

Meson Spectroscopy of Exotic Symmetries of Ising Criticality in Rydberg Atom Arrays

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The Ising model serves as a canonical platform for exploring emergent symmetry in quantum critical systems. The critical point of the 1D Ising chain is described by a conformal Ising field theory, which remains integrable in the presence of a magnetic perturbation, leading to massive particles associated with the exceptional Lie algebra E_8 . Weakly coupling two Ising chains into a ladder breaks this integrability and is predicted to bind the elementary kink excitations of the decoupled chains, giving rise to a richer spectrum of excitations described by the $\mathcal{D}_8^{(1)}$ theory. Experimental signatures of E_8 excitations have arguably been observed in scattering studies of the spin chain material CoNb_2O_6 , but direct observation of the bound-state spectrum emerging from interchain coupling has remained elusive. Here, we probe these emergent symmetries in a Rydberg atom quantum processing unit, leveraging its tunable geometry to realize both chain and ladder configurations. We identify mass spectra consistent with E_8 at the single-chain critical point and, in the weakly coupled ladder, report the first signatures of the reorganization of Ising excitations into the bound-state spectrum predicted by $\mathcal{D}_8^{(1)}$ symmetry. Our results demonstrate the power of Rydberg platforms for investigating symmetry emergence in quantum many-body systems and provide a direct window into the interplay of quasiparticle interactions, geometry, and criticality.

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I. INTRODUCTION

Emergent symmetries at quantum critical points offer profound insights into the universal behavior of many-body systems [1]. Among these, the exceptional Lie algebra E_8 has garnered significant attention because it emerges at the quantum critical point of the basic one-dimensional (1D) transverse field Ising chain (TFIC) when subjected to a longitudinal field [2–4]. Instead of a quantum critical continuum response, discrete peaks of bound states appear in the structure factor, signatures of which have been experimentally observed in the quasi-1D Ising ferromagnet CoNb_2O_6 [5]. Remarkably, the spectrum of bound states has universal energy ratios dictated by the E_8 symmetry given in Fig. 1(a).

However, subsequent studies have indicated that the excitation spectrum of CoNb_2O_6 may be more accurately described by the affine Lie algebra $\mathcal{D}_8^{(1)}$ [6–8], arising from strong interchain interactions [see Fig. 1(a)] that effectively render the system as an Ising ladder rather than a simple chain. This shift in symmetry underscores the sensitivity of emergent phenomena to the underlying geometry and interactions within the system.

Bound states emerging at perturbed quantum critical points can arise through different mechanisms, one of which is confinement, i.e. deep in the ordered phase perturbations lead to a monotonically increasing potential between domain-wall quasiparticles and the formation of discrete mesonic bound states [9,10]. These confined excitations continuously evolve into the massive particles of the corresponding integrable field theories and govern real-time post-quench dynamics [11,12]. In quantum Ising systems, perturbations such as external magnetic fields [12–14], long-range interactions [15,16], and interchain couplings [17,18] can reorganize the elementary excitations of the critical theory, producing rich excitation spectra that reflect the underlying symmetry properties [11,19].

