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Magnetic Properties

Skyrmions**

*Claudia Felser**

chiral magnetism · magnetism · spintronics · topology

Recently the concept of topology has attracted tremendous interest in condensed matter science. New quantum properties such as in topological insulators and skyrmions were designed by using the concept of topology and the guidance of theory. The famous example for different topologies is the donut and a sphere, two objects that cannot be transformed continuously into each other. A donut and a sphere are of different genus. In chemistry, topology is known in the context of the handedness of chiral molecules. A pair of mirror-image enantiomers—a "right-handed" and a "left-handed" molecule—is not superposable. The fascinating phenomenon of chirality was recently found also in condensed matter systems, in magnetic materials with non-centrosymmetric structures and at the surface of topological insulators. Topological insulators are materials that are insulating or semiconducting in the bulk and metallic on the surface or edges as a result of protected chiral spin currents.[1] The protected surface currents are a result of the electronic structure in the reciprocal space. Skyrmions are topological particles in real space, magnetic screw-like nanostructures (see Figure 1), which can be directly observed by neutron scattering[2] and Lorentz microscopy.[3] In analogy to the real-space example of a donut and a Möbius strip, two different topological quantum states cannot be transformed into each other and will coexist. Both concepts—topological insulators and skyrmions—are very interesting for solid-state chemists and materials scientists since new compounds and high-quality single crystals are needed to take advantage of the full potential of these classes of materials. What makes both classes even more exciting is the fact that they can be predicted by theory[4–6] and by chemical intuition, which can help to identify new candidates.[7]

The history of skyrmions goes back to the 1950s when Heisenberg and his colleagues tried to explain the existence of countable particles in continuous fields for a general field theory of elementary particles, without success. This led to the assumption that particlelike configurations are not stable in nonlinear field models. Later Tony Skyrme demonstrated that certain nuclear particles such as neutrons and protons (fermions) can be described as localized states, named skyrmions, a nonlinear boson field.[8] Since then skyrmions have played an important role in various fields of science, for example in nuclear physics, quantum Hall systems, liquid crystals, and ultracold atoms. However, until 2006 skyrmions were believed to be exotic, non-equilibrium particles that cannot form spontaneously without a strong external field. Christian Pfleiderer and his group proved this assumption wrong. They provided the first evidence of a skyrmion lattice in the chiral phase, the so called A phase of the transition-metal compound MnSi by using small-angle neutron scattering (SANS)[2] following the theoretical prediction by Rößler et al.[5] The neutron-scattering results of a single crystal in a small magnetic field show a hexagonal pattern, which is not related to the crystal structure. This hexagonal pattern perpendicular to the applied field is the result of the chiral magnetic arrangement of the skyrmions.[2]

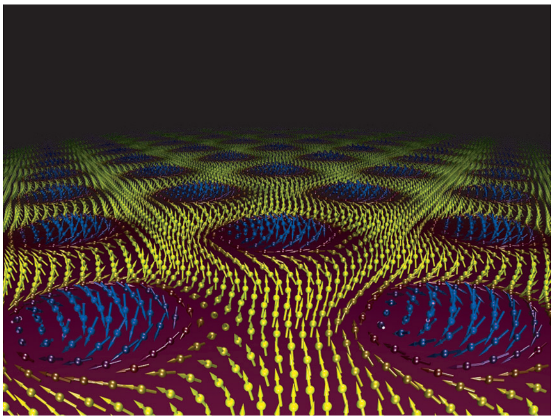

Figure 1. Schematic representation of a skyrmion lattice. The arrows represent the magnetization direction. Skyrmions are topological particles, magnetic screw-like nanostructures in real space, which are much more complex than the classical magnetic arrangements such as the collinear magnetic interactions ferro-, ferri-, and antiferromagnetism. The chiral magnetic nanostructures cannot be removed by gradual rotations of the spin owing to the topology of the quantum state. (Image courtesy of Christian Pfleiderer).

