INTRODUCTION

Emergent magnetic monopoles in frustrated magnetic systems

This Theme Issue reports papers presented at a Discussion Meeting intended to bring together theorists and experimentalists working on magnetic charge carriers, or monopoles, in both natural and artificially nanostructured spin ice lattices, and to explore related topics on Berry phase physics and domain wall motion and a possible solid-state/cosmology interface in these systems. The Discussion Meeting was held in the Royal Society Kavli Centre and the organizers thank all those involved in the development of this marvellous new scientific forum.

Rajantie [1] reviews magnetic monopoles in cosmology and discusses the possibility of an interface between cosmology and a solid state in spin ices. He describes the predictions of the existence of magnetic monopoles in many theories of particle physics beyond the Standard Model, and the absence of experimental or observational sign of them. He reviews the role of magnetic monopoles in quantum field theory and discusses their implications for particle physics and cosmology. He also highlights their differences from and similarities to monopoles found in frustrated magnetic systems. The recent discovery of effective magnetic monopole quasiparticles in spin ices raises the question of whether one could make use of them to take these theoretical advances further. Although the quasiparticles do behave in many ways like fundamental magnetic monopole particles, it is also clear that there are important differences. Perhaps most importantly, the Dirac strings connecting the monopoles are not completely unphysical. This does not mean that one cannot use spin ice experiments to draw conclusions for fundamental monopoles, but one has to be aware of the differences between the systems and the limitations they impose. Situations in which random thermal fluctuations play an important role would therefore appear most promising, such as studying the formation of monopoles in phase transitions.

Chern & Tchernyshyov [2] present a numerical study of magnetic ordering in spin ice on kagome, a two-dimensional lattice of corner-sharing triangles. The magnet is a six-state clock model and has six ground states, with the ordering occurring in two stages. In spin ice with short-range interactions up to second neighbours, Kosterlitz–Thouless transitions separate an intermediate critical phase from the paramagnetic and ordered phases. In dipolar spin ice, the intermediate phase has a long-range order of staggered magnetic charges.

One contribution of 8 to a Theo Murphy Meeting Issue ‘Emergent magnetic monopoles in frustrated magnetic systems’.
The high- and low-temperature phase transitions are of the Ising and three-state Potts universality classes, respectively. In the intermediate phase, the freeze-out of defects in the charge order produces a very large spin correlation length. Thus, they interpret the lower temperature transition to be of the Kosterlitz–Thouless type.

Bramwell [3] explores the spatial and temporal correlations of magnetic monopoles in spin ice using the generalized longitudinal susceptibility. Starting with the monopole model, he derives a mean field expression for the susceptibility as well as expressions for the mean square longitudinal field and induction at a point. He finds that monopole motion is strongly correlated, and that both spatial and temporal correlations are controlled by the dimensionless monopole density. This monopole density defines the ratio of the magnetization relaxation rate and the monopole hop rate. The derived equations are discussed in the context of existing theories of spin ice and the following experimental techniques: dc and ac magnetization, neutron scattering, neutron spin echo and longitudinal and transverse field muon spin rotation. He finds that, while the monopole theory unifies diverse experimental results, there are several discrepancies between theory and experiment. Using a phenomenological modification to the theory, one of these discrepancies, concerning the neutron scattering line shape, is explained.

Hügli et al. [4] study artificial spin ice systems consisting of nanolithographic arrays of isolated nanomagnets. These are model systems for the observation of frustration-induced phenomena. They have recently demonstrated that monopoles and Dirac strings can be directly observed via synchrotron-based photoemission electron microscopy where the magnetic state of individual nanoislands can be imaged in real space. These experimental results of Dirac string formation are in excellent agreement with Monte Carlo simulations of the hysteresis of an array of dipoles situated on a kagome lattice with randomized switching fields. This formation of one-dimensional avalanches in a two-dimensional system is in sharp contrast to disordered thin films where avalanches associated with magnetization reversal are two dimensional. The self-organized restriction of avalanches to one space dimension provides an example of dimensional reduction owing to frustration. They give simple explanations for the origin of this dimensional reduction and discuss the disorder dependence of these avalanches. They conclude with the explicit demonstration of how these avalanches can be controlled via locally modified anisotropies which allow the controlled start and stop of avalanches with potential applications in data storage and information processing.

Schumann & Zabel [5] also study honeycomb artificial spin ice patterns. They analyse the distribution of excitations in the form of strings and vertices carrying triple magnetic charges in honeycomb structures. They compare two types of patterns, terminated with open hexagons and closed hexagons. They find that the dipole configurations and the frequency of spin ice rule violating triply charged vertices have a slight dependence on the boundary conditions of the pattern. The observed charge and string configuration is found to be reversible.

O’Brien et al. [6] study experimentally the interaction of two domain walls at a cross-shaped vertex fabricated from two ferromagnetic nanowires. These structures are very relevant to the artificial spin ice systems. They probe both attractive interactions between oppositely charged walls and repulsive interactions between like-charged walls. They find that, in the repulsive case, a
passing domain wall may directly induce the depinning of another that is already pinned at a vertex. This effect can be qualitatively described considering only simple magnetostatic charge-based arguments. In the attractive case, however, asymmetric pinning is found, with complete suppression of depinning being possible. This observed effect is contrary to simple charge-based arguments and highlights the need for full micromagnetic characterization of the domain wall interactions in more complex systems.

Nagaosa [7] studies the electronic states in magnets as characterized by the quantum mechanical Berry phase defined in both the real and momentum spaces. This Berry phase constitutes the gauge fields, or emergent electromagnetic fields in solids, and affects the motion of the electrons. In momentum space, band crossings act as magnetic monopoles, i.e. sources or sinks of the gauge flux. In real space, the spin textures with non-coplanar spin configurations produce the gauge field by the solid angle subtended by three neighbouring spins leading to spin chirality. The representative structure supporting this gauge field is described as skyrmionic. A representative phenomenon reflecting this gauge field is the anomalous Hall effect, a contribution to the Hall effect produced by the combination of spontaneous magnetization and the relativistic spin–orbit interaction. He reviews recent studies in these systems and presents new results on the skyrmion formation.

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References