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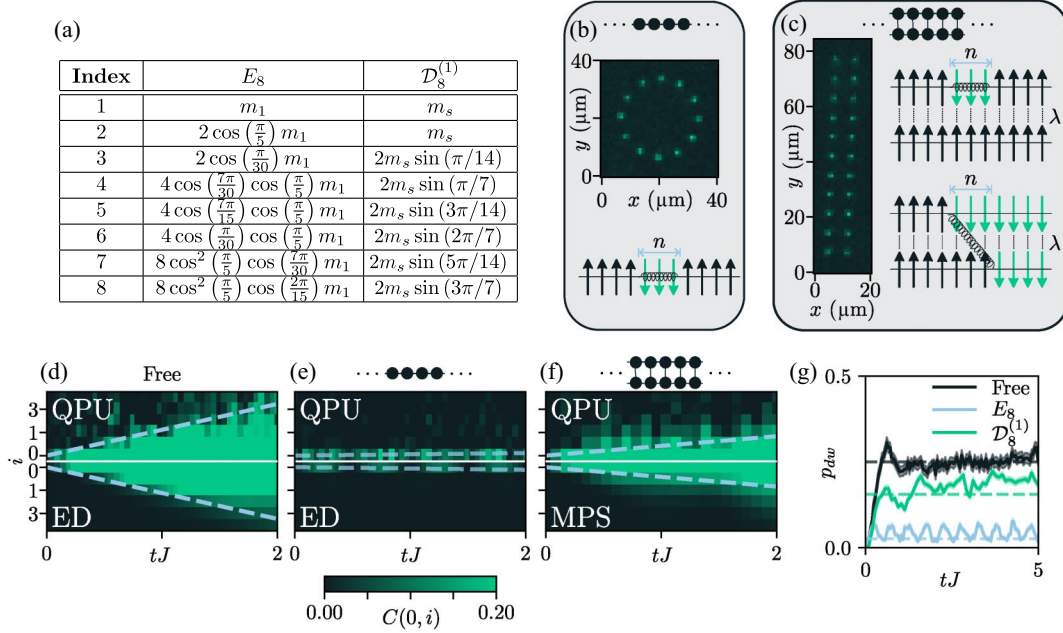


FIG. 1. (a) Meson mass spectra predicted by emergent E_8 and $\mathcal{D}_8^{(1)}$ symmetries [2,6]. (b),(c) Atomic register geometries implemented on the neutral-atom platform to realize (b) a 1D Ising chain and (c) a quasi-1D Ising ladder, together with schematics of the corresponding domain-wall meson excitations. (d–f) Analog QPU measurements (top) and exact numerical results (bottom) for correlation spreading following a quench from the $|00 \dots 00\rangle$ state. Panels (d),(e) show the Ising chain with $N = 12$, $h_x = 1$: (d) $h_z = 0$ and (e) $h_z = 4$. Panel (f) shows weakly coupled Ising ladders with $N = 11$, $h_z = 0$, and interchain coupling $\lambda = 1$. Dashed blue lines indicate theoretical light-cone velocities extracted from meson dispersion relations. (g) Analog QPU measurements of the domain-wall density $p_{dw} = (1 - \langle ZZ \rangle)/2$, where the average is taken over all nearest-neighbor pairs. Horizontal lines denote the long-time average domain-wall number obtained from classical simulations.

In this work, we utilize the versatility of Rydberg atom arrays to experimentally investigate the emergence of E_8 as well as, for the first time, $\mathcal{D}_8^{(1)}$ symmetries in 1D Ising chains and Ising ladders, respectively [20–22]. By precisely engineering the geometry and interactions within these quantum simulators, we are able to probe the critical points of these systems and observe the corresponding emergent particle spectra. While signatures of confinement have previously been observed in isolated Ising chains, both in analog [16] and digital quantum processing units (QPUs) [14,23], the emergence of the corresponding coupled-chain excitation spectra has not yet been explored in Ising ladder geometries within quantum simulators. In this work, we reveal signatures of kink binding in the coupled-chain system, together with characteristic frequencies consistent with the particle spectra predicted by the E_8 and $\mathcal{D}_8^{(1)}$ theories. This provides the first experimental evidence of kink binding induced by interchain coupling in an Ising ladder implemented on a quantum simulator, and establishes the emergence of these symmetries at the corresponding critical points. Our study demonstrates the power of QPUs in the analog mode in exploring complex many-body physics and paves the way for future investigations into higher-dimensional systems and other exotic symmetries.

II. CONFINEMENT AND BOUND PARTICLES IN ISING CHAINS

Throughout this work, we consider the transverse field Ising model, which describes interacting spin- $\frac{1}{2}$ particles

$$H_I = -J \sum_{i,j} \sigma_i^z \sigma_j^z - h_x \sum_i \sigma_i^x, \quad (1)$$

where σ_i^α are the usual Pauli matrix operators acting on the i th site, J is the spin-spin interaction, and h_x is the transverse field. In the rest of the work, we set $J = 1$.

