

Emergent magnetic monopole in artificial polariton spin ice

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Artificial spin ice provides a versatile setting for emergent gauge fields and magnetic monopole excitations. Here, we propose a driven-dissipative polariton realization of artificial spin ice, in which the circular polarization of each link mode plays the role of an Ising degree of freedom, while an auxiliary lossy vertex mode dynamically enforces a local ice-rule constraint. Adiabatic elimination of the vertex mode yields an effective spin ice penalty, favoring the two-in two-out manifold in the steady state. We show that local polarization flips generate monopole-antimonopole defects, and that sequential flips transport these defects across the lattice while defining a Dirac string. In an extended spin ice geometry, the vertex charges and their dynamics can be directly reconstructed from polarization-resolved real-space imaging. Our results establish polariton lattices as a controllable driven-dissipative platform in which local ice-rule constraints and monopolelike vertex defects can be generated, manipulated, and reconstructed through polarization-resolved optical measurements.

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I. INTRODUCTION

Frustrated magnetic systems provide a fertile ground for emergent phenomena in condensed matter physics [1–7]. Among them, spin ice materials [8–16] have attracted particular attention because their local constraints lead to collective behavior analogous to gauge theories [17,18]. In classical spin ice, magnetic moments reside on the bonds of a lattice and obey the so-called two-in two-out ice rule [19,20], meaning that two spins point into and two spins point out of every vertex. This constraint can be interpreted as a divergence-free condition on an emergent magnetic field,

$$\nabla \cdot \mathbf{S} = 0, \quad (1)$$

where $\mathbf{S}$ denotes the spin field. Remarkably, violations of this rule create pointlike excitations that behave as effective magnetic charges. These defects, corresponding to three-in one-out or one-in three-out configurations, have been interpreted as emergent magnetic monopoles [21,22] and were experimentally observed in rare-earth pyrochlore spin ice compounds [23–26].

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The concept of emergent monopoles has inspired extensive efforts to engineer artificial spin ice systems in a variety of platforms [27–31]. Artificial spin ice based on lithographically fabricated magnets allows direct imaging of spin configurations and defect dynamics [32–34]. Related ideas have also been explored in colloidal systems [35,36], superconducting circuits [37,38], and Rydberg atom arrays [39,40]. These platforms provide powerful ways to study frustration, defect propagation, and nonequilibrium dynamics beyond what is possible in natural materials. Nevertheless, many existing realizations remain limited by slow dynamics or restricted control over defect creation and manipulation.

Exciton-polariton condensates in semiconductor microcavities provide a versatile platform for exploring nonequilibrium many-body physics [41–43]. Because polaritons combine strong optical nonlinearity with direct optical accessibility, their amplitude, phase, and polarization can be measured in real time [44–48]. Recent advances in patterned microcavities [49] and polariton lattices [50] have enabled the realization of a wide variety of driven-dissipative many-body states, including topological phases [51,52], synthetic gauge fields [53,54], and nonlinear collective excitations [55]. Moreover, exciton-polaritons in GaAs-based microcavities are intrinsically spinor particles [56–58]. Only bright excitons with angular-momentum projections $J_z = \pm 1$ along the structure axis strongly couple to the cavity photon modes. This spinor nature is responsible for effects such as the optical spin Hall effect and the spin Meissner effect [59,60]. These capabilities make polariton systems particularly promising for implementing artificial frustrated lattices with dynamically tunable interactions.

In this work, we propose a scheme to realize a driven-dissipative polariton spin ice in a lattice of coupled polariton Bose-Einstein condensates [41,61,62]. By engineering an auxiliary lossy mode at each vertex, the system dynamically enforces a local constraint that penalizes nonzero vertex charge. Adiabatic elimination of the vertex mode leads to an effective interaction

