state from a signal processing system. Candidates for a link of skyrmion system to electric circuits are the skyrmion Hall effect [35] or magneto resistive effects, like the tunnel magneto resistance, as they are nowadays also used in magnetic storage devices.

Skyrmions for applications

As introduced in the previous sections, skyrmions attract enormous interest in the context of their potential use as high-speed information carriers with low energy consumption. This expectation received the initial impetus from pioneering experimental work on the skyrmion phase in MnSi, both by SANS in 2010 [19] and Topological Hall effect (THE) measurements in 2012, [36]. In these experimental studies the Bloch-type skyrmions were observed to be depinned and driven into motion by application of an ultralow threshold electric current density of 10^6 A·m^{-2}. On the one hand, since this threshold current density is 5 orders smaller than that required to depin ferromagnetic domain walls, the expectation for using skyrmions in low power spintronic devices was ignited and continues unabated. On the other hand, under such a low depinning current density, the skyrmions

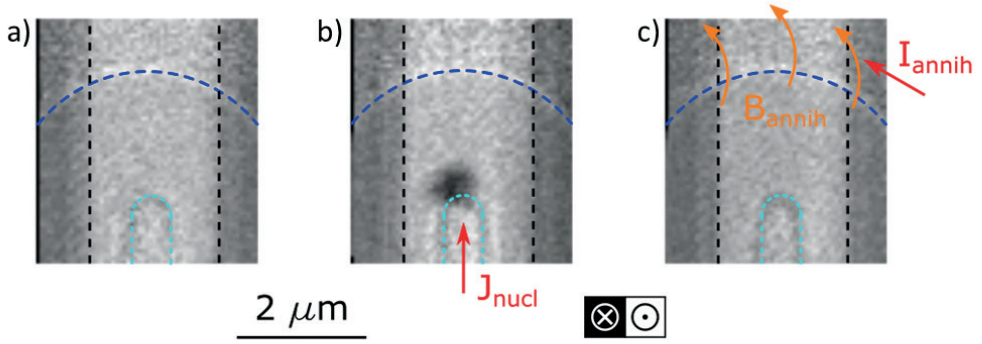

Figure 7: Quasi-static investigation of the skyrmion nucleation and deletion processes. (a–c) Quasi-static XMCD-STXM images of the current-induced nucleation and field-induced deletion of a magnetic skyrmion. (a) Initial uniform magnetic configuration. The edges of the microwire are marked by the black dashed lines, the edge of the injector is marked by the light blue dashed line, and the edge of the microcoil is marked by the dark blue dashed line. (b) Nucleation of a magnetic skyrmion (area of dark contrast in the image) by injecting a 5 ns long current pulse in the microwire. (c) Recovery of the initial magnetic configuration by injecting a current pulse across the microcoil, leading to the generation of an out-of-plane magnetic field pulse. (Figure taken from [33], with permission of the American Chemical Society])

display a low velocity of less than 1 cm·s^{-1}. As mentioned in the previous section, for a realistic device, higher current densities are required to drive skyrmions at speeds of order tens m·s^{-1}.

The often quoted critical requirements for practical applications of skyrmions are i) their stability at room temperature (or even higher), ii) for high-density applications, a compact size of less than 100 nm and ideally closer to 10 nm, iii) for spintronics applications, controllability by weak external stimuli such as low electric currents, magnetic fields or electric fields. Some of the presently known bulk skyrmion host systems at least partially satisfy these conditions, and as such they may eventually find use in applications. Still, these requirements are more readily achieved by skyrmions in synthetic MML systems. A clutch of discoveries in 2016 of mid- to small-sized skyrmions (< 100 nm) at room temperature, in zero magnetic field, and furthermore their current-driven dynamics, was reported in various multilayers such as Pt/CoFeB/MgO [37], Pt/Co/Ta [38] and Pt/Co/MgO [39] stacks. This makes synthetic MMLs presently the most promising class of skyrmion host system for the nascent field skyrmion-based electronics, or skyrmionics.

The field of skyrmionics focuses principally on the development of information storage and processing devices using skyrmions, whereby the energy-efficient writing, deletion, read-out and processing processes are needed. The writing and deleting of skyrmions in various systems has been achieved by different methods, such as by using magnetic fields, electric fields, electric currents, and laser pulses, while the electrical read-out of a skyrmion can be achieved making use of the topological Hall effect or an embedded magnetic tunnel junction (MTJ) that detects a skyrmion-induced change in the magnetoresistance. For further details of the research status on these issues, the reader is referred to one of the reviews cited at the end of the article.