What are skyrmions and why are they so stable? Common magnetic materials show collinear magnetism with the magnetic moment aligned along one axis and with ferro-, ferri-, or antiferromagnetic interactions. The non-collinear magnetic structure of skyrmions is much more complex (see Figure 1). The magnetic moments point towards the center of the nanostructure, reminiscent of vortex-type structures,

[*] Prof. C. Felser
Max Planck Institut für Chemische Physik fester Stoffe
Nöthnitzer Strasse 40, 01187 Dresden (Germany)
E-mail: felser@cpfs.mpg.de
Homepage: http://www.superconductivity.de

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which are common in condensed matter physics, as, for example, in type II superconductors. In skyrmion systems the chiral magnetic nanostructures are typically 10 to 100 nm in size and are topologically protected. The skyrmion lattice is stable for the same reason that a Möbius ring cannot be continuously transformed into a donut, or a "right-handed" molecule into a "left-handed" molecule. The vortices with "right-handed" chirality cannot be scattered into "left-handed" vortices without changing the spins of many atoms simultaneously. Topologically stable knots between the vortices play the role of the atoms in a crystal structure. The topological properties of skyrmions are the chirality (skyrmion number ± 1) and the winding number (0 for a donut and 1 for a Möbius strip).

What kinds of materials show these chiral magnetic bundles, the skyrmions? Theory predicts that these topological magnetic structures appear only in non-centrosymmetric structures. The crystal structure of the prototype, MnSi, is the cubic B20 structure with the chiral space group $P2_13$.[9] MnSi

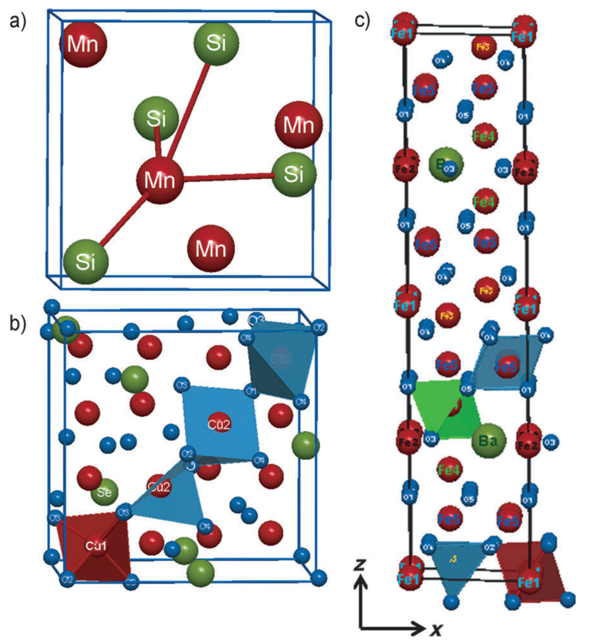

Figure 2. Crystal structure types of skyrmion systems: a) the non-centrosymmetric structures of a) MnSi and b) Cu_2OSeO_3, characterized by two inequivalent Cu^{2+} sites with different oxygen coordination and the c) centrosymmetric hexagonal barium ferrite $BaFe_{12}O_{19}$.

exhibits a rich magnetic phase diagram (Figure 2) that represents the typical phase diagram of a skyrmion system. MnSi is not a "normal" strong ferromagnet: the magnetization "feels" the crystal structure containing a screw axis by means of spin–orbit coupling. MnSi undergoes a magnetic phase transition below 29.5 K (Curie transition temperature, T_C) at ambient pressure and zero applied magnetic field. The magnetic structure of MnSi is a helical magnet in which the spins precess along the cubic space diagonal $\langle 111 \rangle$. The magnetization is uniform in the direction perpendicular to the axis of the helix. The rotation of the spins show a periodicity of around 20 nm in MnSi,[2] which is large compared to the lattice constant of 4.56 Å. The skyrmion structure (or A phase) emerges just below T_C when the applied field exceeds 100 mT.[2] In the skyrmion phase the vortices are unpinned from the crystal axis and they rotate in the direction of the applied magnetic field. The long-range helical modulations, a superposition of three spirals arranged with a 120° angle between each spiral, are responsible for the observed hexagonal pattern.