$$H_{\text{ice}} = \frac{U}{2} \sum_v Q_v^2, \quad (2)$$

where

$$Q_v = \sum_{\ell \in v} \eta_{\ell v} \sigma_\ell \quad (3)$$

represents the vertex charge defined by the polarization imbalance on the surrounding links. The lowest-penalty configurations therefore satisfy $Q_v = 0$, corresponding to the two-in two-out ice rule. Violations of this constraint give rise to localized defects with $Q_v = \pm 2$, which behave as emergent magnetic monopoles in the effective spin ice description. Because the polariton polarization on each link can be measured directly, the local vertex charges and their dynamics can be reconstructed experimentally. This provides a direct optical probe of monopole creation, propagation, and annihilation in a driven-dissipative lattice. Our results establish polariton lattices as a controllable platform for exploring artificial spin ice and the nonequilibrium dynamics of emergent gauge charges. The combination of strong nonlinear interactions, optical tunability, and real-time detection opens new opportunities for studying defect transport [63], Dirac strings [64–67], and collective phenomena in frustrated photonic systems.

II. MODEL

We consider a square lattice in which each lattice link hosts a spinor polariton mode

$$\Psi_\ell = \begin{pmatrix} \psi_{\ell,+} \\ \psi_{\ell,-} \end{pmatrix}, \quad (4)$$

where $\psi_{\ell,+}$ and $\psi_{\ell,-}$ denote the right and left circular polarization components (pseudospin up and down), respectively (see details in Sec. I of the Supplemental Material [68], which includes Refs. [69,70]). The polarization imbalance defines an effective Ising variable on each link (same as the

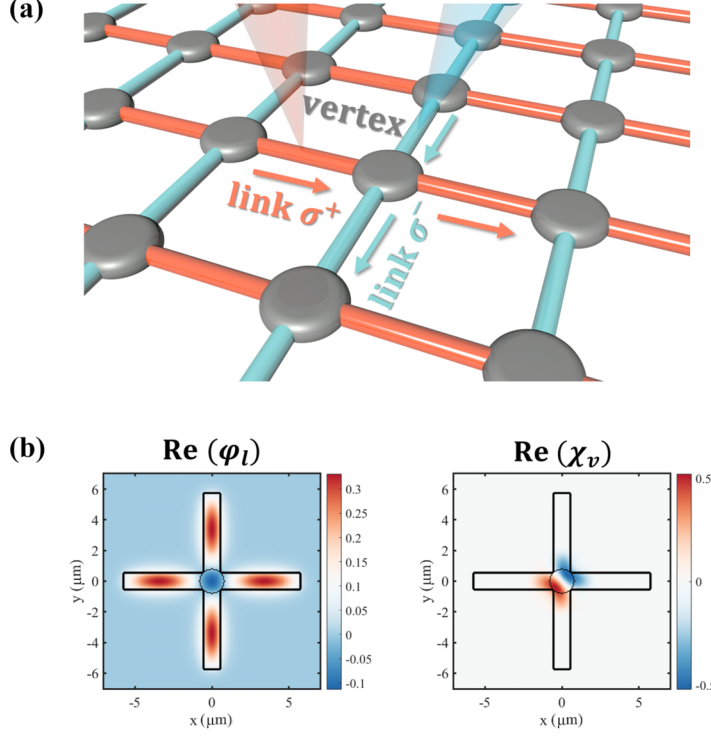


FIG. 1. (a) Schematic figure of ground state of the artificial spin ice. Red and blue links represent the polariton condensates with pseudospin up and down, generated by spin-polarized pumps, respectively. The vertex couples the two-in and two-out condensates. Arrows pointing toward and outward the vertex indicate opposite lattice gauges. (b) Real part of wavefunction of the link eigenmode φ_l and vertex eigenmode χ_v . The width and length of each link are 0.6 and 5 μm , and the radius of vertex cavity is 0.8 μm . Lattice gauge is designed as $(\eta_L, \eta_R, \eta_D, \eta_U) = (+1, -1, +1, -1)$. The spin-polarized pump at each link follows an elliptic Gaussian profile.