In a one-dimensional TFIC quasiparticle excitations of this Hamiltonian correspond to free fermions. By considering $h_x < h_c$, where $h_c = 1$ is the critical point of the Hamiltonian, quasiparticles are well approximated by simple domain walls. Introducing a finite longitudinal field, $-h_z \sum_i \sigma_i^z$, two quasiparticles experience a linear confining force proportional to both their separation and h_z [9], see Fig. 1(b). Consequently, each pair of quasiparticles forms a mesonic bound state with a mass defined by $m_i = E_i - E_0$ where E_i is the i th energy level (with zero momentum). Confinement is known to slow correlation and entanglement spread [14], delay thermalization [15,24] and lead to interesting phenomena such as string breaking [25] and inelastic collisions [23,26–31].

Weakly coupling two transverse field Ising chains provides another route for binding the domain-wall excitations of the individual chains (for $h_x < h_c$) *without* the need for an additional magnetic field. The resulting transverse field Ising ladder (TFIL) Hamiltonian reads

$$H = H_I^1 + H_I^2 - \lambda \sum_i \sigma_{1,i}^z \sigma_{2,i}^z, \quad (2)$$

in which H_I^i acts on the i th chain, $i \in \{1, 2\}$, and $\lambda \ll 1$. A domain wall in one chain relative to the other creates a region of unfavorable interchain alignment, such that separating pairs of kinks costs an energy proportional to their separation and to the interchain coupling λ . Recent theoretical studies employing time-dependent density matrix renormalization group methods have revealed that the TFIL supports a rich hierarchy of bound excitations [17]. These include bound states involving excitations within individual chains, excitations spanning both chains, and higher-order composite bound states, see Fig. 1(c). This rich structure reflects the additional degrees of freedom introduced by coupling two Ising conformal field theories [6]. From the lattice perspective, this binding of the kink excitations of the decoupled chains can be viewed as a confinement mechanism. However, the corresponding continuum description differs from the TFIC with a longitudinal field: while the latter gives rise to true kink confinement and the E_8 meson spectrum, the coupled-chain system is described by the attractive sine-Gordon theory, whose $\mathcal{D}_8^{(1)}$ spectrum consists of stable deconfined solitons and their bound states (breathers) [32]. For simplicity, throughout this work we use the term confinement in the lattice sense to refer to the interchain-induced binding of Ising kinks, while explicitly distinguishing this from confinement in the field-theoretical sense where necessary.

Although the quantum field theory predictions associated with the spectra of both the E_8 and $\mathcal{D}_8^{(1)}$ symmetries are derived in the idealized limit of short-range interactions, recent theoretical work has shown that quench spectroscopy signatures associated with stable quasiparticle excitations can remain robust in the presence of long-range interactions [33]. This robustness is consistent with previous observations of the E_8 spectrum in systems containing long-range interaction tails and additional perturbations beyond the ideal nearest-neighbor model, such as those encountered in trapped-ion implementations [34] and in more accurate microscopic descriptions of CoNb_2O_6 [11]. In the following sections, we extend this perspective to the $\mathcal{D}_8^{(1)}$ spectrum, demonstrating that the corresponding quench spectroscopy signatures remain observable in the presence of the long-range interactions naturally realized in Rydberg atom arrays.

III. EXPERIMENTAL CONSIDERATIONS

An Ising-type Hamiltonian can be naturally realized with arrays of neutral atoms in optical tweezers. When excited to high-lying Rydberg states, they exhibit large dipolar interactions. By defining the atomic ground state as $|0\rangle$ and the Rydberg state as $|1\rangle$, the Hamiltonian can be expressed as

$$H_{\text{Ryd}} = \sum_{i,j>i} \frac{C_6}{|\mathbf{r}_i - \mathbf{r}_j|^6} n_i n_j + \frac{\hbar\Omega(t)}{2} \sum_i \sigma_i^x - \sum_i \frac{\hbar\delta_i(t)}{2} \sigma_i^z, \quad (3)$$

where $n_i = (1 + \sigma_i^z)/2$, $C_6 > 0$ is the strength of the van der Waals antiferromagnetic interaction, and $\Omega(t)$ and $\delta(t)$ are the Rabi frequency and detuning induced by the external laser [35]. By adjusting both the Rabi frequency and detuning, one can map this Hamiltonian to an Ising model exactly for systems with periodic boundary conditions (PBC), and up to a local longitudinal field at the edge of the system for open boundary conditions (OBC), full details can be found in Supplementary material I. Furthermore, we can also probe the dynamics of the ferromagnetic Ising model for initial states preserving time-reversal symmetry [36].

