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# Streamlined approach to mapping the magnetic induction of skyrmionic materials

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ABSTRACT

Recently, Lorentz transmission electron microscopy (LTEM) has helped researchers advance the emerging field of magnetic skyrmions. These magnetic quasi-particles, composed of topologically non-trivial magnetization textures, have a large potential for application as information carriers in low-power memory and logic devices. LTEM is one of a very few techniques for direct, real-space imaging of magnetic features at the nanoscale. For Fresnel-contrast LTEM, the transport of intensity equation (TIE) is the tool of choice for quantitative reconstruction of the local magnetic induction through the sample thickness. Typically, this analysis requires collection of at least three images. Here, we show that for uniform, thin, magnetic films, which includes many skyrmionic samples, the magnetic induction can be quantitatively determined from a single defocused image using a simplified TIE approach.



## 1. Introduction

Magnetic skyrmions are particle-like spin textures that possess nontrivial topology [1]. The stability of skyrmions and the low current density necessary to move them [2] has inspired many suggested applications that employ skyrmions as bits in both memory and logic devices which are predicted to be highly energy-efficient [3–8]. These magnetic quasi-particles were initially identified only at low temperatures in non-centrosymmetric crystals including MnSi [9,10], FeCoSi [11] and FeGe [12], but recent observations have shown that skyrmions can be stabilized in a more diverse class of materials including those with perpendicular magnetic anisotropy (PMA) [8,13–17]. This larger swath of materials suggests the need for more rapid characterization techniques to both facilitate the efficient search for materials suitable for applications in skyrmionic devices and explore the basic physics of these magnetic textures.

Lorentz transmission electron microscopy (LTEM) is one of a very few techniques that provides direct real space images of magnetic features at the nanoscale. Recent improvements in aberration correction and instrument stability have led to a new resolution benchmark of 1 nm for scanning LTEM [18]. Additionally, new tomographic reconstruction algorithms have led to the demonstration of 3D vector field electron tomography by Phatak et al. [19]

Most of the LTEM studies of skyrmion materials have employed analysis based on the transport of intensity equation (TIE), [20,21] an equation that relates the *z*-derivative of the image intensity to the phase shift of an electron. This approach yields quantitative maps of the local in-plane magnetic induction integrated through the sample thickness, but requires multiple images (under-, in-, and over-focused) be taken at a specific point of interest in the sample [21]. In a post-processing step these images are first aligned and then used to approximate the *z*-derivative of the image intensity. In order to maximize the final field of view, the microscopist must carefully align the microscope to minimize image movement between images recorded at different focus values. These alignments can be sensitive to changes in other experimental parameters including magnetic field applied to the sample. This physical alignment, coupled with the need to properly align images, which can be difficult to automate [22], increases the total time needed to extract useful information from a magnetic sample. This often makes certain experiments prohibitively time-consuming, such as determining the in-plane magnetic induction during an *in-situ* applied field sweep (although this type of study does exists in the LTEM literature [23,24]). One approach, differential phase imaging [25], developed by Pollard et al., maps the

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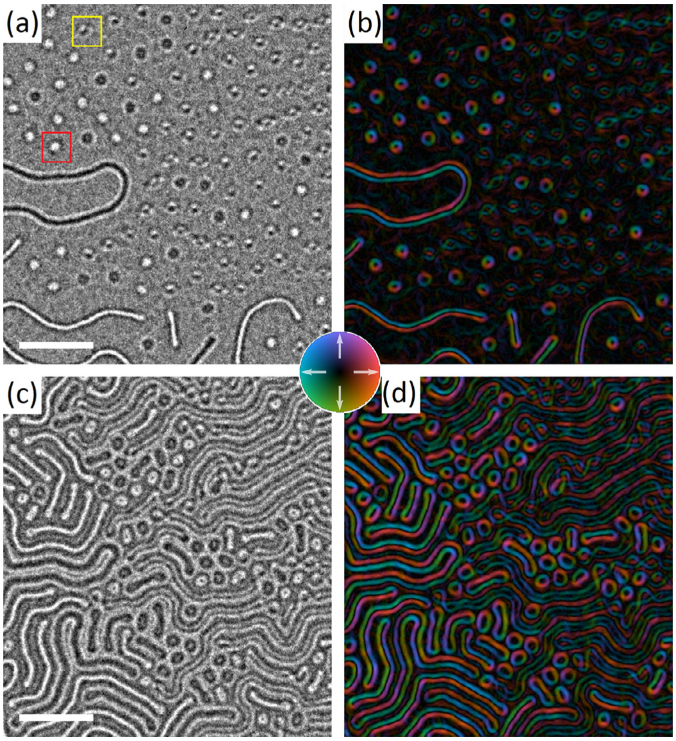


**Fig. 1.** (a) and (c) Selected under-focused Lorentz TEM images from a field sweep performed on a Fe/Gd multilayered thin film with (a, b) 180 mT and (c, d) 70 mT field applied perpendicular to the film. Scale bar is 1 μm. The red and yellow square in (a) highlight a skyrmion and topologically trivial magnetic bubble respectively. (b), (d), The magnetic induction calculated using our single image analysis on the image to the left (hue and saturation of color indicate the direction and magnitude of the magnetic induction). See supplemental material video for full field sweep. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

change in magnetic state during a dynamic measurement. This approach can be applied to non-uniform films. Alternatively, one can forego mapping the magnetic induction, and instead answer questions that depend only on the location of domain walls, which can in general be accomplished with a single defocused image. This method has been used to determine the non-adiabatic spin torque parameter [26], image domain wall nucleation [27], and record skyrmion motion [28]. Additionally, Phatak et al., showed that both the polarity and chirality of a vortex magnetization pattern of a magnetic disk can be determined from a single Fresnel contrast image of a tilted sample [29].

