Artificial Spin Ice

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Spin ices are rare earth pyrochlores where the crystal geometry leads to frustration of the rare earth moments [1], which meet at tetrahedra in the lattice. Like water ice, they violate the third law of thermodynamics, and have been extensively studied by neutron scattering. Recently it has been realised that excitations of this system can be described as deconfined emergent monopoles and associated Dirac strings [2]. Nanotechnology allows many of the essential features of this physical system can be reproduced in arrays of patterned nanomagnets where moments meet at the vertices of a square grid [3]. This approach offers the opportunity to continuously tune the various parameters controlling the magnetic microstate, and also to inspect that microstate using advanced magnetic microscopy [4,5]. A significant difference with the naturally occurring spin-ices is that the change in symmetry gives rise to a true long-range ordered ground state, although the frustrated interactions in these athermal systems mean that its observation is extremely difficult [6].

Here I will describe our recent work on such a system, an array of 250 nm × 80 nm Permalloy islands in the square ice geometry (shown in Figure 1), including the achievement of a thermalised ground state during fabrication and the observation of the effects of fractionalised monopoles on excitations out of it (shown in Figure 2) [7], and athermal achievement of the ground state using a suitable field protocol, both observed using magnetic force microscopy. I will also describe some preliminary data from soft x-ray scattering measurements, the effects of dc field reversal, and also the application of an effective temperature formalism [8] to the frozen microstates we observe.

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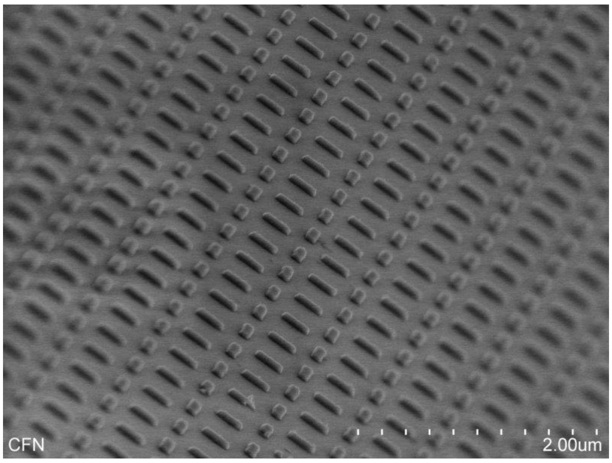

Figure 1: Scanning electron micrograph of a array of Permalloy nanomagnets, prepared using electron beam lithography, that form a frustrated square ice lattice.

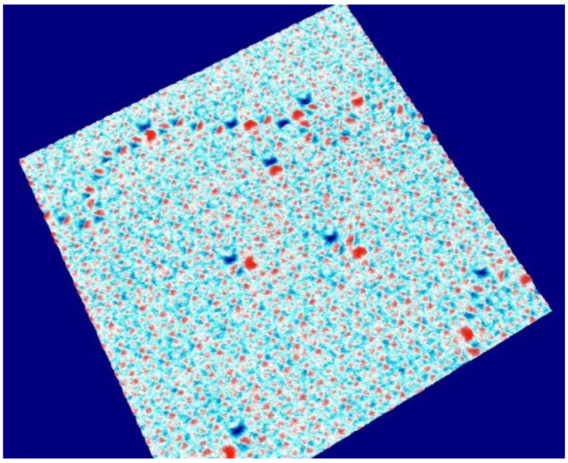

Figure 2: Rendering of a magnetic force micrograph showing the smeared magnetic charge density: monopole defects in the periodic ground state are clearly visible.