Stokes parameter S_z/S_0),

$$\sigma_\ell = \frac{|\psi_{\ell,+}|^2 - |\psi_{\ell,-}|^2}{|\psi_{\ell,+}|^2 + |\psi_{\ell,-}|^2}. \quad (5)$$

Figure 1(a) shows the setup, while Fig. 1(b) shows the real part of the eigenmodes of links and vertex. We use $(\eta_L, \eta_R, \eta_D, \eta_U) = (+1, -1, +1, -1)$ as the lattice gauge for the left, right, down, and up links. The in/out configuration is determined by the sign of $\sigma_\ell \eta_\ell$ on each link ℓ . If $\text{sgn}(\sigma_\ell \eta_\ell) = 1$, the link is defined as “in” (toward the vertex), while $\text{sgn}(\sigma_\ell \eta_\ell) = -1$ means “out” (outward the vertex). A discussion on experimental realization can be found in Sec. IV of the Supplemental Material [68]. Strong gain competition between the two polarization components drives the system toward states with $|\sigma_\ell| \approx 1$, effectively realizing an Ising degree of freedom on each lattice link. We shall emphasize that σ_ℓ is not a strictly conserved microscopic spin. It is a driven-dissipative order parameter defined by the polarization imbalance of a spinor polariton mode. The Ising limit $\sigma_\ell \approx \pm 1$ is approached dynamically when gain competition, nonlinear interactions, and the vertex-induced selection suppress mixed-polarization states. Consequently, monopole defects in the present system are finite-lifetime nonequilibrium defects and deviations from perfectly quantized values of Q_v reflect the continuous spinor nature of the polariton field and the finite relaxation time during

polarization switching. The dynamics of the link modes are described by

$$i\dot{\psi}_{\ell,\pm} = \left(\Delta - \frac{i}{2}\gamma + \alpha|\psi_{\ell,\pm}|^2 + \beta|\psi_{\ell,\mp}|^2 \right) \psi_{\ell,\pm} + F_{\ell,\pm} \pm g\eta_{\ell v}c_v, \quad (6)$$

where $F_{\ell,\pm}$ describes resonant pumping, γ is the polariton decay rate, $\eta_{\ell v}$ is the lattice gauge constant, and c_v denotes a vertex mode coupled to the links surrounding vertex v . The vertex mode obeys

$$i\dot{c}_v = \left(\Delta_v - \frac{i}{2}\Gamma \right) c_v + g \sum_{\ell \in v} \eta_{\ell v} (\psi_{\ell,+} - \psi_{\ell,-}), \quad (7)$$

where Γ represents dissipation at the vertex. For $\Gamma \gg \gamma$, the vertex mode can be adiabatically eliminated, leading to an effective real-valued quadratic penalty functional

$$F_{\text{eff}} = U_{\text{eff}} \sum_v |\xi_v|^2, \quad (8)$$

with

$$\xi_v = \sum_{\ell \in v} \eta_{\ell v} (\psi_{\ell,+} - \psi_{\ell,-}), \quad U_{\text{eff}} \approx \frac{2g^2}{\Gamma}. \quad (9)$$

In the Ising limit, this yields the standard spin ice form

$$Q_v = \sum_{\ell \in v} \eta_{\ell v} \sigma_{\ell}, \quad (10)$$

which plays the role of a magnetic charge at vertex v . The driven-dissipative dynamics induces an effective steady-state penalty equivalent to a spin ice charge cost

$$H_{\text{ice}} = \frac{U}{2} \sum_v Q_v^2, \quad (11)$$

where the prefactor 1/2 is introduced in the conventional way for a quadratic energy penalty, such that the conjugate restoring field is simply $\partial H / \partial Q_v = U Q_v$. The coefficient U therefore characterizes the energetic cost of violating the local ice-rule constraint. The detailed derivation and microscopic implementation of the important effective spin ice Hamiltonian of polaritons [Eq. (11)] are shown in Secs. I–III of the Supplemental Material [68]. Minimization of this energy requires

$$Q_v = 0, \quad (12)$$

corresponding to the two-in two-out spin ice rule. Numerical simulations of the driven-dissipative dynamics confirm that the steady state of a single vertex preferentially selects configurations satisfying the ice rule, while configurations with $Q_v \neq 0$ are strongly suppressed by the vertex dissipation.