Skyrmions have been found in metallic as well as in insulating compounds; it seems that only the symmetry counts. Besides MnSi, isostructural metallic $Fe_{1-x}Co_xSi$[3,10] and FeGe[11] as well as the insulating chiral-lattice magnet Cu_2OSeO_3[12] were identified as skyrmion systems. The Tokura group has used a real-space method, Lorentz transmission electron microscopy, to observe skyrmions in thin films as well as in single crystals.[3,10–12] The skyrmions in insulating Cu_2OSeO_3 were induced by electric polarization. The magnetoelectric coupling may make it possible to manipulate the skyrmion with an external electric field without losses due to joule heating.[12] Chemists and materials scientists know that non-centrosymmetric crystal classes in general can exhibit a variety of interesting physical and technologically important properties such as piezoelectricity, ferroelectricity, and pyroelectricity, and second-order nonlinear optical behavior.[13] The combination of one of these properties with helical magnetism in non-centrosymmetric compounds might open new directions for compounds with multifunctional properties.

Rößler et al. predicted also that skyrmion lattice ground states could exist in all structures lacking inversion symmetry. Therefore skyrmions should also be observed at surfaces and in thin films.[5] Stefan Heinze and colleagues experimentally confirmed this theoretical prediction: they reported on skyrmions in a one-atomic-layer-thick Fe film on Ir(111).[14] In a magnetic thin film, the broken translational symmetry and the shape anisotropy are responsible for the formation of this new magnetic quantum phase[11] under an external field along a direction normal to the film. The observed lattice of vortices is topologically protected. Heinze et al. used spin-polarized scanning tunneling microscopy, which can directly image the non-collinear spin texture in real space on the atomic scale. As in MnSi, the observed structure is incommensurate with the underlying atomic lattice. In general, the stability of the skyrmions depends on the dimensions of the system; in the phase diagram of thin-film samples of $Fe_{1-x}Co_xSi$[10] skyrmions are stable over a wide range of temperatures and magnetic fields (see Figure 3), whereas the skyrmion area shrinks for bulk MnSi.[2] From these results it was concluded that skyrmions must occur in a large number of thin-film systems.

The skyrmion systems reminded Tokura and his group of magnetic bubbles and therefore they started to investigate the magnetic structure of even a centrosymmetric compound, M-type hexaferrite doped with small amounts of scandium.[15] The magnetic bubbles in ferromagnetic thin films were explored in the 1970s for data storage applications. However, the magnetic-bubble memory could not compete commercially with the hard disk drives. Bubble memory is a non-volatile memory like a hard disk. The ideal materials for the

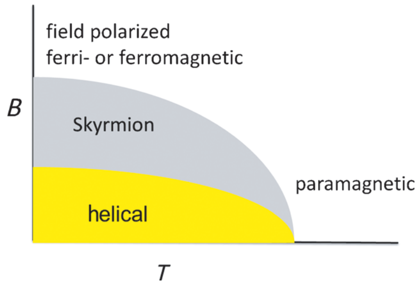

Figure 3. Schematic magnetic phase diagram of a compound with a skyrmion ground state. For $B=0$, helimagnetic order develops below a critical temperature (yellow area). Above a critical field the helical order collapses. In MnSi the skyrmion phase appears only in a small area; in thin films the skyrmion phase is observed for intermediate fields and low T (gray area). At high magnetic fields a collinear interaction is induced and at high temperatures the systems become paramagnetic.

magnetic bubble memory were thin films of magnetic garnets, but magnetic bubbles are also observed in uniaxial ferromagnets and amorphous alloy films with the perpendicular anisotropy. From the materials perspective, the ratio of the magnetic anisotropy and magnetostatic energies and the film thickness are important for the bubble formation. Since magnetic bubbles and skyrmions have common signatures, it was not surprising that Tokura and his team have investigated the topological properties of the multiferroic hexagonal barium ferrite, with a tunable magnetic anisotropy. Surprisingly they found even more complex magnetic structures at room temperatures than expected for the non-centrosymmetric skyrmion systems and helimagnets.[15] However, the observed spin structures have different origins; long-range magnetodipolar forces in a ferromagnetic thin film are potentially the origin of skyrmions as discussed by Yu et al. in detail in Ref. [15].

