

# MFM imaging of a Skyrmion lattice and a helimagnetic phase in the attoDRY1000

Balázs Sipos, Thomas Scheler  
attocube systems, Munich, Germany

## Introduction

Currently, magnetic skyrmions are one of the most studied phenomena in magnetic materials. The structure was originally proposed in particle physics by Tony Skyrme in 1962 [1] as a result of his unified field theory. However, it turned out that these topological objects exist in many more areas than just in high-energy physics. Similar structures have been reported in liquid crystals, superconductors, and magnetic materials.

A skyrmion can be best pictured as a magnetic frozen tornado. However, in a magnetic material they consist of local spins that form the whirl rather than wind (Figure 1). Like tornados, magnetic skyrmions are exceptionally stable through their geometric construction. This topological stability enables them to be a candidate for magnetic storage. A commercial hard disc drive (HDD) is an array of 2D topological magnetic structures, *i.e.* the domain walls. However, there are size limitations to how small a magnetic domain can be. Following the discovery of skyrmions by neutron scattering [2], skyrmions as small as 1 nm have been observed [3,4], promising storage densities far beyond the current limitations. Furthermore, in a magnetic structure the energy required to change its state is proportional to the number of spins it contains. The reduced size of a skyrmion not only allows for higher storage densities but also more energy-efficient writing. Recently, N. Romming and co-workers reported on the first artificial creation and annihilation of a single skyrmion [5]. This manifested in effect the first writing experiment, confirming their potential for applications in information-technology.

The potential use of skyrmions in magnetic storage is just one of the many reasons why studying their dynamics and individual properties are of the upmost interest. To achieve more insight into these questions, it is important to be able to study them in real space. Select one, see how

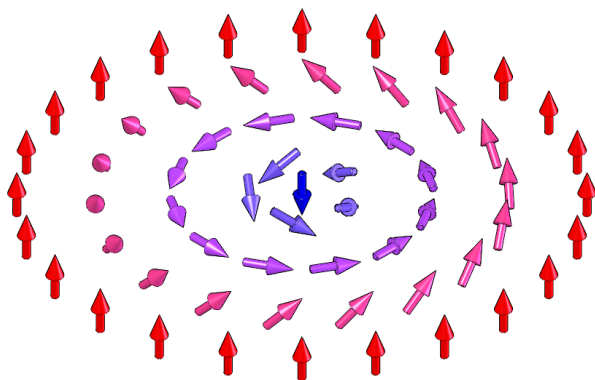


Figure 1: Spin arrangement in a single skyrmion.

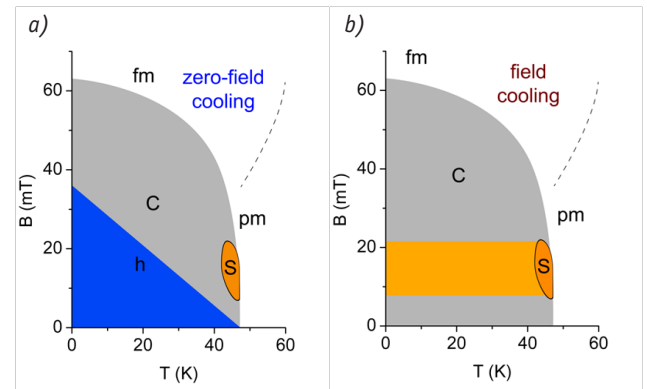


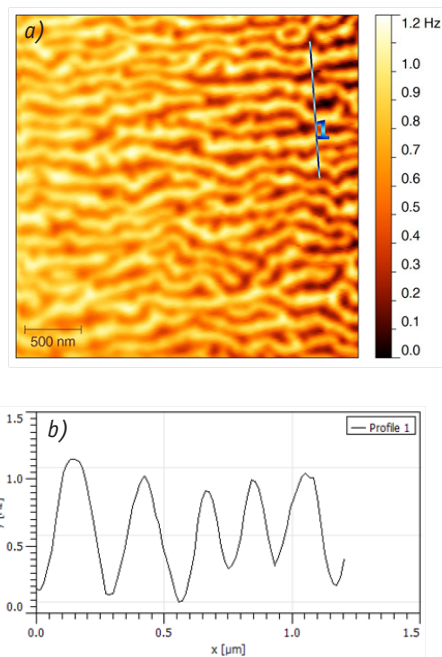
Figure 2: a) Phase diagram of  $\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}$  in zero field cooling (zfc). The location of the pocket where the skyrmions are present (S) is very small and its boundaries are strongly sample dependent. h denotes the helimagnetic phase, C is a conical phase, fm is ferromagnetic and pm is paramagnetic. b) The phase diagram under field cooling for field values in the range of the skyrmion lattice phase. It is important to see that contrary to the zfc case, under field cooled conditions the skyrmion lattice is extended to the lowest temperatures. Figure adapted from [3].

they move, appear, and disappear. In this application note we show the observation of the skyrmion lattice and its dynamics in a bulk  $\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}$  crystal with a low temperature MFM in a cryogen-free environment similar to the first real space observations shown on this material by Peter Milde and co-workers [6].

$\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}$  is a material without an inversion symmetry. This property is important because it allows the formation of skyrmions. The measurements reported in this application note were performed on a single crystal sample of this material (courtesy of A. Bauer and C. Pfleiderer, Technical University of Munich, Germany). The sample, despite being a bulk crystal, exhibits exceptional surface quality with a surface roughness of less than 1 nm. From the phase diagram (see Figure 2), one can see that the skyrmion lattice phase, stable only under certain  $B$ - $T$ -conditions, can be transferred into a metastable state at lower temperatures by field-cooling. This not only makes it easier to find the interesting phases, but lowering the temperature also increases the magnetic signal, due to reduced fluctuations in the sample.