Similar to the work by Eastwood et al. [30] or Koch [31], in which they present iterative algorithms for single image phase reconstruction, here we show that one defocused image is sufficient to determine the magnetic portion of the electron phase shift of a uniform film using a simplified TIE approach. This allows one to map the magnetic induction without the trade-off of a slower, more involved focal series experiment, making it ideal for *in-situ* experiments on suitable samples. Fig. 1 shows an application of the single image TIE approach we are discussing here, applied to an [Fe0.36nm/Gd0.4nm] × 80 multilayered film [16,32], under quasi-dynamic conditions. The data was taken as an applied perpendicular magnetic field was swept from a field strong enough to saturate the sample to a slightly negative applied field. The data shows dipole skyrmions (black/white circles (red square in Fig. 1 (a))), disordered stripe domains, and bubbles with zero topological charge (elliptically shaped (yellow square in Fig. 1 (a))) nucleating as the field strength is reduced. These features then evolve during the field sweep into a mixture of skyrmions and labyrinth domains. The top two images (a,b) are the under-focus LTEM image and reconstructed magnetic induction with $\Delta f = -300$ μm, and applied field $H_z = 180$ mT, while (c) and (d) are the under-focus and magnetic induction at $H_z = 70$ mT.

Additional algorithms for single-image phase retrieval or exit-wave reconstruction exist but require specific sample geometries such as an isolated object [33], or specific illumination conditions and a diffraction image [34,35] which make them not suitable for this type of sample or difficult to implement in a TEM. It is worth emphasizing that the general paradigm for these single-image phase retrieval algorithms is to use *a priori* knowledge to simplify the analysis, which in practice usually means restricting oneself to a subset of samples. In this case we are choosing to restrict our analysis to uniform, thin, magnetic films, which can be treated as pure magnetic phase objects. Utilizing our new approach, the full in-plane magnetic induction can be determined for each image in a quasi-dynamic measurement with no extra experimental requirements and fewer post-processing steps. This fuller understanding is often required to interpret the LTEM images of the complex magnetization textures present in skyrmionic materials.

## 2. Theory

The phase imparted on an electron plane wave traveling along the $z$-axis after transmission through a sample with electric potential $V$ and vector potential $\mathbf{A}$ is given by the Aharonov–Bohm phase shift [36]:

$$\phi(\mathbf{r}_\perp) = C_E \int_L V(\mathbf{r}_\perp, z)\mathrm{d}z - \frac{\pi}{\Phi_0}\int_L \mathbf{A}(\mathbf{r}_\perp, z)\cdot \mathrm{d}\mathbf{r} \equiv \phi_e + \phi_m, \tag{1}$$

where $L$ is a path parallel to the propagation direction of the electron beam, $\mathbf{r}_\perp$ is the location in the sample plane, $C_E$ is the interaction constant [21], and $\Phi_0$ is the magnetic flux quantum ($\frac{h}{2e}$). If we assume a homogeneous foil of uniform thickness $d$ and constant mean inner potential ($V_0$) the electrostatic term can be easily evaluated and yields,

$$\phi_e = C_E V_0 d,$$

Additionally, the effects of inelastic scattering and high angle scattering of electrons out of the optical system can be described by an exponential drop in the initial amplitude of the electron wave function. Thus, assuming parallel illumination, the complex amplitude exiting the foil is,

$$\psi_0(\mathbf{r}_\perp) = Ae^{-\alpha d}e^{iC_E V_0 d}e^{i\phi_m(\mathbf{r}_\perp)}. \tag{2}$$

The intensity of the wave at the image plane using the microscope transfer function ($\mathcal{T}(\mathbf{q}_\perp)$) is then given by,

$$I(\mathbf{r}_\perp, \Delta f) = |\mathscr{F}^{-1}\{\mathscr{F}[\psi_0(\mathbf{r}_\perp)]\mathcal{T}(\mathbf{q}_\perp)\}|^2 \tag{3}$$

where $\mathbf{q}_\perp$ are the in-plane spatial frequencies. A relevant transfer function that models the effects of spherical aberration ($C_s$) and a damping envelope ($E_s(q_\perp)$) due to a spread in illumination angles caused by lens instabilities is:

$$\mathcal{T}(\mathbf{q}_\perp) = a(|\mathbf{q}_\perp|)e^{-i\chi(q_\perp)}e^{-E_s(q_\perp)}, \tag{4}$$

where $a(q_\perp)$ is an aperture function, the phase transfer function $\chi(q_\perp)$ is described by,

$$\chi(q_\perp) = \pi\lambda\Delta f q_\perp^2 + \frac{1}{2}\pi C_s \lambda^3 q_\perp^4, \tag{5}$$

and $E_s(q_\perp)$ given in terms of the divergence angle $\Theta_c$ is [37],

$$E_s(q_\perp) = \left(\frac{\pi\Theta_c}{\lambda}\right)^2 \left(C_s\lambda^3 q_\perp^3 + \Delta f\lambda q_\perp\right)^2. \tag{6}$$