The most highlighted application concept is that of skyrmion racetrack memory device initially proposed by Fert *et al.* in 2013 [40] as development of the domain-wall based racetrack memory concept proposed earlier by Parkin *et al.* in 2008 [41]. In the context of multilayer systems, many theoretical studies have elucidated the current-induced dynamics of transporting isolated skyrmions along otherwise ferromagnetic racetracks, though the experimental realization of a fully functional skyrmion-based racetrack memory device is still awaiting demonstration. By means of a conceptual example of a racetrack memory concept, Figure 8 shows a hypothetical material in which both skyrmions and antiskyrmions may exist (presumably as metastable states) and information is encoded in terms of their different in-plane magnetization textures.

Bulk ferrimagnetic materials play a central role in microwave technology already for oscillators, band-pass filters, power limiters, and circulators. As their operational frequencies are tunable via an applied magnetic field they are exploited over a large frequency regime from roughly 1 to 100 GHz. In this regime the free-space wavelength of electromagnetic waves varies from about 30 cm to 3 mm, respectively. Key microwave components such as circulators are (still) of a similar macroscopic size to directly modify the microwave signal transmission via their non-resonantly excited dynamic magnetic permeability. Future mobile communication and the internet of things however require miniaturized and multi-functional microwave devices. Here skyrmion crystals if realized in potentially low-damping thin-film materials might put a new spin on microwave technologies based on magnets. Their periodic lattice can be viewed as an artificial crystal for collective spin excitations, i.e., spin waves (magnons) [42]. It offers a specifically tailored band structure for magnons which can be controlled e.g. by a magnetic or, more efficiently, by an electric field in case of magnetoelectric coupling. Fine-tuning J and D magnonic crystals with lattice constants on

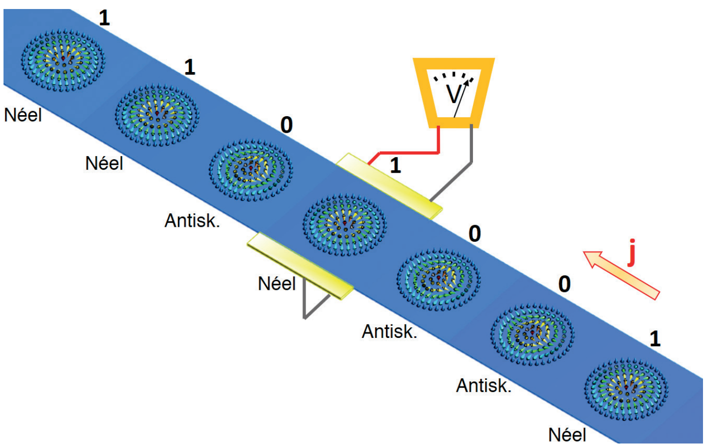

Figure 8: Racetrack memory concept based on a train of skyrmions and antiskyrmions. Here Néel-type skyrmion and antiskyrmion represent either a digital 1 or 0, respectively. Required information can be transported based on the manipulation of the skyrmion-antiskyrmion train through pulses of applied current density j. The detection scheme is able to differentiate between the in-plane magnetization textures as they pass through the region with gold voltage contacts. In the present case, the skyrmions and antiskyrmions can be distinguished by producing a different sign of THE as determined in transport measurements.

the 10 nm length scale can be envisioned which are much smaller than ever achieved by state-of-the-art top-down nanotechnology in clean rooms. Microwave signals coupled to the corresponding magnons in the GHz frequency regime experience wavelengths which would be five to six orders of magnitude shorter than their corresponding free-space wavelength. Skyrmion crystals could thereby serve as nanoscale on-chip band-pass filters which process microwave signals on unprecedentedly short length scales, further fueling the prospects of magnonics.

Other application concepts that involve harnessing the GHz energy excitations of the skyrmion internal modes thus include skyrmion-based microwave detectors [43] and nano-oscillator applications [44], the creation and exploitation of skyrmion-based logic computing gates [45] and transistor devices [46], each of which can be combined with a race-track architecture, and even biophysics-inspired devices such as an artificial synapse device for neuromorphic-like computing systems [47]. Overall, it is anticipated that skyrmion-based electronic devices will emerge eventually to achieve a widespread commercial and societal impact.

More skyrmions in the future?

As illustrated, magnetic skyrmions have inspired studies from fundamental physics to possible applications. With this article we sought to provide appetizers by highlighting a few of these exciting developments, chosen in part with a bias to Swiss activities in the field. For readers who would like to learn more, we recommend some of the recent reviews [48-52]. Whether skyrmions will eventually become part of future main-stream technologies remain to be seen, but the study of their rich physics has already led to new ways of thinking about topological magnetic textures, their manipulation and potential uses. Many more exciting results and extensions to the field continue to appear from a growing scientific community.

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