Two-dimensional magnetic monopole gas in oxide heterostructures

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Magnetic monopoles in spin ice emerge as fractionalized excitations of the underlying spin configuration [1]. However, in bulk spin ice, the populations of monopoles and antimonopoles are always equal, resulting in zero net magnetic charge.

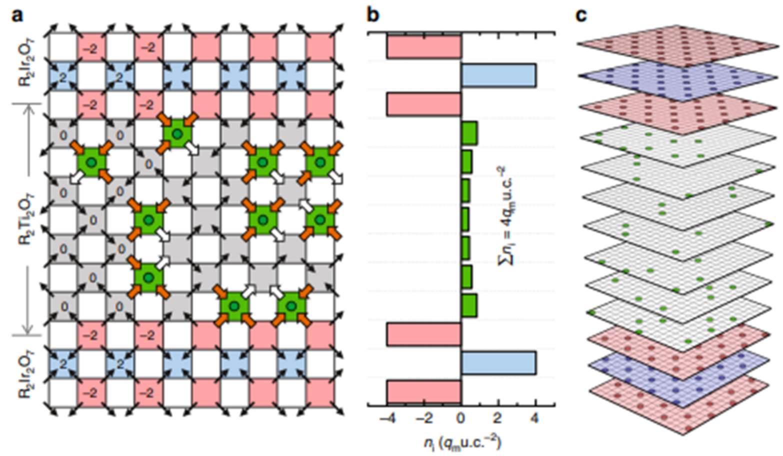

Figure 1. **a**. 2D illustration of a static snapshot of a 2DMG in a spin ice $R_2Ti_2O_7$ slab sandwiched between two AFM $R_2Ir_2O_7$ slabs with the boundary moments terminated to be pointing toward the $R_2Ti_2O_7$ slab. **b**. A depth profile of the monopole distribution taken from the average of snapshots, and **c**. an example of the snapshot of monopole from the ground state.

Here we demonstrate a two-dimensional magnetic monopole (2DMG) gas formed at a spin ice/antiferromagnet (AFM) interface, using Monte Carlo simulation [2]. Unlike the bulk case, this interfacial monopole gas exhibits a non-zero net charge arising from the boundary conditions. We show that a singly charged monopole gas can exist in an AFM/spin ice/AFM sandwich heterostructure, as shown in Fig. 1. Although monopole motion within the spin ice layer costs no energy, the monopoles preferentially accumulate near the AFM/spin ice interface due to entropy maximization [3]. Furthermore, we demonstrate that this charged monopole gas enables novel functionalities: (1) it can be manipulated by external magnetic fields, functioning analogously to a field-effect transistor [2], and (2) engineered monopole traps can store non-volatile magnetic information, with the monopole position serving as a binary state that can be read and written magnetically [4].

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[3] P. Timsina, B. Kiefer, L. Miao, Phys. Rev. B **110**, 184420 (2024).
[4] P. Timsina, A. Chappa, D. Alyones, B. Kiefer, L. Miao, arXiv: 2507.22315 (2025).