TITLE: Magnetic noise measurements and demonstration of a field-induced magnetic monopole plasma in artificial spin ice

AUTHORS (LAST NAME, FIRST NAME): Goryca, Mateusz[1, 2]; Zhang, Xiaoyu[3]; Li, Jing[2]; Balk, Andrew[2]; Watts, Justin D.[4]; Leighton, Chris[4]; Nisoli, Cristiano[2]; Schiffer, Peter[3]; Crooker, Scott[2]

INSTITUTIONS (ALL): 1. University of Warsaw, Warsaw, Poland.
2. Los Alamos National Laboratory, Los Alamos, NM, United States.
3. Yale University, New Haven, CT, United States.
4. University of Minnesota, Minneapolis, MN, United States.

ABSTRACT BODY:

Abstract Body: Arrays of interacting nanomagnets known as Artificial Spin Ice (ASI) have allowed the design of geometrically frustrated exotic collective states not found in natural magnets. A key emergent description of fundamental excitations in ASIs and in natural pyrochlore spin ices 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". While the presence of monopoles in ASI has been observed in pioneering imaging measurements [1-3], dynamical studies of monopole kinetics, and (especially) the ability to tune continuously through monopole-rich regimes in thermal equilibrium, remain at an early stage.

In this work we use a high-bandwidth magneto-optical noise spectrometer (Fig. 1(b)) to passively "listen" to spontaneous magnetization fluctuations in archetypal, thermally active square ASI. The noise reveals specific regions in the magnetic field-dependent phase diagram (Fig. 1(a),(c)) where the density of mobile monopoles increases well over an order of magnitude compared with neighboring regimes, a consequence of the field-tunable tension on the Dirac strings connecting mobile monopoles. Moreover, detailed noise spectra demonstrate that monopole kinetics are minimally correlated (*i.e.*, most diffusive) in this plasma-like regime [4]. Experiments and Monte-Carlo simulations of more complex ASIs (including quadrupolar and vertex-frustrated Shakti and Tetris lattices) show similarly fascinating behavior, revealing surprisingly rich field-dependent phase diagrams of these systems.

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 the studies of magnetricity in artificial magnetic materials.

References: [1] S. Ladak *et al.*, Nat. Phys. 6, 359 (2010).
[2] E. Mengotti *et al.*, Nat. Phys. 7, 68 (2011).
[3] C. Phatak *et al.*, Phys. Rev. B 83, 174431 (2011).
[4] M. Goryca *et al.*, Phys. Rev. X 11, 011042 (2021).

KEYWORDS: spin ice, magnetic monopoles, frustrated magnetism, magnetization fluctuations.

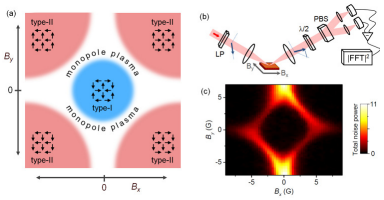

Fig. 1. (a) Notional schematic of the anticipated field-dependent phase diagram of square ASI. Between antiferromagnetic ordering at small magnetic field (blue) and fully polarized order at large field (red), a monopole-rich regime is expected. (b) Schematic of experimental setup for optical detection of magnetization fluctuations in ASI. (c) Measured map of the total magnetization noise power from square ASI 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.