This feature is contrasted with magnetic artificial spin ice, where dipolar and higher multipolar interactions can lift the degeneracy of the ice-rule manifold by an energy scale comparable to the monopole creation energy [71]. In addition, monopole dynamics in magnetic artificial spin ice is often limited by slow magnetic relaxation. The polariton platform proposed here offers a complementary limit in which the local charge penalty is dissipative. Degeneracy-lifting terms can in principle be reduced or tuned, and defect motion can be programmed optically on polariton relaxation timescales.

In the idealized model described by Eq. (11), the energy depends only on the local vertex charge Q_v . All two-in two-out configurations with $Q_v = 0$ are degenerate at the level of the local charge penalty, and a Dirac string connecting two opposite charges does not acquire an additional energy proportional to its length. This corresponds to the nearest-neighbor spin ice limit. In a realistic polariton lattice, this ideal degeneracy can be weakly lifted by link-link couplings, TE-TM splitting,

disorder, pump inhomogeneity, imperfect mode overlap at the vertex, etc. Such terms may generate configuration-dependent corrections within the ice-rule manifold and lead to a finite effective string tension. In the present work, we focus on the clean case in which these perturbations are small compared with the vertex-induced dissipative charge penalty.

III. EMERGENT MAGNETIC MONOPOLES

The spin ice constraint introduced above naturally gives rise to pointlike topological defects that behave as emergent magnetic monopoles. In the ground state of spin ice, the vertex charge Q_v vanishes at every vertex, corresponding to the two-in two-out rule $Q_v = 0$. In this regime, the polarization field satisfies a local divergence-free condition that is directly analogous to Gauss's law, $\nabla \cdot S = 0$.

A violation of the ice rule creates a nonzero vertex charge. We show this in Fig. 2, which summarizes the energetic selection mechanism of the artificial polariton spin ice vertex and provides direct dynamical evidence that the dissipative vertex constraint favors the ice-rule configuration. Figure 2(a) illustrates three representative stationary polarization configurations of a single four-coordinated vertex, corresponding to $Q_v = 0$, $Q_v = 2$, and $Q_v = 4$, together with their real-space distributions of the Ising-like polarization variable. In the present convention, $Q_v = 0$ corresponds to the two-in two-out configuration and therefore represents the spin ice ground-state manifold. In contrast, $Q_v = 2$ corresponds to a three-in one-out defect generated by flipping the polarization of the pump at the down link, while $Q_v = 4$ corresponds to the fully polarized all-in configuration. The accompanying real-space σ_l distributions clearly visualize these three distinct polarization textures.

To further quantify the stability of these configurations, in Fig. 2(b) we prepare the initial state in each of the three polarization sectors and let the system evolve freely without external pumping. The initial population of each link is normalized to unity, such that the total initial link population is $N(0) = 4$. The subsequent decay dynamics reveal a clear hierarchy: The two-in two-out configuration ($Q_v = 0$) decays slowest, the $Q_v = 2$ defect decays faster, and the all-in state ($Q_v = 4$) exhibits the most rapid decay. This behavior directly reflects the effective dissipative penalty induced by the lossy vertex mode. States with larger Q_v generate a larger oriented polarization imbalance ξ_v , which enhances the vertex-induced loss channel after adiabatic elimination of the auxiliary mode. As a consequence, configurations with larger charge are dynamically suppressed, whereas the ice-rule sector survives for the longest time. This interpretation is further supported by Fig. 2(c), which shows the time evolution of the penalty quantity $|\xi_v|^2$ for the same three initial configurations. Consistent with the effective steady-state functional

