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## Observing emergent magnetic correlations in artificial spin systems with neutron and x-ray scattering

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Artificial spin ices—engineered arrays of nanoscale magnetic elements arranged on various lattices—serve as highly controllable platforms for studying emergent phenomena in frustrated magnetism [1]. These systems, inspired by natural spin ices and spin liquids, host rich phase diagrams and exotic excitations, such as emergent magnetic monopoles [2,3] and Coulomb phases [4]. Currently established imaging techniques, such as lab-based magnetic force microscopy and synchrotron x-ray photoemission electron microscopy (PEEM) have provided direct real-space access to static configurations, or at best slow dynamics on the seconds to minutes timescale; but they lack the capability to probe ensemble-averaged and dynamic correlation functions. Neutron scattering, with its sensitivity to magnetic correlations over a broad range of length and time scales, is ideally suited to fill this gap—but has been historically underutilized due to the inherently low volume of these lithographically defined systems.

In recent work [5], it has been demonstrated that grazing-incidence small-angle neutron scattering (GISANS) can be successfully applied to artificial spin ices. GISANS was used to probe spin correlations in distorted triangular-lattice artificial Ising systems, on the MARIA reflectometer at JCNS. This revealed diffuse magnetic scattering signatures consistent with spin-liquid-like correlations, extracted from the weak spin-flip scattering signal. This work established GISANS as a viable probe of in-plane spin correlations in thin frustrated systems. Complementary results were obtained in Ref. [6], where soft x-ray resonant magnetic scattering (SXRMS) was employed to study critical behavior in thermally active artificial square ice. The SXRMS patterns revealed the evolution of magnetic Bragg peaks as the system was cooled through the phase transition temperature. Critical exponents consistent with the two-dimensional Ising universality class could be extracted, underscoring the power of reciprocal-space probes for characterizing phase transitions.

Despite these advances, several experimental challenges remain. The magnetic neutron scattering signal from artificial spin systems is extremely weak, requiring large sample areas ( $\sim \text{cm}^2$ ), large sample volumes obtained by stacking several samples together, long integration times, and careful polarization analysis to isolate spin-flip channels from the structural background. The upcoming European Spallation Source (ESS) is expected to significantly expand the experimental possibilities for neutron studies of artificial spin systems. In particular, the polarized reflectometer can perform GISANS measurements and is being designed with the study of arrays of nanomagnets in mind. These advances will open new avenues to explore frustration, glassiness, and topological phenomena in artificial spin lattices using neutron scattering.

- [1] Skjærvø, S. H. et al., *Nature Reviews Physics* 2, 13 (2020)
- [2] Ladak, S. et al., *Nature Physics* 6, 359–363 (2010)
- [3] Mengotti, E. et al., *Nature Physics* 7, 68–74 (2011)
- [4] Canals, B. et al., *Nature Communications* 7, 11446 (2016)
- [5] Pip, P. et al., *Nanoscale Horizons* 6, 474 (2021)
- [6] Sendetskyi, O. et al., *Physical Review B* 99, 214430 (2019)

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