Magnetic Field Mapping at the Nanoscale in the Transmission Electron Microscope

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Off-axis electron holography is a powerful technique for recording the phase shift of a high-energy electron wave that has passed through an electron-transparent specimen in the transmission electron microscope. The phase shift is, in turn, sensitive to the electrostatic potential and magnetic induction in the specimen, projected in the electron beam direction. Recent developments in the technique have included the use of advanced specimen holders with multiple electrical contacts to study nanoscale working devices and the use of ultra-stable transmission electron microscopes to achieve sub-2π/1000-radian phase sensitivity.

We are currently working on a model-based approach that can be used to reconstruct the three-dimensional magnetization distribution in a specimen from a series of phase images recorded as a function of specimen tilt angle using off-axis electron holography. In order to perform the reconstruction, we generate simulated magnetic induction maps by projecting best guesses for the three-dimensional magnetization distribution in the specimen onto two-dimensional Cartesian grids. Our simulations make use of known analytical solutions for the phase shifts of simple geometrical objects, with numerical discretization performed in real space to avoid artifacts generated by discretization in Fourier space, without a significant increase in computation time (Figs. 1 and 2). Our forward simulation approach is used within an iterative model-based algorithm to solve the inverse problem of reconstructing the three-dimensional magnetization distribution in the specimen from tilt series of two-dimensional phase images recorded about two independent tilt axes. In this way, we avoid many of the artifacts that result from the use of classical backprojection-based tomographic techniques, as well as allowing additional constraints and known physical laws to be incorporated.

In such applications of off-axis electron holography, which require the recording of weak phase shifts, it is important to remember that the sample must remain clean and undamaged for the time required to acquire images with a sufficient signal to noise ratio, that electron-beam-induced charging can affect the measured phase shift and that for crystalline specimens careful comparisons with dynamical simulations may be required even for a thickness of only a few atoms.