In particular, a TFIC with a longitudinal field can thus be realized in a Rydberg atom platform through arranging atoms in a 1D chain, or in our case, a circular geometry allowing for the consideration of PBC, see Fig. 1(b). Furthermore, we realize the TFIL in our Rydberg atom platform through arranging atoms in two 1D chains. Note that, given a two-dimensional (2D) trapping region, it is not possible to exactly realize an Ising ladder with PBC and thus throughout this work we consider OBC for this quasi-1D system, see Fig. 1(c).

IV. OBSERVATIONS OF CONFINEMENT

A quintessential signature of confinement dynamics is the suppression of correlation spreading following a sudden quench, that is $C(i, j) = \langle \sigma_i^z \sigma_j^z \rangle - \langle \sigma_i^z \rangle \langle \sigma_j^z \rangle$. In conventional critical systems, correlations typically spread ballistically, governed by the maximal group velocity of quasiparticles, for the TFIC this is given by $\mathcal{V} = 2 \min(1, h_x)$ [12,37,38]. However, in confined systems, the presence of an effective potential between quasiparticles significantly slows down their propagation, leading to a characteristic suppression of entanglement growth and a modification of the dominant light-cone velocity, both of which depend on the strength of the confining field. This behavior has been extensively studied in both theoretical models [12,15,17] and experimental platforms [14,16,39], making it a key observable for identifying confinement effects.

In our experiments, we measure the connected correlation function $C(i, j)$ following a quantum quench from the

$|00\cdots 0\rangle$ state, allowing us to directly track the propagation of correlations across the system. The experimentally obtained correlation data show strong quantitative agreement with classical numerical simulations across all explored regimes, up to the experimental noise, see Figs. 1(d)–1(f). Furthermore, we directly observe the effect of confinement by comparing different regimes. In the absence of confinement, correlations spread with a clear light-cone, consistent with the Lieb-Robinson bound analytically known for the TFIC with $h_z = 0$, $v = 2J \min(1, h_x)$ [12,38], which governs the maximum speed of information propagation in quantum systems, see Fig. 1(d). However, in the presence of a longitudinal field, or for weakly coupled Ising chains, the spreading of correlations is significantly slowed, see Figs. 1(e) and 1(f).

This behavior aligns with theoretical predictions for confined systems, where the effective meson velocity, calculated through the maximal group velocity of the low lying energy level (see Supplementary material II), governs the dynamics of correlation spreading [14]. However, this prediction is not exact, as seen in the TFIL results. Here, correlations are observed beyond the light cone defined by the meson velocity in both the analog QPU and classical data, indicating that the true Lieb-Robinson velocity of the system is larger. This is expected since the meson velocity characterizes the dominant correlation front associated with the lowest-lying confined excitations, while weaker contributions from higher-energy quasiparticle modes can propagate at larger velocities [40]. Thus, in this system, mesons modify the dominant spreading dynamics without changing the ultimate causal bound of the system. Beyond this, small additional fluctuations outside the light cone can also arise from experimental noise.

Beyond slowing the spread of correlations, we also observe that confinement suppresses the growth in the number of domain walls, a hallmark of constrained dynamics, see Fig. 1(g) right panels. This suppression is consistent with the picture of meson-like bound states limiting the available phase space for domain wall proliferation. These results provide direct experimental evidence of confinement-induced modifications to correlation spreading and excitation dynamics—a qualitative feature also observed in quantum simulations of confined lattice gauge theories in one [41] and two dimensions [42].

