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Topological Defects and Interaction of Electron Waves and Localized Magnetic Charge

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Topological defects are critical to understanding a wide range of physical phenomena because they can carry energy and momentum [1]. Moreover, they are not only stable against small external perturbations but they also cannot easily decay or be un-entangled since they cannot be continuously transformed into a "trivial" form. For example, the study of topology and defects for understanding the physics of materials has given rise to a new class of materials known as topological insulators that possess conducting surface states that are protected due to topology [2]. Monopoles can also be considered zero dimensional topological defects that arise due to breaking of spherical symmetry. In condensed matter systems, the emergence of magnetic monopole excitations arising from fractionalization of magnetic dipoles connected by Dirac strings can be shown to emulate Maxwell electromagnetism [3]. Understanding the behavior and the novel physics arising from these topological defects requires utilizing their inherent topological quantum mechanical properties to observe how they interact with their local environment.

Similarly, phase singularities or topological defects are a ubiquitous feature of wave topology and have been studied extensively in order to understand both their fundamental behavior and their potential applications. The study of phase singularities in optical, X-ray and electron wavefronts, both quantized and classical, has been an extensive area of research over the past decade [4-5]. Due to the nature of the resulting wavefront, these waves carry orbital angular momentum and are characterized as vortex beams. At present, the most common methods for generating electron vortex beams is using phase masks, or diffraction gratings. However, these methods reduce the effective intensity of the beam carrying OAM due to beam splitting.

In this work, we bring together two condensed matter systems to understand the behavior of topological defects and their interaction with electron waves. We have explored the quantum mechanical properties of magnetic monopole excitations in artificial spin ices, in which the excitations are localized to specific sites in the lattice. We show that the presence of monopole excitations with magnetic charge introduces a topological defect or phase singularity in the propagating electron plane wave, thereby resulting in localized electron vortex states as shown in Figure 1. We will discuss the influence of the sign and magnitude of the local magnetic charge of the monopole excitations on the vortex states. We will also discuss using the transport-of-intensity equation to retrieve the phase of the electron wave with localized vortex states as shown in Figure 2. We will discuss the numerical implementation using finite element methods and importance of boundary conditions for phase retrieval [6].

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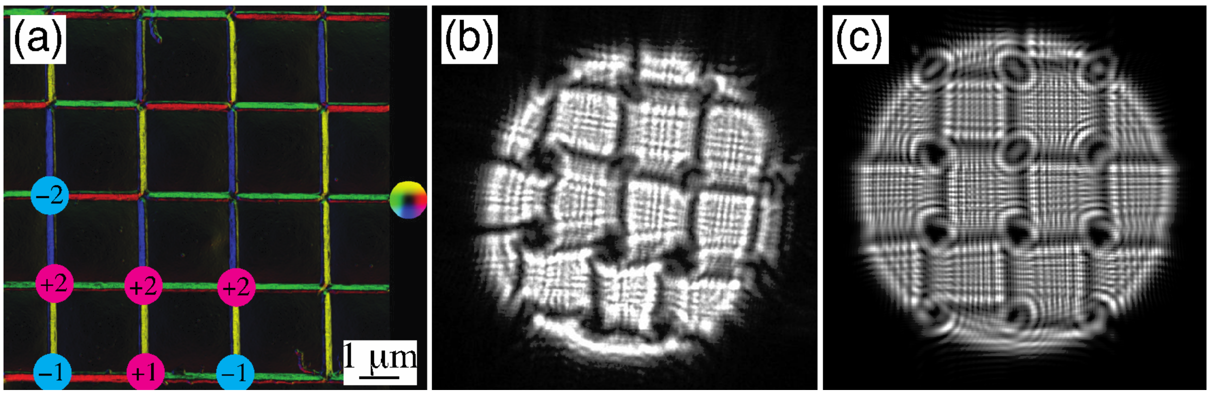

Figure 1. (a) Color map showing the magnetic induction in and around square artificial spin ice lattice indicating local magnetic charge, (b) Corresponding experimental diffraction image showing localized vortex states, and (c) Simulated diffraction image for the same magnetic configuration.

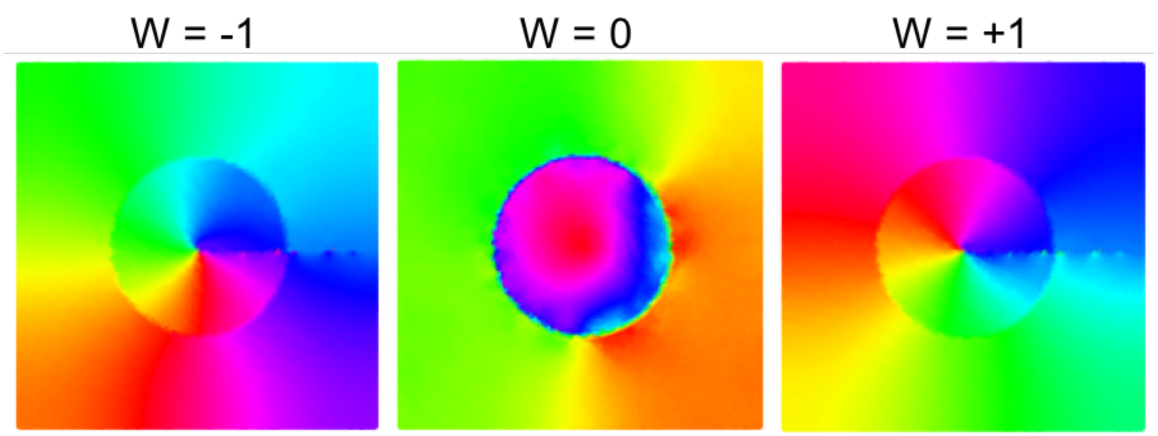

Figure 2. The reconstructed phase shift using finite element approach to solve the transport-of-intensity equation of a disc with magnetic vortex and a electron beam with vortex state characterized by a winding number given by w = -1, 0, +1.

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