$$F_{\text{eff}} \propto |\xi_v|^2, \quad (13)$$

the all-in state carries the largest penalty, the three-in one-out state has an intermediate penalty, and the two-in two-out state minimizes this quantity. The temporal evolution confirms that the dissipative selection rule is not merely a static classification of spin configurations, but is encoded directly in the dynamics of the coupled link-vertex system. Figure 2(d) provides an even more direct signature of the role of this penalty under driven conditions. Here, the four links are driven by pumps of equal intensity, and the system is evolved from an initially empty state. If no vertex-selective penalty were present, one would expect comparable total populations for different polarization arrangements, since the external input power is identical in all cases. However, the numerical results show a strong configuration dependence: The two-in two-out state reaches a total link population close to $N = 4$, whereas the three-in one-out and all-in configurations remain at lower populations. This result demonstrates that the difference between the three sectors does not originate from unequal driving, but from their distinct effective dissipative costs. The $Q_v = 0$ configuration experiences the weakest vertex-induced loss and can therefore retain nearly the full population injected by the pumps. In contrast, configurations with nonzero charge suffer stronger dissipation and are unable to sustain the same steady-state population even under identical pumping conditions.

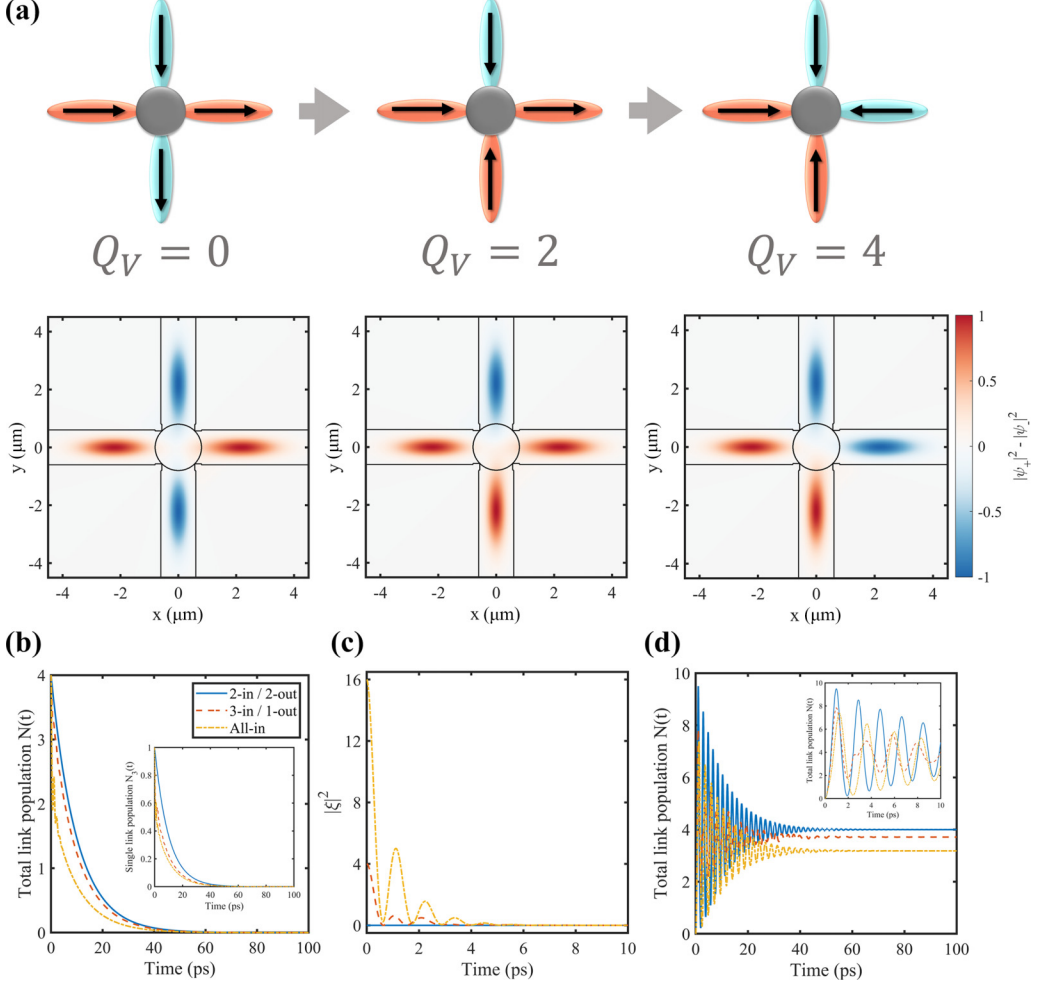