V. OBSERVATION OF SYMMETRIES

The hallmark of the emergent E_8 symmetry is the appearance of eight massive excitations whose mass ratios are universal and fixed by the integrable field theory describing the Ising chain at critical transverse field perturbed by a longitudinal field. The exact solution predicts a complete mass spectrum uniquely determined by the E_8 Lie algebra structure, with ratios that are independent of microscopic details. These universal ratios

therefore provide a direct “smoking-gun” signature of the symmetry. In practice, we extract the excitation gaps from the peak positions of the zero-momentum dynamical structure factor (DSF) $S(k=0, \omega/J)$, whose peak frequencies ω_i correspond to the meson masses m_i . The ratios ω_i/ω_1 can then be directly compared to the theoretical predictions [5,11].

A closely analog situation arises for the ladder geometry, whose scaling limit is described by the integrable field theory associated with the $\mathcal{D}_8^{(1)}$ algebra. This theory likewise predicts a universal set of massive excitations with fixed mass ratios. However, as discussed in Refs. [7,8], symmetry constraints imply that not all predicted modes contribute with visible weight to the zero-momentum dynamical structure factor. As a result, only a subset of the theoretical masses appear as peaks in $S(k=0, \omega)$. Taking these selection rules into account, the observed peak structure is consistent with the universal $\mathcal{D}_8^{(1)}$ predictions.

To study the emergent E_8 and $\mathcal{D}_8^{(1)}$ symmetries at the critical points of the Ising chain and ladder, we first optimize the atomic register, Rabi frequency, and detuning to ensure that the systems under investigation accurately reflect the theoretically predicted energy spectra. In order to verify the presence of an E_8 symmetry, we examine a 12-qubit Ising chain with PBC. By tuning the Rabi frequency and detuning such that $h_x = 1$ and $h_z = 4$ we obtain the resulting $S(k=0, \omega/J)$ from the full eigenspectrum obtained via exact diagonalization, as shown in Fig. 2(a). The ratios of the peaks seen in these results closely match the theoretical predictions for E_8 symmetry. Small deviations from the ideal mass ratios arise from finite-size effects, which introduce state-dependent shifts in the excitation energies relative to their infinite-volume values. Nevertheless, the strong longitudinal field significantly reduces these corrections [34].

Similarly, to assess whether the Rydberg ladder is well described by the $\mathcal{D}_8^{(1)}$ symmetry, we consider two 11-qubit Ising chains with OBC. The atomic separation, Rabi frequency, and detuning are adjusted such that $\lambda = 1$, $h_x = 1$, and $h_z = 0$, with a total of 22 qubits. We simulate the DSF with the help of matrix product state methods [43]. As shown in Fig. 2(b), the dominant peaks in $S(k=0, \omega/J)$ are consistent with the predicted peaks for the $\mathcal{D}_8^{(1)}$ symmetry. The reduced resolution compared with the E_8 case arises from the finite time window used in the MPS-based dynamical simulations, which introduces frequency broadening.

To observe both emergent symmetries, E_8 and $\mathcal{D}_8^{(1)}$, on the analog QPU we extract meson spectra through real-time data: we first perform a quench in each system and measure the resulting fluctuations in the local magnetization, $\langle \sigma_i^z \rangle$. By subsequently performing a Fourier transform on the post-quench dynamics of $\langle \sigma_i^z \rangle$, we obtain a clear spectral decomposition with dominant frequencies, ω_i , that

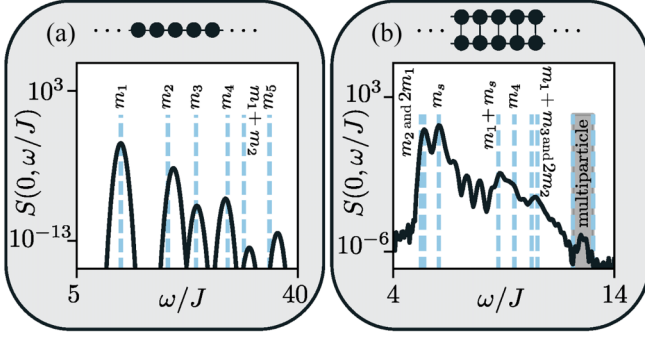


FIG. 2. Zero-momentum dynamical structure factor for (a) the TFIC with a longitudinal field with $h_x = 1$ and $h_z = 4$, and (b) the TFIL with $h_x = 1$, $h_z = 0$, and interchain coupling $\lambda = 1$. In both cases, vertical dashed lines indicate the theoretically predicted mass ratios associated with emergent symmetries: E_8 in the chain and $D_8^{(1)}$ in the ladder.

