Magnetization Noise and Magnetic Monopoles in Artificial Spin Ice

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Arrays of interacting nanomagnets, known as Artificial Spin Ice (ASI, Fig. 1(a)), have enabled the design of geometrically frustrated exotic collective states that are not found in natural magnets. A key emergent description of fundamental excitations in ASIs is that of magnetic monopoles – mobile quasiparticles that carry an effective magnetic charge. These charge excitations can interact with each other and with applied magnetic fields via the magnetic analog of the electronic Coulomb interaction, representing the emergence of a range of novel phenomena, including the possibility of "magnetricity" (a magnetic analog of electricity). While the presence of monopoles in ASI has been observed in pioneering imaging measurements, dynamical studies of monopole kinetics remain less explored.

In our work we use optical magnetometry to passively "listen" to spontaneous magnetization fluctuations associated with the motion of the magnetic monopoles in thermally active ASI lattices. The noise reveals specific regions in the field-dependent phase diagrams (Fig. 1(b,c)) where the density of mobile monopoles increases well over an order of magnitude, a consequence of the field-tunable tension on the Dirac strings connecting the monopoles. Detailed noise spectra demonstrate that monopole kinetics are minimally correlated (i.e., most diffusive) in this plasma-like regime [1]. Those experimental results, combined with detailed Monte-Carlo simulations, allow us to explore a rich landscape of collective magnetic behavior in a variety of complex ASI geometries [2], including low-symmetry frustrated systems [3]. The discovery of on-demand monopole regimes with tunable kinetic properties opens the door to new probes of magnetic charge dynamics and provides a new paradigm for studies of magnetricity in artificial magnetic materials.

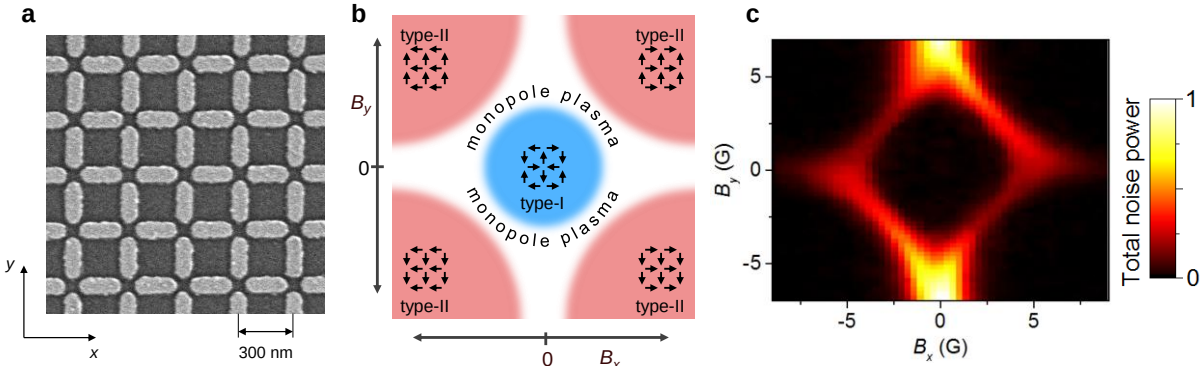

Fig. 1: (a) SEM image of an exemplary ASI lattice exhibiting square geometry. (b) Notional field-dependent phase diagram of square ASI. Between antiferromagnetic ordering at small magnetic field (blue) and fully polarized order at large field (red), a monopole-rich regime is expected. (c) Measured map of the total magnetization noise power versus applied in-plane magnetic fields B_x and B_y. The diamond-shaped feature indeed reveal a plasma-like regime, with the high density of mobile magnetic monopoles.

[1] M. Goryca, X. Zhang, J. Li, *et al.*, *Phys. Rev. X* **11**, 011042 (2021).
[2] M. Goryca, X. Zhang, J. D. Watts, *et al.*, *Phys. Rev. B* **105**, 094406 (2022).
[3] M. Goryca, X. Zhang, J. Ramberger, *et al.*, *PNAS* **120**, e2310777120 (2023).