Spin models, such as the Ising model, have been very successful in describing a wide range of condensed matter phenomena [1]. In addition, these models can be mapped to real-world optimization problems [2,3], for example, in transport scheduling, artificial intelligence, and financial portfolio optimization [4,5]. Consequently, there is a growing interest in building controlled spin lattices both to study computationally complex spin systems such as spin glasses [6], but also as a potential computing architecture [7,8]. Several systems have been explored, including ultracold atoms [9], degenerate optical parametric oscillators [10,11], electromechanical resonators [12], and CMOS transistors [4,5,13]. Recently, individual exciton-polariton (polariton) condensates [14–21] have been observed to spontaneously magnetize [22], and when two condensates are close together the spins can be controllably aligned (or anti-aligned) [23]. Using these building blocks, we now explore the scaling up to a large 1D system, constructing a non-equilibrium spin lattice.

Here, we study the spin properties of a closed interacting chain of exciton-polariton condensates. When the pump laser is turned on, the system spontaneously condenses into a magnetically ordered state on picosecond time scales, and remains frozen in that state for many seconds. By optically tuning the Josephson coupling between the condensates, the system can be tuned from a ferromagnetic to antiferromagnetic phase, via a disordered crossover phase. Remarkably, in a system of 4 identical spin condensates, where there is no spatial disorder, a paired spin state with alternating FM-AFM bonds is observed. Such a state cannot exist in a smaller system. Furthermore, despite the larger phase degree of freedom offered by the larger spin chain, from comparison to theory we conclude that the FM (AFM) bonds only adopt a phase shift of 0 (π), respectively. This locking of the phase and spin effectively results in a binary spin system. As the system size is increased to longer condensate chains, spatial inhomogeneity in the microcavity becomes an issue. We demonstrate a strategy to engineer ferromagnetic, antiferromagnetic, or glassy states of longer spin chains by simultaneously tailoring each individual nearest neighbor (NN) coupling between sites. Our work introduces interacting trapped polariton condensates as a controllable system for studying complex nonlinear spin models out of equilibrium.

Polaritons are mixed light-matter quasiparticles appearing due to the strong coupling of photons in a microcavity and excitons in a semiconductor quantum well [24]. Polaritons are driven-dissipative bosons that can condense into macroscopically coherent many-body states [14–17]. High optical accessibility, picosecond dynamics, large nonlinearity [25] and other unique properties [26–32], with potential application in semiconductor chip devices [18,19,33–37] make them particularly attractive.

Our system is a GaAs quantum-well microcavity (see Supplemental Material [38], 1) with an optically induced...
two-dimensional square lattice potential where a magnetized polariton condensate (emitting almost fully circularly polarized light) forms at each lattice site [Figs. 1(a)]. Below threshold PL showing the pump spots. Global NN barrier is tuned by modulating the intensity of the center spot (ur, dashed circle). Dashed circle of condensate spin chain comprised of two coupled Bose-Hubbard chains. Each condensate (indices 1–4) has two spin states (+ and −), which are coherently coupled by e. Each is also coherently coupled to its same spin NN by Josephson coupling J. (e) Magnetization of condensate chain (expt) above the spin-bifurcation threshold (Purushotham et al. 2017). We observe four distinct phases of the spin chain as we increase ur, (Fig. 2): (i) FM with two spin degenerate states, formed from all spin-up or spin-down states, (ii) paired ferromagnetic (PFM) separated by two domain walls, with four possible spin degenerate states and zero total spin, (iii) AFM with two possible spin degenerate states, and (iv) paramagnetism with nearly zero spin correlations between condensates (see also Supplemental Material [38], 2). In each case, the spin chain spontaneously collapses into any of the degenerate states due to random spin fluctuations from the reservoir at the onset of magnetization. Although the final state of the chain is indeterminate for each realization, once the spin chain forms it stays in that particular steady state if a longer pump pulse (e.g., 100 ms) is applied.

To characterize the spin correlations in each phase, we calculate the 4 × 4 correlation matrix C where the elements Cmn = ρ(Sz,m, Sz,n) are the Pearson correlation of spins of condensates m and n [as labeled in Figs. 1(c), 1(d)].
The correlation matrices for 100 realizations in the AFM and PFM regimes [Figs. 3(a), 3(b)] demonstrate robustly correlated spin chains. To build their phase diagram we plot the average diagonal \( \bar{C}_{\text{diag}} = (C_{13} + C_{24})/2 \) and side \( \bar{C}_{\text{side}} = (C_{12} + C_{23} + C_{34} + C_{41})/4 \) condensate spin correlations as a function of \( u_r \) [Fig. 3(c)]. We observe the FM phase for \( u_r < 0.9 \) followed by a sharp and narrow crossover to PFM for \( 0.9 < u_r < 0.96 \) and a second sharp crossover to a broad AFM phase for \( 0.96 < u_r < 1.1 \), succeeded by a rapid decay of correlations to near zero at higher \( u_r \). 2D Ginzburg-Landau numerical simulations (see the Supplemental Material [38, 4]) accurately reproduce the experimental phase map [Fig. 3(d)].