FIG. 2. (a) Ground state $Q_v = 0$ and excitation $Q_v = 2, 4$ of the artificial polariton spin ice. The black arrows indicate the in/out configurations for the links. $Q_v = 0$ has two-in two-out configuration, while for the first excitation $Q_v = 2$ it becomes three-in one-out and for $Q_v = 4$ all arrows point to the vertex. The real-space Ising variables σ_ℓ for $Q_v = 0, 2, 4$ states are shown at the stationary state. (b) The total link population $N(t)$ for the three configurations $Q_v = 0$ (blue solid curve), $Q_v = 2$ (red dashed curve), and $Q_v = 4$ (yellow dash-dotted curve), without external pumping. Inset: Single link population $N_3(t)$ for the down link. (c) Evolution of $|\xi|^2$ for the three configurations. (d) The total link population $N(t)$ under spin-polarized pumps with the same intensity. Inset: A close-up for the time window 0–10 ps. Parameters: $m = 3 \times 10^{-5} m_e$ is the effective mass of polariton (m_e is the mass of an electron), $\gamma = 0.132$ meV, $\Gamma = 2.63$ meV, and $g = \alpha = \beta = 1.58$ meV.

Figure 3 extends the single-vertex physics discussed in Fig. 2 to a minimal one-dimensional spin ice lattice composed of three adjacent vertices and demonstrates how local polarization flips can be used to controllably create, move, and read out emergent monopole defects in the driven-dissipative polariton platform. The initial spin ice configuration can be programmed by the pump polarizations on the links, and subsequent local pump-polarization flips can create, move, or annihilate monopole-antimonopole defects. In realistic structures, the effective flip rates may become anisotropic and configuration dependent because of pump inhomogeneity, polariton loss, residual polarization splitting, link orientation, and the surrounding vertex charges. Figure 3(a)

