Investigating Skyrmions Using Lorentz Transmission Electron Microscopy

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Magnetic skyrmions are localized spin textures with nanometric size and non-zero topological charge. Due to their robustness and particle-like nature, skyrmions are promising candidates for spintronic applications. We have developed powerful tools to analyze Lorentz Transmission Electron Microscopy (LTEM) images such as algorithms for identification and tracking of skyrmions and various correlation functions. We use them to investigate how disorder and defects affect the long-range order of the skyrmion lattice (SkL) and to quantify the creation of skyrmions using electric fields.

For the first time we have performed real-space imaging of skyrmions on a large sample area of thin plate Cu_2OSeO_3 using cryo-LTEM to access positional coordination and local orientational numbers as a function of an external magnetic field [1]. The direct space images (see figure 1 center) are Fourier transformed to allow for a cross correlation analysis in reciprocal space. This provides information on the symmetry of the spatial frequency distribution in the sample. In figure 1 left, the cross correlation function (CCF) is displayed for various magnetic fields and for a certain scattering vector. The case of 160 G is particularly interesting since the peaks for the helical phase (purple curve) are modulated by a disordered hexagonal lattice of skyrmions (red curve). It is a first order phase transition characterized by a glassy co-existence of both helical and skyrmion phase. In this glassy phase, the CCF indicates an incipient orientational order of the skyrmion distribution. By repeating the analysis for different scattering vectors, we further reveal an octogonal distortion of the skyrmion lattice in this phase [1].

In the skyrmion phase, we evaluate the role of disorder and defects in the lattice by locating the skyrmions in the real-space image and counting the number of nearest neighbors of each skyrmion via Delaunay triangulation [1]. To this end, we deploy our algorithms for skyrmion identification, as depicted in figure 1 center. Perfect skyrmion coordination has hexagonal symmetry, imperfect coordination means a skyrmion has more or less than six neighbors thus forming a lattice defect. Plotting the spatial angle map of orientation (figure 1 right) one can see the formation of a multidomain skyrmion lattice whose boundaries coincide with the defects. With higher magnetic fields, the dislocation density decreases and larger single domain regions form [1].

Due to spin-orbital effects, the insulator Cu_2OSeO_3 shows magnetoelectric coupling. An applied magnetic field induces an electric polarization, which in turn can couple to an external electric field. Using LTEM, we have shown that we can write skyrmions from a helical spin background by applying an electric field [2], as depicted in figure 2. We place the sample in the helical phase but close to the SkL phase. A positive E-field along the [11-1] direction creates skyrmions whereas a negative E-field shows no effect. This asymmetric response rules out that the phase boundary is crossed by Joule heating due to the leakage current.

The number of skyrmions as a function of time throughout the acquired LTEM movies is determined by an algorithm capable of identifying skyrmions coexisting with the helical phase [2]. The procedure was inspired by algorithms used for fingerprint identification. Multiple E-field cycles are averaged to be mapped into a single period, as shown in figure 2 right. Our findings are highly coveted since they imply that skyrmionics can be integrated into present-day field effect transistor based electronic technology, where very low energy dissipation can be achieved, and hence realizes a large step forward to its practical applications [2].

References:

[1] Rajeswari Jayaraman *et al*., PNAS **112** (2015), 14212-14217.
[2] Ping Huang *et al*., arXiv preprint (2017), arXiv:1710.09200.
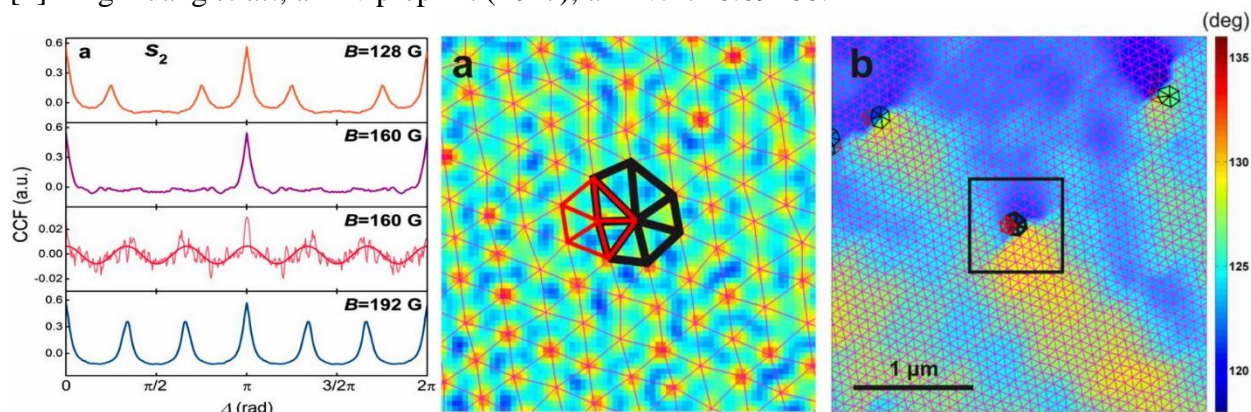
Figure 1. Left: cross correlation function at scattering vector s2 for various fields. Center: direct space LTEM image (after image treatment for better visualization) with Delaunay triangulated lattice. Right: spatial angle map of skyrmion lattice.
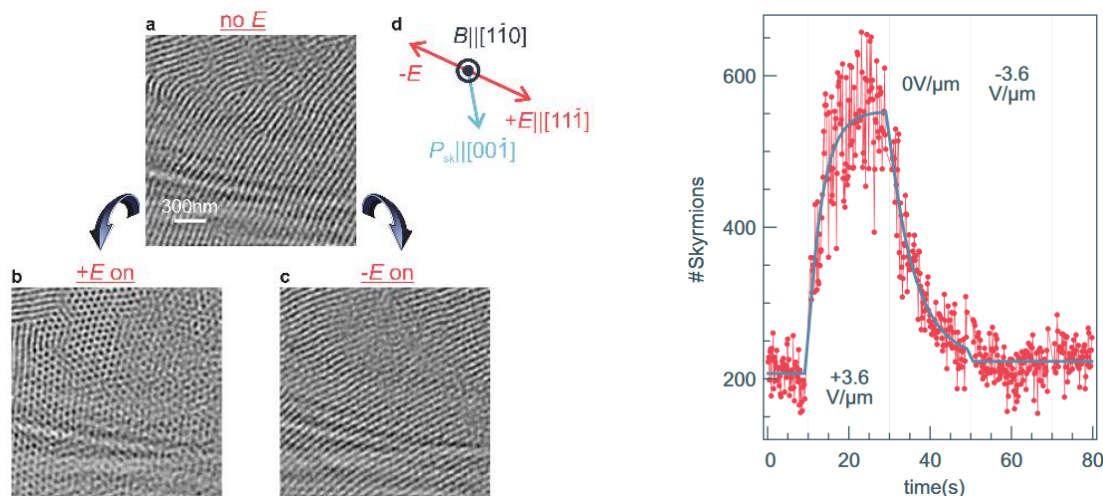

Figure 2. Left: direct space LTEM images at different E-fields. Right: number of skyrmions after averaging over multiple E-field on/off-cycles.