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Towards Induction Mapping of the 3D Spin Texture of Skyrmions

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Skyrmions [1] are topologically non-trivial vortex-like spin textures, anticipated for application in spintronic technologies, in next generation magnetic data processing and storage due to their facile manipulation by spin-polarized currents of very low magnitude [2, 3]. Unfortunately, little is known about the 3D structure of skyrmions [4, 5], ubiquitous in thin film technology. Here, we bridge that gap by combining the concept of the transport of intensity equation (TIE) [6], focal series in-line electron holography (EH), and off-axis EH [7] to quantitatively reconstruct the projected magnetic field pertaining to both the helical and the skyrmion lattice phase in single crystal nanoparticles of the isotropic chiral magnet $Fe_{0.95}Co_{0.05}Ge$.

The skyrmion phase in $Fe_{0.95}Co_{0.05}Ge$ particles (Fig. 1 (b)) was investigated using a double corrected FEI Titan³ 80-300 microscope operated in image corrected Lorentz mode. A focal series of Lorentz TEM (L-TEM) images of a single isolated nanoplatelett oriented along the [001] zone axis (Fig. 1 (a)) was recorded. Reconstruction of the phase of the electron wave and thereby of the magnetic induction was obtained with the help of a modified Gerchberg-Saxton type algorithm. To supplement the focal series reconstructions from large field of views, smaller areas of the identical nanoplatelett were investigated by off-axis EH. A direct tomographic investigation of the 3D structure of the skyrmionic lattice is currently experimentally unfeasible, because this would require an externally applied out-of-plane magnetic field to be tilted with the sample.

Thus, indirect experimental evidence for the 3D structure of the skyrmionic lattice may currently only be inferred from a quantitative analysis of the projected magnetic induction in the sample conducted with the help of EH. Fig. 2 (a) depicts an underfocused L-TEM micrograph showing the hexagonal that reveals the skyrmion lattice. The image is one out of 21 of the focal series used for an in-line holography reconstruction of the object exit wave in amplitude and phase. Figs. 2 (b, c) show magnetic induction maps $\bar{B}_{\perp}(x, y)$ in cylindrical coordinate representation visualizing the spin texture of the skyrmions by $\bar{B}_{\phi}(x, y)$ (Fig. 2(b)) and their donut-shaped magnitude by $\bar{B}_{r}(x, y)$ (Fig. 2 (c)). Likewise, we observed magnetic induction maps (Figs. 2 (e, f)) from a phase image reconstructed by off-axis EH (Fig. 2(d)) on the same $Fe_{0.95}Co_{0.05}Ge$ nanoplatelett. Most strikingly, we consistently observe a reduction of the projected in-plane B-fields ($\bar{B}_{max} = (0.2 \dots 0.3)\, T$) as compared to those of a homogeneous skyrmion throughout the film thickness. Two alternative models for the 3D structure of skyrmions are thus derived.

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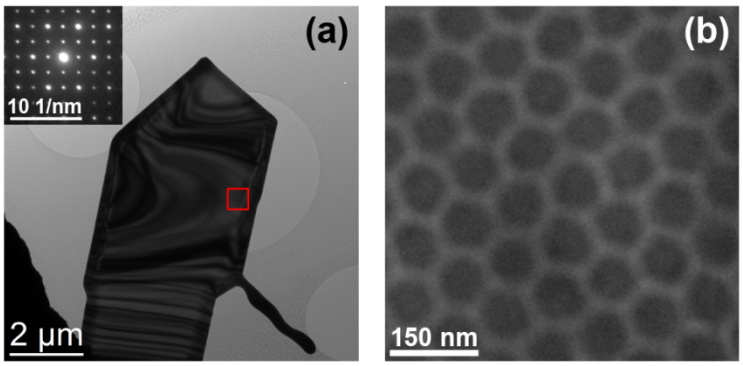

Figure 1. (a) TEM image of a $Fe_{0.95}Co_{0.05}Ge$ nanoplatelett in [001] with the diffraction pattern in the inset. (b) Skyrmion lattice as observed within the marked area in panel (a).

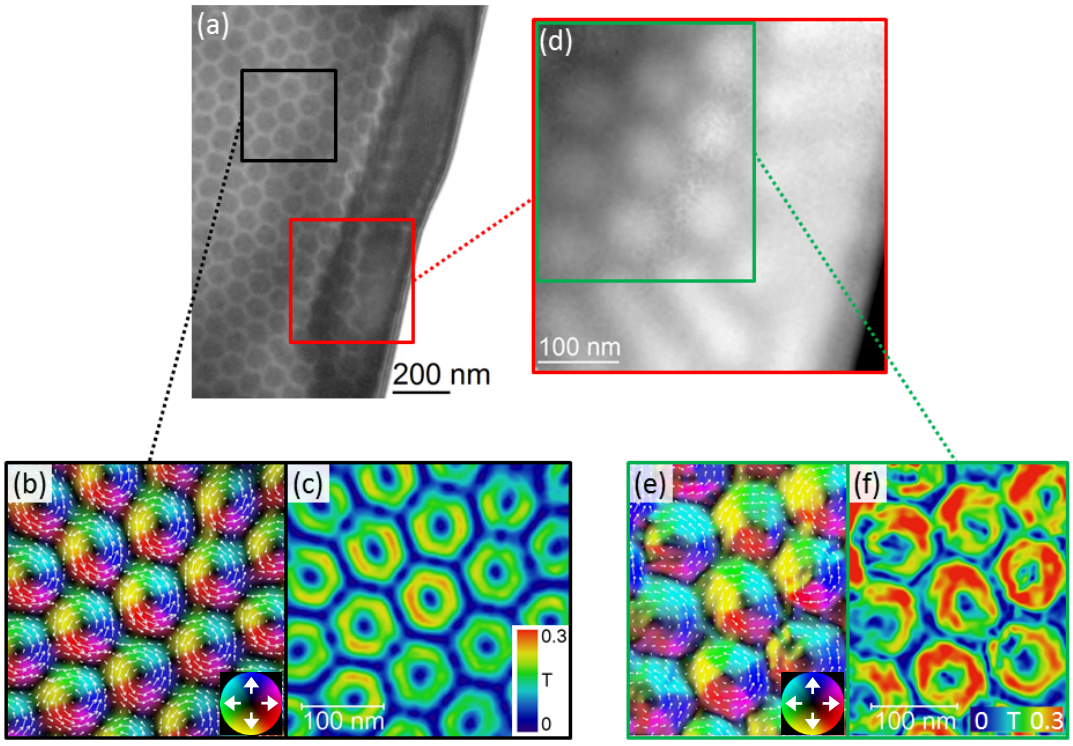

Figure 2. (a) L-TEM image in under-focus showing the skyrmions as dark contrast. (d) Phase image of the position indicated by the red square in (a). (b, e) Mapping of the direction of the in-plane magnetic flux by combining a vector plot (white arrows) and a false color image. (c, f) False colour mapping of the magnitude of the in-plane magnetic flux.

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