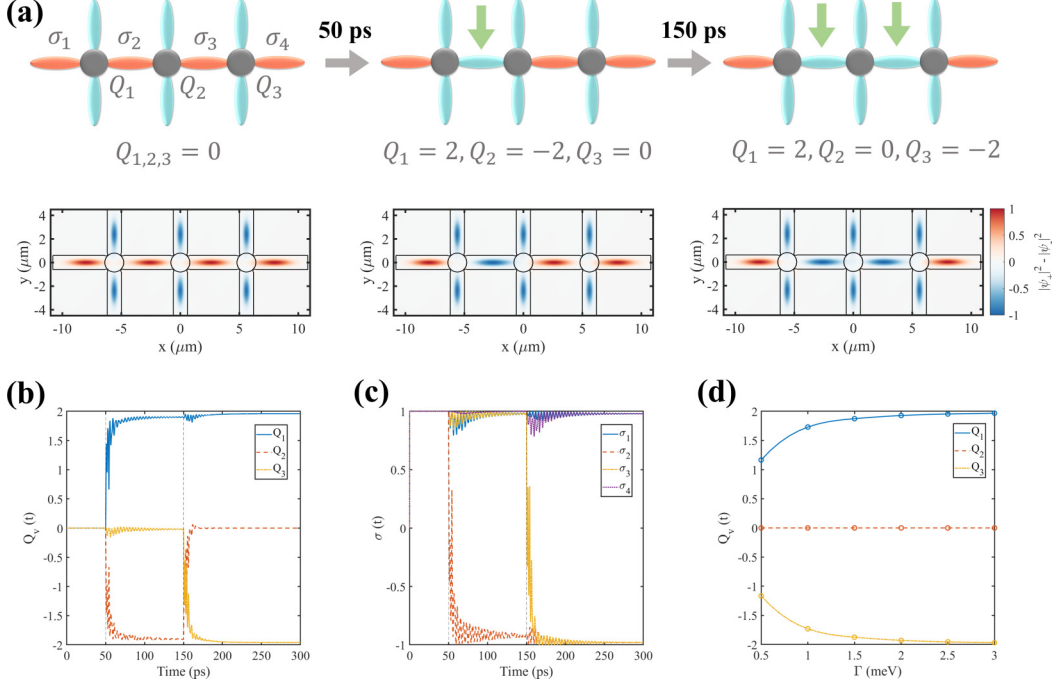


FIG. 3. (a) Schematic of the protocol. The system is initially prepared in the ice-rule state with $Q_1 = Q_2 = Q_3 = 0$. At $t = 50$ ps, the pump polarization on link 2 is flipped, creating a monopole-antimonopole pair, $(Q_1, Q_2, Q_3) = (2, -2, 0)$. At $t = 150$ ps, the pump polarization on link 3 is flipped, transferring the defect to the right vertex and yielding $(Q_1, Q_2, Q_3) = (2, 0, -2)$. Green arrows point to the links where the pump polarization is flipped. (b) Time evolution of the vertex charges Q_1 (blue solid curve), Q_2 (red dashed curve), and Q_3 (yellow dash-dotted curve). (c) Time evolution of the corresponding link Ising variables σ_1 (blue solid curve), σ_2 (red dashed curve), σ_3 (yellow dash-dotted curve), and σ_4 (purple dotted curve). (d) Final vertex charges vs vertex dissipation rate Γ . Larger Γ drives the charges closer to the ideal values $Q_v = \pm 2$, consistent with the adiabatic-elimination picture and the Ising limit. Parameters are the same as in Fig. 2 unless otherwise specified.

presents the schematic protocol and the corresponding real-space polarization textures. From the left to right, define the vertices as $Q_{1,2,3}$ and the Ising variables on the horizontal links as $\sigma_{1,2,3,4}$, respectively. The initial state is prepared in the ice-rule manifold, such that all three vertices satisfy

$$Q_1 = Q_2 = Q_3 = 0. \quad (14)$$

At $t = 50$ ps, the pump polarization on link 2 is flipped, which locally reverses the corresponding Ising variable. Since this link is shared by vertices Q_1 and Q_2 , the flip changes the charges on these two neighboring vertices with opposite signs, while leaving the third vertex unaffected. As a result, a monopole-antimonopole pair is created:

$$(Q_1, Q_2, Q_3) = (2, -2, 0). \quad (15)$$

After a further 100 ps of evolution, at $t = 150$ ps the pump polarization on link 3 is flipped. This second flip transfers the charge defect from the middle vertex to the right vertex, leading to

$$(Q_1, Q_2, Q_3) = (2, 0, -2). \quad (16)$$

In this way, the monopole is moved across the lattice in a controlled manner by sequential local spin flips. The string of links whose polarization has been reversed relative to the original ice-rule background constitutes the Dirac string connecting the two opposite charges.