## Experimental Setup

The measurements were carried out in an attoDRY1000. The attoDRY1000 is attocube's answer to the continuously shrinking helium supplies and skyrocketing He prices. It is a cryogen-free measurement platform specially designed for scanning probe experiments. For the measurement a standard attoAFM/MFM I was used. To have the best possible lateral resolution, we chose a Nanosensors SSS-type magnetic tip.



**Figure 3:** a) MFM image of the helimagnetic phase of  $\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}$ . The measurement was carried out at 3.2 K under zero magnetic field. b) Line profile of the MFM phase shift along the line cut 1. The periodicity of the stripes is between 100 and 250 nm.

## Measurement Results

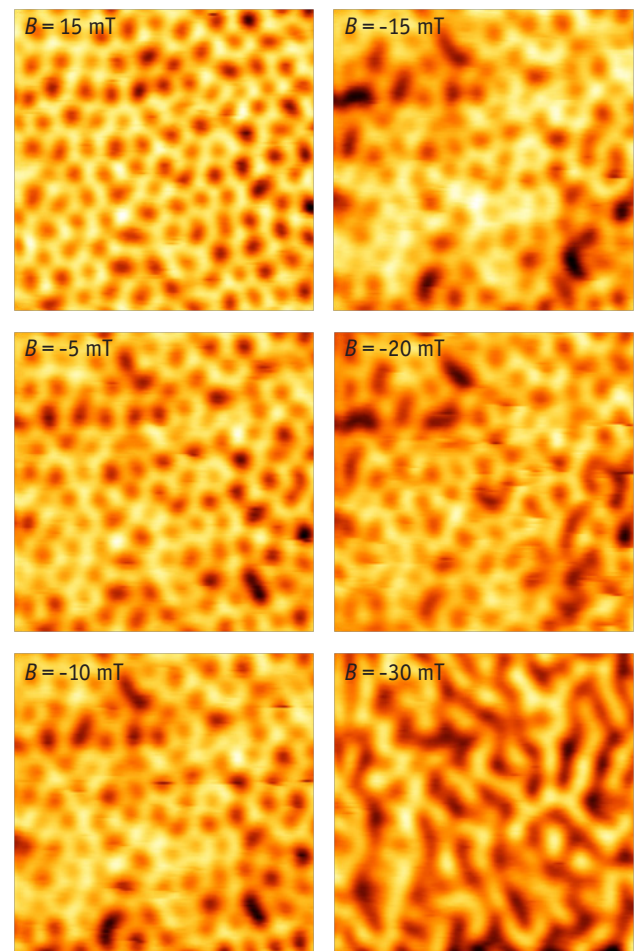
We measured both the helimagnetic and the skyrmion lattice phase. For the former, we cooled the sample in zero magnetic field to 3.22 K. The results are shown in Figure 3. The periodicity of the magnetic structure is between 100 and 250 nm as it can be seen from the line cut.

After measuring the helimagnetic phase the sample was warmed up to 60 K, the magnetic field raised to 15 mT, and the sample cooled again to 3.44 K. At this temperature several images were taken at varying magnetic fields to see the effect of the field on the metastable skyrmion lattice (Figure 4). As the magnetic field decreases, a few skyrmions start to fuse into larger structures. Furthermore, at -30 mT, the helimagnetic phase is abruptly restored. We did not observe the gradual transition described by Milde *et al.* [6]. This may be due to the significantly lower temperature, where reduced magnetic fluctuations make the skyrmions more stable.

In a subsequent series of measurements, the magnetic field was reduced to zero and temperature increased to 10 K to induce thermal effects and increase magnetic fluctuations. A series of 28 images on the same area was taken over time. The time between frames was approximately 30 min with 15 min frame time. From frame to frame, a slight reordering of the helimagnetic lines can be seen, usually in the form of two previously separated lines snapping into contact.

## Summary

In this application note we showed the very first real space observation of skyrmions with MFM in a cryogen free cryostat. The setup used is a standard commercially available



**Figure 4:** MFM image of the skyrmion phase of  $\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}$  (scan size is  $1.5 \mu\text{m} \times 1.5 \mu\text{m}$ ). The sample was first cooled down from 60 K under 15 mT magnetic field to 3.4 K. Then the field was gradually changed to 5 mT, -10 mT, -15 mT, -20 mT and -30 mT in that order, and a new image was acquired at each field. On the figures one can see the skyrmions starting to merge already at -5 mT and they abruptly disappear at -30 mT.

attoAFM/MFM in an attoDRY1000. We hope that this will greatly facilitate the understanding of these exotic magnetic structures and accelerate their introduction into commercial applications.

We would like to thank Jan Seidel, University of New South Wales, Sydney, Australia for communicating the sample and fruitful discussions. We gratefully acknowledge A. Bauer and C. Pfleiderer, Technical University of Munich, Garching, Germany for preparing and providing the  $\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}$  sample.

## References

- [1] T. H. R. Skyrme, Nucl. Phys. **31**, 556-560 (1962).
- [2] S. Mühlbauer *et al.*, Science **323**, 915 (2009).
- [3] X. Z. Yu *et al.*, Nature **465**, 901 (2010).
- [4] S. Heinze *et al.* Nature Physics **7**, 713 (2011)
- [5] N. Romming *et al.*, Science **341**, 636 (2013).
- [6] P. Milde *et al.*, Science **340**, 1076 (2013).