can be matched to linear combinations of the theoretically predicted meson mass ratios. Second, we refine the frequency peak positions via a multi-frequency Fourier ansatz. We choose the same number of dominant frequencies, ω_i as predicted by the underlying symmetries and fit using the ADAM optimizer [44]. We run 20 independent fits over a maximum of 20,000 epochs each to ensure convergence and robustness (see Supplementary material III). The extracted frequencies are then averaged across fits. This procedure allows for a more precise extraction of the dominant frequencies, which we then compare to the theoretical meson mass ratios.

For the TFIC with a longitudinal field, the meson spectrum spans a wide energy range, so we select a relatively large longitudinal field, $h_z = 4$, which allows us to compress multiple relevant frequencies into the timescales obtainable by the quantum hardware's operational regime, $tJ = O(10)$, significantly exceeding those achieved in previous works [16,19,45]. However, this large field causes the trivial initial state $|0\rangle^{\otimes N}$ to primarily couple to the lowest masses, m_1 and m_2 , of the E_8 spectrum, severely limiting the visibility of higher meson states. To address this, we employ a two-stage quench protocol. The system is first evolved under a ramp protocol from $h_x = 1$ and $h_z = 0$ to the desired and $h_z = 4$ over a 400 ns period of time; this generates an intermediate state with nontrivial structure with an enhanced overlap with multiple E_8 meson eigenstates. We then evolve this state with $h_x = 1$ and $h_z = 4$. The real-time data collected by the analog QPU (upper panel) show remarkable agreement to the exact results obtained with classical methods, with deviations attributable to experimental noise in the analog QPU data, see Supplementary material IV. In the lower panels of Fig. 3(a) we show the resulting spectrum, which shows an excellent agreement with the four dominant E_8 theoretical frequencies ω_i .

For the $D_8^{(1)}$ case realized in the TFIL geometry, the ground state $|0\rangle^{\otimes 2N}$ naturally overlaps with several meson modes. As such, a single quench from this initial state is sufficient to excite a broad spectrum of meson masses, eliminating the need for a preparatory evolution stage.