The charge dynamics are shown explicitly in Fig. 3(b), which plots the time evolution of the three vertex charges Q_1 , Q_2 , and Q_3 . Before the first polarization flip, all three charges remain close to zero, confirming that the initial state belongs to the two-in two-out manifold. Immediately after the first flip at $t = 50$ ps, Q_1 and Q_2 evolve toward approximately $+2$ and -2 , respectively, while Q_3 stays near zero. This is precisely the expected signature of a monopole-antimonopole pair generated on the two vertices adjacent to the flipped link. After the second flip at $t = 150$ ps, the middle vertex charge Q_2 relaxes back toward zero, whereas Q_3 evolves toward -2 , confirming the shift of the existing monopole from the second vertex to the third one. This behavior is the hallmark of defect transport in a spin ice system and provides a dynamical realization of monopole motion driven by controlled local polarization operations. Figure 3(c) shows the corresponding time evolution of the link Ising variables $\sigma_1, \sigma_2, \sigma_3, \sigma_4$. Their behavior is fully consistent with the changes in the vertex charges displayed in Fig. 3(b). In the beginning, the four horizontal links are prepared with σ^+ polarizations, while the first abrupt change occurs on the link whose pump polarization is flipped at 50 ps. As a result, σ_2 is flipped. Then, the second change occurs on the adjacent link at 150 ps and σ_3 is flipped. The combination of Figs. 3(b) and 3(c) thus verifies, at both the vertex and link levels, that the monopole motion follows the expected spin ice charge constraint. Figure 3(d) examines the dependence of the asymptotic vertex charges on the vertex dissipation rate Γ . It can be observed that, as Γ increases, the magnitude of the generated charges approaches more closely the ideal quantized value $|Q_v| = 2$. This trend is in direct agreement with the theoretical discussion in Secs. II and III of the Supplemental Material [68]. In the regime of strong vertex dissipation, the auxiliary vertex mode becomes a fast variable that can be adiabatically eliminated, producing an effective penalty proportional to the square of the oriented polarization imbalance, $F_{\text{eff}} \propto |\xi_v|^2$. At the same time, stronger dissipative selection enhances the tendency of each link to behave as an effective binary polarization degree of freedom, thereby improving the validity of the Ising-limit description of the link pseudospins. Consequently, the charge sectors become better defined and the numerically extracted values of Q_v approach the ideal spin ice values 0 and ± 2 .

The sequential polarization-flip protocol in Fig. 3 provides a direct interpretation of the Dirac string in the present driven-dissipative spin ice lattice. Starting from the ice-rule manifold with $Q_v = 0$ on every vertex, the first flip of an internal link creates a monopole-antimonopole pair with charges $Q = \pm 2$ on the two adjacent vertices. Within the effective spin ice description, $H_{\text{ice}} = \frac{U}{2} \sum_v Q_v^2$, this operation raises the total charge cost from 0 to

$$\Delta H_{\text{ice}} = \frac{U}{2} [(+2)^2 + (-2)^2] = 4U. \quad (17)$$

Importantly, subsequent flips along a connected path do not create additional charged vertices. Instead, they restore the intermediate vertex to the ice-rule sector $Q_v = 0$ and transfer the nonzero charge to the next vertex. As a result, the number and magnitude of the end-point charges remain unchanged, and the total effective penalty stays constant while the separation between the monopole and antimonopole increases. Therefore, the chain of links whose polarizations have been reversed relative to the initial ice background naturally plays the role of a Dirac string. In this sense, the Dirac string in the present model is energetically neutral in the ideal spin ice limit. Its existence is encoded in the polarization pattern, but the effective charge penalty depends only on the monopole charges at the two end points and not on the string length. Equivalently, the ideal string tension vanishes [72,73]; therefore the defect-pair energy is determined solely by monopole creation. We note that, in a realistic driven-dissipative implementation, small corrections associated with imperfect Ising polarization may generate a weak effective string tension, but the dominant behavior observed in Fig. 3 is that monopole transport proceeds at nearly constant charge cost. The simulations presented here focus on the proof-of-principle realization of the proposed polariton spin ice. Larger patterned polariton lattices based on coupled micropillars, etched traps, or waveguide networks

have been demonstrated in related settings. Extending the present link-vertex design to larger arrays would provide a route for future studies of monopole gases, charge correlations, and collective nonequilibrium spin ice dynamics.

IV. CONCLUSION

We have proposed a driven-dissipative realization of artificial spin ice in a lattice of coupled spinor polariton modes. In our scheme, the circular polarization on each link acts as an effective Ising variable, while a lossy auxiliary vertex mode induces an effective charge penalty that dynamically stabilizes the two-in two-out manifold. This mechanism provides a photonic implementation of the spin ice constraint in terms of the degree of freedom of the polarization-resolved condensate. Our results establish polariton lattices as a promising platform for studying emergent gauge charges in a nonequilibrium setting with direct optical access, programmable driving, and real-time readout. Beyond the proof of principle demonstrated here, this approach opens the way to exploring monopole transport and more complex frustrated photonic lattices in driven-dissipative quantum fluids, where a coherent quantum spin ice extension would be an interesting and important direction.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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