Imaging Chiral Spin Textures with Electron Interferometry and Polarimetry

Professor Benjamin McMorran[1], Dr. Sergio Montoya[2], Prof. Eric E. Fullerton[2]

[1]University of Oregon, Eugene, USA, [2]Center for Memory and Recording Research, University of California, San Diego, USA

Background incl. aims

Magnetism and spintronics play increasingly significant roles in modern technologies such as data storage and logic devices, sensors, quantum computing, and transportation and electricity generation. The three-dimensional nanoscale spin texture within magnetic materials plays a large role in the behavior of these technologies, and also provides a rich area of fundamental study. Electron, x-ray, and scanning probe microscopies can be used to image 2-D projections of spin textures, yet each technique has strengths and limitations. Lorentz TEM, for example, projects images of the average magnetic field inside a specimen while exposing it to an external field or temperature, but it is insensitive to the field component along the beam path. We aim to combine these techniques with new ones to obtain the 3-D structure of magnetic spin textures.

Methods

Here we discuss the use of specialized electron microscopies, STEM holography and scanning electron microscopy with polarization analysis (SEMPA), to understand the 3D structure of nanomagnetic spin textures such as skyrmions. STEM holography [1,2] is an interferometric 4D-STEM technique where electrons in the beam are coherently divided into a superposition of two or more separate probes and then scanned over the specimen. If one probe passes through vacuum while the other transmits through the specimen, the resulting phase shift can be measured by recording the interference pattern formed in the far-field at the detector. That is, the bright field discs of the two probes overlap at the detector, forming interference fringes (Fig. 1). Unlike defocus- and deflection-based magnetic imaging techniques such as Lorentz TEM or DPC which are sensitive to phase gradients within the specimen, STEM holography is directly sensitive to the phase relative to the reference beam. With this, STEM holography can be used to directly measure the component of the magnetic vector potential parallel to the beam.

SEM with polarization analysis (SEMPA) [3] is a surface-sensitive technique that can image all three vector components of the surface magnetization. Special detectors can measure the average spin polarization of secondary electrons. Each detector returns information about two components of the magnetization vector; one returns in-plane (Mx and My) and the other returns one in-plane (Mx) and the out-of-plane component (Mz). Therefore, two consecutive scans provides complete, quantitative imaging of the in-plane and out-of-plane magnetic nanostructure as well as normal SE contrast.

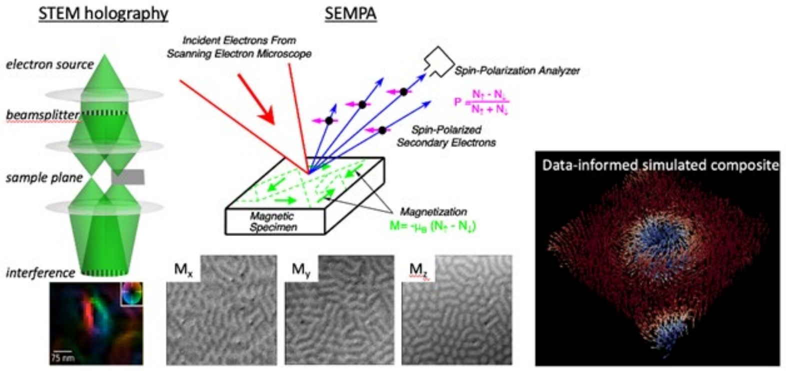
Results

STEM holography and Lorentz TEM were used to provide images of the skyrmion magnetic field projected through the thickness of the specimen, and SEMPA was provided images of the magnetization at the surface. We find that whereas crystalline specimens can host magnetic skyrmions with whorl-like magnetic fields that extend uniformly through the thickness of the material, here we observe a more intricate magnetic structure. TEM indicates that in the bulk of the material, the magnetic flux wraps around the core like a vortex, yet SEMPA indicates that near the surface the magnetic flux points radially [4], such that the 3D structure is akin to that of a vortex ring.

Conclusion

We used SEMPA, STEM holography, and Lorentz TEM on the same Fe/Gd multilayer materials to understand the 3D structure of magnetic skyrmions, observing knotted vortex ring-like structures. This illustrates that multimodal magnetic electron microscopy can be used to provide 3D information about magnetic skyrmions that cannot be observed with a single technique alone.

Graphic:



Keywords:

Skyrmions, magnetic microscopy, electron holography

Reference:

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