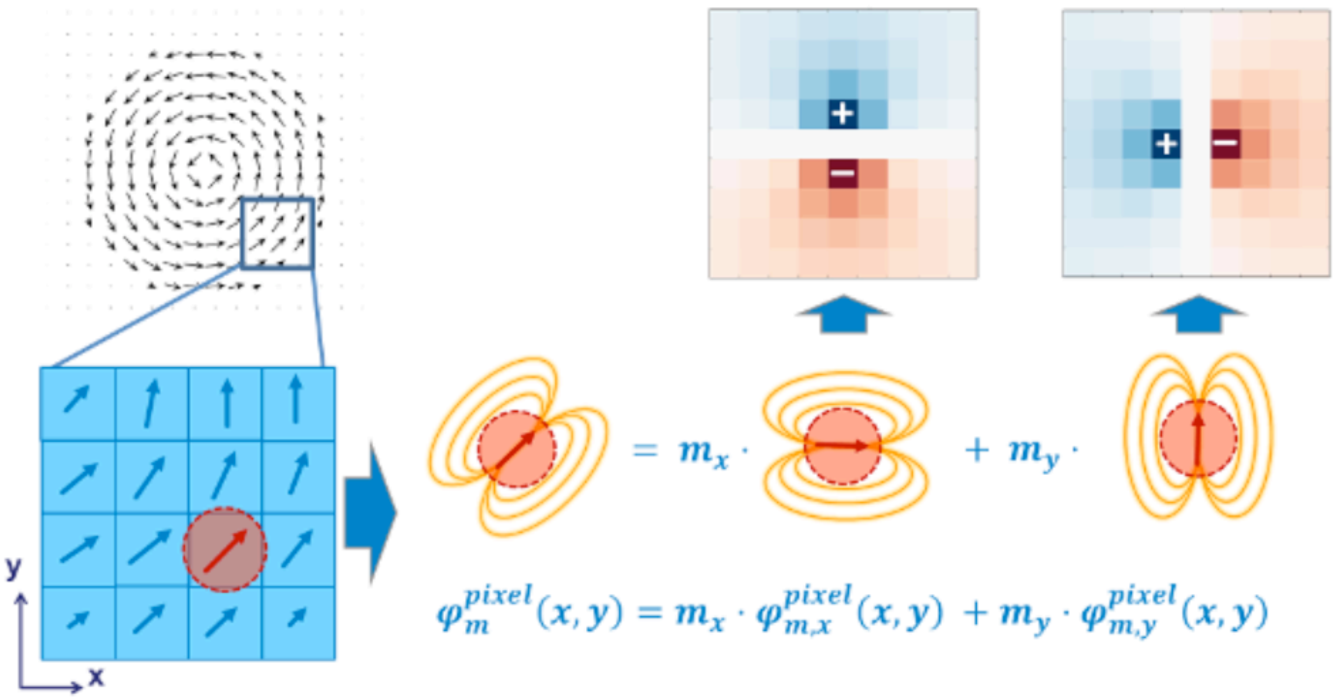

Figure 1. Illustration of the simulation process: The projected two-dimensional magnetization distribution is sub-divided into pixels which are represented by simple geometries (e.g., a disc). The contribution to the phase shift from every pixel is calculated in the form of two pre-computed components, which are oriented along the axes of the grid.

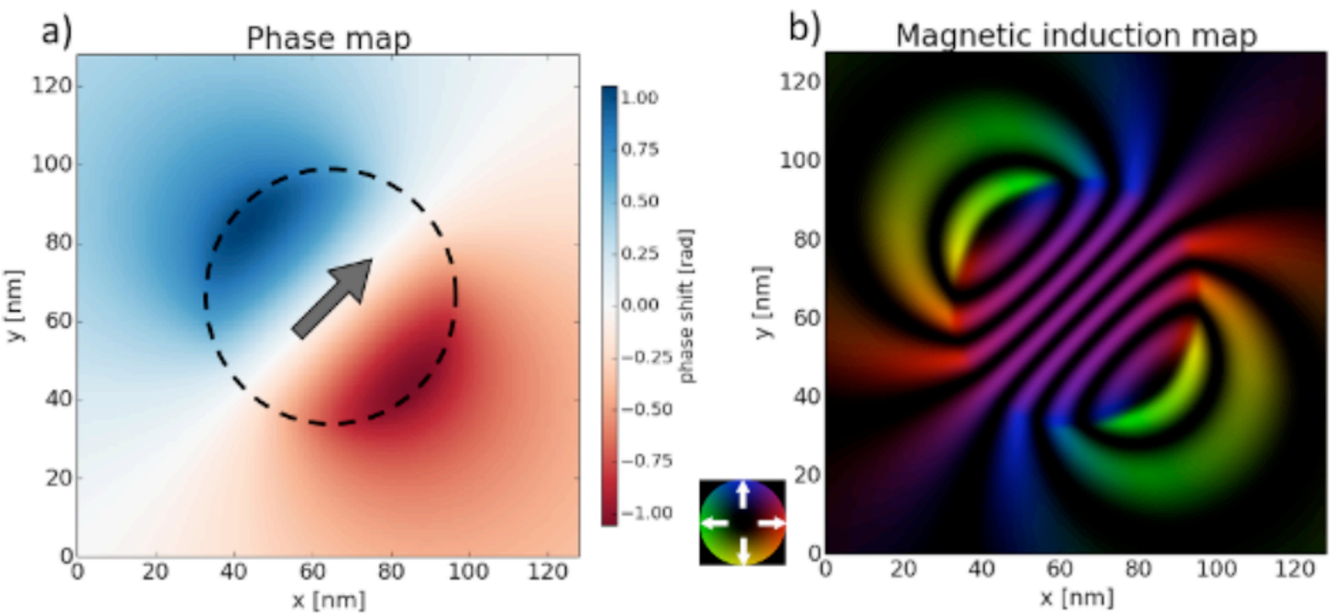

Figure 2. a) Simulated magnetic phase shift of a uniformly magnetized sphere with a radius of 64 nm in a $128\times128\times128$ nm^3 volume. The magnetization direction is indicated by the arrow. b) Corresponding magnetic induction map (20× phase amplified). The colors represent the direction and magnitude of the phase gradient, according to the color wheel shown.