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Towards Three-dimensional Mapping of Skyrmionic Spin Textures in an FeGe Nanodisk Using Off-axis Electron Holography

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In nanoscale magnetic materials and devices, three-dimensional (3D) spin textures link fundamental physical properties, such as exchange stiffness and magnetocrystalline anisotropy, with more "macroscopic" quantities such as hysteresis and coercivity. Numerous efforts have been made to develop experimental techniques that can be used to measure and visualise 3D spin textures, typically by recording and analysing tilt series of phase contrast images, diffraction patterns or spectra recorded using electrons, X-rays or neutrons [1]. However, most previous studies have suffered from the use of sub-optimal imaging techniques or reconstruction algorithms [2-4]. Furthermore, they have not discussed the uniqueness of the reconstructed spin textures and have not compared them with simulated datasets that incorporate physical material parameters.

Here, we assess some of these challenges through the analysis of phase images recorded using off-axis electron holography in the transmission electron microscope from an FeGe nanodisk (~150 nm in diameter and ~120 nm in thickness) that contains a magnetic target skyrmion, which is stable in the absence of an external magnetic field [5]. It can therefore be imaged as a function of sample tile angle in magnetic-field-free conditions with the conventional microscope objective lens switched off and without the need to tilt the applied magnetic field together with the sample or to use a magnetizing specimen holder [6-7]. Figure 1 shows an experimental tilt series of electron holographic phase images recorded from the FeGe nanodisk. At each sample tilt angle, the mean inner potential contribution the phase was removed by subtracting a phase image recorded at room temperature, when the sample is paramagnetic.

This dataset was analysed using several different approaches. For example, a numerical model-based algorithm was used to reconstruct the three-dimensional magnetization distribution in the nanodisk from the full tilt series of magnetic phase images [8], making use of *a priori* information about the geometry of the sample. A regularisation parameter was also used to achieve a balance between consistency with the experimental data and smoothness of the reconstructed magnetization. These results will be compared with an alternative approach, which involves the direct comparison of the experimental results with predicted images based on micromagnetic simulations [9].

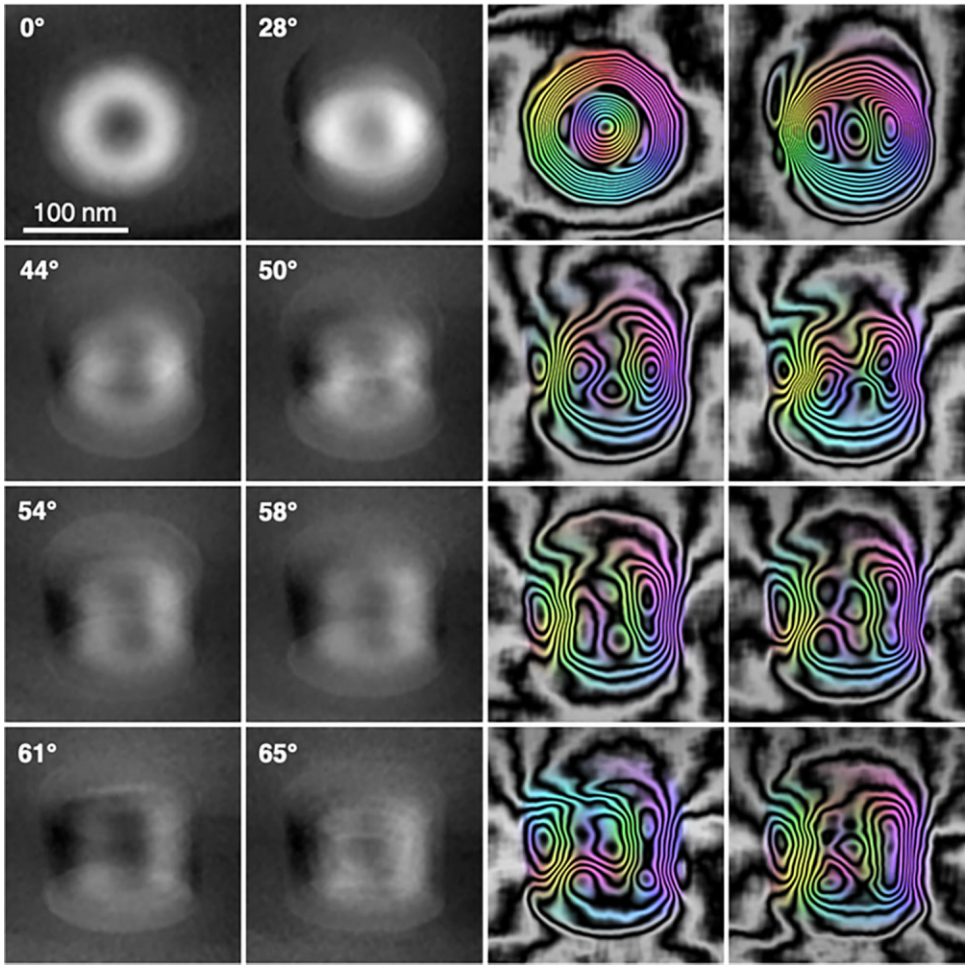

Fig. 1. (Left) Tomographic tilt series of magnetic phase images of a target magnetic skyrmion in an FeGe nanodisk recorded using off-axis electron holography at the indicated sample tilt angles about a horizontal axis. At each sample tilt angle, the mean inner potential contribution to the phase was removed by subtracting the phase reconstructed from an equivalent hologram recorded at room temperature, when the sample is paramagnetic. (Right) corresponding magnetic induction maps. Contour spacing is $2\pi/30$ radian.

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