What is the origin of this new topological skyrmion state? The helical ground state of the skyrmion systems is formed as a result of the competition between the ferromagnetic exchange and the so-called Dzyaloshinsky–Moriya (DM) interaction.[16,17] If the coupling between the spin and the orbital moment (spin–orbit coupling, SOC) is strong as, for example, in compounds with elements of high nuclear charge, relativistic effects play an important role. Instead of the Schrödinger equation, the fully relativistic counterpart, the Dirac equation, must be solved. In quantum field theory a special term occurs for these non-centrosymmetric structures, which leads to an antisymmetric spin exchange contribution and allows the observation of SOC effects even in compounds with light elements. The DM interaction arises from the spin–orbit scattering of electrons in systems that lack structural inversion symmetry and tends to stabilize helical spin texture with fixed handedness. The skyrmions appear in a small range of magnetic fields and temperature. A small external magnetic field brings the skyrmions to life. The lack of inversion symmetry in MnSi and the resulting DM interaction generates slow rotations of all magnetic structures such that the magnetic and atomic structures are decoupled. The observed hexagonal symmetry of the skyrmions is consistent with the superposition of three spirals at an angle of 120° and perpendicular to the applied magnetic field. Above 550 mT the magnetization is fully aligned with the field and MnSi becomes ferrimagnetic.

How can we identify skyrmions? A first hint is still a non-collinear magnetic arrangement in a compound with a non-centrosymmetric crystal structure. A non-collinear magnetic structure can be identified, for example, by neutron diffraction. With specific heat and susceptibility measurements the helical A phase in MnSi was established. Real-space methods—spin-polarized scanning tunneling microscopy, magnetic force microscopy, scanning Hall microscopy, and Lorentz transmission electron microscopy—and the reciprocal space method small-angle neutron scattering can be used to investigate the skyrmion lattice. However, these methods are not accessible for everybody. Fortunately the signature of the topological behavior can also be identified by transport measurements. A distinct additional contribution to the Hall effect was measured, the topological Hall effect.[18,19] The topological Hall effect is restricted to the A phase[18] and arises in addition to the normal Hall effect, which is proportional to the applied magnetic field, and the anomalous Hall effect (AHE), which scales with the ferromagnetic components of the magnetization. Under pressure, the topological Hall effect was observed in a much larger range of temperatures and magnetic fields, probably owing to dynamic fluctuations.[19] The sign and the magnitude are in nice agreement with the predicted values based on Berry curvature calculations.[19] The Berry phase reflects the chirality and winding number of the knots in skyrmions as well as in topological insulators.

What is the potential technological impact of skyrmions? As mentioned before, skyrmions are topologically equivalent to magnetic bubbles, which were considered as nanostructures for data storage. In the context of future spintronics applications skyrmions might have an enormous impact. In read heads of hard disks based on the GMR effect, the magnetization controls the magnetoresistance (electric current). Modern spintronics uses the complementary process: an electrical current manipulates magnetic structures. Today the typical currents are still too high ($>10^{11}$ A m^{-2}). In spin transfer torque based magnetic random access memory (STT-MRAM), skyrmions in magnetic systems with transition temperatures above room temperature, such as FeCoSi and FeGe, and in magnetic thin films are therefore of great interest. Skyrmions, which can be manipulated by current densities of only 10^6 A m^{-2} and small magnetic fields in the mT range[20] can open new directions for MRAM research, but also for racetrack memory. Racetrack memory, discovered by Parkin et al. (IBM),[22] a memory in which magnetic domain walls are moved by an electrical current, can be compared with a low-dimensional version of bubble memory. Also here small skyrmions could have an impact on reducing the energy consumption. Another direction in spintronics is the use and manipulation of a pure spin current, a current without charge transport. Skyrmions are circulating dissipationless spin currents.[21] Multifunctional application can be envisaged for multiferroic skyrmion materials; the electric control of the magnetic chirality might allow the manipulation of the skyrmion by an external electric field without losses due to joule heating.[12]

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