We can easily extend the square pumping geometry to accommodate longer spin chains forming now a total of 8 condensates [Figs. 4(a), 4(b)]. Once again, we observe FM, AFM, and a variety of spin glass states in this magnetic chain. Because the number of barriers to modulate increases, their simultaneous control is not as straightforward. At the same time, as the system size increases, tiny spatial inhomogeneities in the microcavity become increasingly important. The latter arise from the growth process and slightly change the local energy of the polaritons, modulating the coupling strength between neighboring sites. If the energy modulation is large enough, it can even change the type of the coupling at each bond. Without more sophisticated approaches, this spatial inhomogeneity of the microcavity would limit the size of condensate lattices that can be studied, and thus prospects for using the system as a simulator. This general issue is, however, generic in all condensate lattices.

We can, however, explore and correct for the spatial inhomogeneity here by tailoring the imprinted excitation pattern. Since the background energy landscape is unknown, we employ an iterative search algorithm with feedback to find the optimal pattern needed to produce a desired correlated spin chain (see the Supplemental Material [38, 3]). At the end of each search process, which only takes a few minutes, the most likely spin states can be inspected [Fig. 4(c)]. Principal component analysis (PCA) of the spin-up and spin-down intensities reveals the most probable states after optimization [Fig. 4(d)]. In the FM and AFM phases, the pure states (1st PCA components) are obtained in 60% of instances, more than twice as likely as trapping a single defect (2nd PCA component) with two domain walls. Other states have \(< 10\%\) probabilities. By contrast, in the glass state we find near-degenerate states with four domain walls that dominate. Our two-dimensional (2D) simulations show that a disorder potential of \( \sim 5 \mu \text{eV} \) is enough to break spin chain symmetry (see the
Finally, $J > 0$ is the spin-preserving Josephson coupling [44-46] between nearest-neighbor condensates.

By making an ansatz where FM (AFM) bonds have a relative phase of 0 ($\pi$) between nearest neighbors, we construct a mean-field model (see the Supplemental Material [38], 5). This maps the system to a single condensate with an energy shift $\omega J$ and a renormalized polarization splitting $\epsilon_J$. This allows us to apply the findings of Ref. [22] for a single condensate to explain the phase diagram of Figs. 3(c), 3(d) using two criteria: (i) the final state must be stable, and (ii) if multiple states are stable, then the most probable final state is the one which turns magnetic at the lowest power. To be stable requires $\epsilon_J > 0$, so that on-site spin coupling is strong enough to give magnetized condensates. In addition, the spin-bifurcation threshold favors states with low $\epsilon_J$ (see Eqs. S5 and S6, [38]). The three most favorable spin phases then yield modified splittings: $\epsilon_J^{FM} = \epsilon$, $\epsilon_J^{PFM} = \epsilon - J$, $\epsilon_J^{AFM} = \epsilon - 2J$. Hence, the phase diagram of Fig. 3(c) is explained as follows. For $J < \epsilon/2$, all three states are stable but the AFM state is favored since it has the lowest $\epsilon_J$. For $\epsilon/2 < J < \epsilon$, the AFM state becomes unstable and the glass state is selected since it is now the lowest threshold state. For $J > \epsilon$, only the FM state is stable. This explains all the key behaviors observed.

In conclusion, we demonstrate control of the spin states of closed chains of four- and eight-polariton condensates. For small chains, the nonequilibrium driven-dissipative spin lattice gives rise to a unique paired spin (paired-FM) ordered state. This observation shows that our system is not governed by the minimization of free-energy, as in, for example, the standard equilibrium Ising model. To our knowledge, this paired-FM phase has not been observed in any equilibrium or nonequilibrium binary spin system. In a 2D square lattice, in the paired-FM phase each site must have two FM and two AFM bonds. Realizations of this phase can be mapped to different tilings of a chessboard with dominoes, which is a \#P-complete problem [47]. We find that sample inhomogeneity hinders straightforward scaling to larger chains. We overcome this problem by careful feedback algorithms that compensate for sample inhomogeneities and demonstrate a proof-of-principle scaling method. In the absence of any corrections, the system behaves like spin glass, where interactions are randomly chosen by the sample inhomogeneities acting as “quenched disorder.”

The raw data for this work is available at Ref. [48].

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