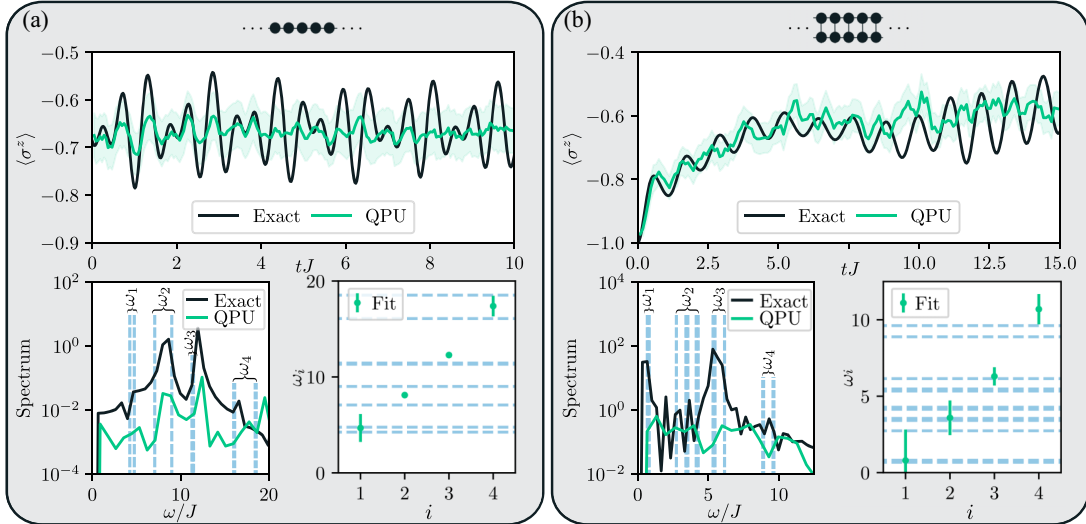


FIG. 3. Analysis of post-quench dynamics performed on from the $|00\cdots 0\rangle$ state to both the TFIC with a longitudinal field with (a) $N = 12$, $h_x = 1$ and $h_z = 4$ and (b) the TFIL with $N = 11$, $h_x = 1$, $h_z = 0$ and $\lambda = 1$. The upper panels show real-time data for σ^z for both analog QPU, in which a moving average has been used to reduce statistical fluctuations, and classical simulations. The bottom left panel shows the Fourier transformation of this data, with the dominant peaks, corresponding to the linear combinations of the meson masses predicted by E_8 and $D_8^{(1)}$ symmetry, and their differences, are indicated by vertical dashed lines. The lower right panel shows a comparison between the dominant frequencies of the Fourier analysis of classical data and the fitted frequencies of the ansatz fitted to the QPU data.

Hence we consider a single quench from $|0\rangle^{\otimes N}$ to the TFIL with $h_x = 1$ and $\lambda = 1$, see Fig. 3(b). The QPU magnetization time-signal (upper panel) is consistent with the exact result, which shows a richer behavior than in the E_8 case. In particular, it exhibits both slow and fast modulations, leading to a broad spectrum for $\omega/J < 10$, with a dominant peak around $\omega/J \approx 5$ (bottom left panel). The broad nature of the sub-dominant peaks makes it more challenging to extract the $\mathcal{D}_8^{(1)}$ frequencies in the presence of device decoherence and residual Hamiltonian miscalibrations [46]. The latter leads to larger uncertainties in the multi-Fourier fit of ω_i , shown in the lower panels of Fig. 3(b). Despite this, the frequencies identified by the fitting procedure remain consistent with the theoretical predictions of the underlying $\mathcal{D}_8^{(1)}$ symmetry. A detailed understanding of the analog QPU noise model has been established [46], enabling quantitative predictions of the device output across a wide range of physical phenomena in classically tractable regimes; further details are provided in the Supplementary material IV.

The agreement with classical simulations thus confirms that the analog QPU captures the key spectral signatures associated with both E_8 and $\mathcal{D}_8^{(1)}$ symmetries. We stress that the physical mechanisms underlying the bound-state formation in the two models are distinct. In the TFIC, the E_8 spectrum arises from genuine kink confinement induced by the longitudinal field, whereas in the Ising ladder the interchain coupling gives rise to the attractive sine-Gordon regime supporting stable solitons and their bound states.

VI. CONCLUSION AND OUTLOOK

In this paper, we observed emergent symmetries of Ising models at criticality with the help of a neutral atom QPU in analog mode. We first probed confinement for both a 1D Ising chain with PBC and an Ising ladder with OBC by taking advantage of the flexibility of the atomic register. In particular, we observed the slowdown of correlation spread due to confinement in these models. Finally, by performing spectroscopy, we showed that the emergent E_8 and $\mathcal{D}_8^{(1)}$ symmetries in these models can be extracted from the real time quench dynamics. Our analog QPU therefore allows us to probe the low-energy spectrum of a toy model capturing the essential magnetic physics of CoNb_2O_6 , and we observe qualitative agreement with neutron scattering measurements.

While all the dynamics simulated on the analog QPU in this work are classically tractable for the system sizes and dimensions considered, neutral atom QPUs in analog mode can be scaled to hundreds of atoms in 2D. In fact, some studies have already studied the physics of confinement in 2D systems with neutral-atom platforms [47], as well as superconducting qubits [42]. With improved initial state preparation, meson scattering experiments [23,26–28] will

be possible and will allow for a better characterization of the elastic or inelastic nature of the scattering.

Finally, neutral atom QPUs in analog mode can readily be used to probe Hilbert Space Fragmentation [48]. The latter has been observed in 1D neutral-atom platforms [49,50] and going to 2D promises a much richer phenomenology. It is well established that accurately simulating the dynamics of two-dimensional models near criticality is exponentially challenging in both memory and computational cost using classical methods [51,52]. In contrast, analog QPUs naturally realize these many-body systems without such bottlenecks, offering a new window into the study of quantum criticality in 2D.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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