

Deconfined Quantum Criticality on a Triangular Rydberg Array

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Fluctuations can drive continuous phase transitions between two distinct ordered phases—so-called deconfined quantum critical points (DQCPs)—which lie beyond the Landau-Ginzburg-Wilson paradigm. Despite several theoretical predictions over the past decades, experimental evidence of DQCPs remains elusive. We show that a DQCP can be explored in a system of Rydberg atoms arranged on a triangular lattice and coupled through van der Waals interactions. Specifically, we investigate the nature of the phase transition between two ordered phases at $1/3$ and $2/3$ Rydberg excitation density, which were recently probed experimentally in [Scholl *et al.*, Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms, *Nature (London)* **595**, 233 (2021)]. Using a field-theoretical analysis, we predict both the critical exponents for infinitely long cylinders of increasing circumference and the emergence of a conformal field theory near criticality showing an enlarged $U(1)$ symmetry—a signature of DQCPs—and confirm these predictions numerically. Finally, we extend these results to ladder geometries and show how the emergent $U(1)$ symmetry could be probed experimentally using finite tweezer arrays.

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Introduction—Rydberg atoms trapped in optical tweezers [1,2] have emerged in recent years as a powerful platform for quantum simulation [3], enabling the exploration of quantum many-body physics in a highly controllable setting [4–17]. In particular, the ability to arrange atoms in arbitrary geometries, combined with long-range Rydberg interactions, makes these systems especially well suited for investigating frustrated spin models [18]. These models are characterized by many competing classical configurations, a setting where quantum fluctuations can give rise to long-range entangled states [19], as exemplified by the recent experiments probing a topological spin-liquid phase [11].

The interplay between competing orders and quantum fluctuations can also lead to deconfined quantum critical points (DQCPs) [20–22], which correspond to continuous phase transitions between two distinct ordered phases and that lie beyond the conventional Landau-Ginzburg-Wilson (LGW) paradigm [23,24]. DQCPs are characterized by emergent fractionalized excitations and deconfined gauge

fields and have been predicted in a variety of models [25]. Despite significant theoretical and numerical efforts over the past decades, experimental evidence for DQCPs remains scarce [26–29]. Identifying experimental platforms capable of probing this phenomenon directly is, therefore, of great interest.

In this Letter, we show that deconfined quantum criticality can be explored in a system of Rydberg atoms arranged on a triangular lattice and coupled via van der Waals interactions. Such systems have already been realized experimentally [9], where the ordered phases at $1/3$ and at $2/3$ filling were adiabatically prepared. In the region between these two phases, however, it is unclear whether the system hosts an intermediate phase induced by the order-by-disorder mechanism [30–34] or instead features a first-order or continuous phase transition. For a point in parameter space lying in between the two ordered phases, Ref. [35] found a finite-temperature Kosterlitz-Thouless (KT) phase—characterized by an emergent $U(1)$ symmetry. Here, we connect the emergent $U(1)$ symmetry to a DQCP—a continuous phase transition—separating the two distinct ordered phases observed in Ref. [9].

To this end, we first study the model on infinitely long cylinders of increasing circumference. Combining field-theoretical analysis with large-scale density-matrix renormalization group (DMRG) simulations [36], we demonstrate the presence of a DQCP in the ground-state phase diagram of these quasi-1D systems. As in previous studies of

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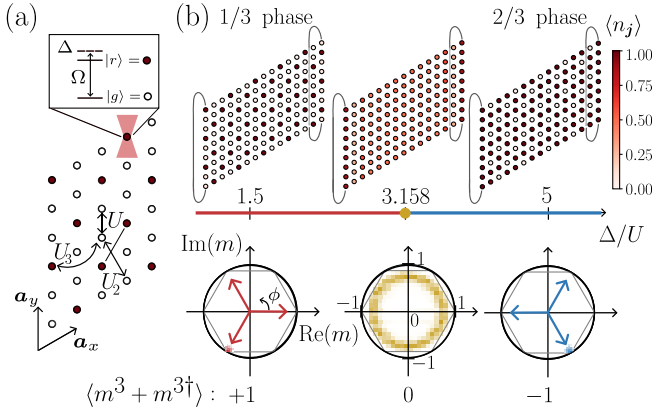


FIG. 1. (a) Neutral atoms trapped on a triangular tweezer array with lattice vectors $\mathbf{a}_x$ and $\mathbf{a}_y$, where we depict the laser-coupled electronic levels. (b) Ground-state phase diagram for a cylinder with $N_x = 15$ atoms along the x axis and $N_y = 9$ atoms along the periodic y axis. (Top) Average occupation number $\langle n_j \rangle$ in the 1/3 phase ($\Delta/U = 1.5$), at the DQCP [$(\Delta/U)_c = 3.158$], and in the 2/3 phase ($\Delta/U = 5$). (Bottom) The 1/3 (2/3) phase spontaneously breaks the $\mathbb{Z}_3$ symmetry: $m = |m|e^{i\phi}$ can point along $\phi = 0, 2\pi/3, 4\pi/3$ ($\phi = \pi/3, \pi, 5\pi/3$), corresponding to a real order parameter $\langle m^3 + m^{3\dagger} \rangle = +1(-1)$. At the transition, the $\mathbb{Z}_6$ symmetry is enlarged to $U(1)$. The histograms show the distribution of m [Eq. (2)] over 10^4 snapshots in the occupation basis when restricting the sites to the “bulk,” i.e., excluding the first and the last three rows of atoms along $\mathbf{a}_x$. Results obtained using a finite MPS with bond dimension $\chi = 100$ for $\Delta/U = 1.5$ and $\Delta/U = 5$ and $\chi = 500$ for $\Delta/U = 3.158$.

DQCPs in 1D [37–44], the critical point is described by a conformal field theory (CFT) with central charge $c = 1$ and an emergent $U(1)$ symmetry. We interpret the cylinder circumference as an inverse temperature of the corresponding 2D model and, using a dimensional reduction argument, show that our results are consistent with a DQCP over a finite temperature range—connecting our results with those found in Ref. [35]. Furthermore, we extend our analysis to experimentally accessible ladder geometries, where we also find a DQCP in the ground state. Finally, we describe how the emergent $U(1)$ symmetry could be directly probed in Rydberg experiments via measurements in the occupation basis.

Model and results—We consider neutral atoms trapped in optical tweezers arranged on a triangular lattice with basis vectors $\mathbf{a}_x = (\sqrt{3}/2, 1/2)a$ and $\mathbf{a}_y = (0, 1)a$, where a is the lattice constant [Fig. 1(a)]. The atoms are driven by a coherent laser field with Rabi frequency Ω and detuning Δ , which couples two internal electronic states—the ground state $|g\rangle$ and a highly excited Rydberg level $|r\rangle$. This system is described by the following Hamiltonian [9]:

$$H_{\text{Ryd}} = \frac{\Omega}{2} \sum_j \sigma_j^x - \Delta \sum_j n_j + \sum_{i,j} U_{ij} n_i n_j, \quad (1)$$

where $n_j = |r\rangle_j \langle r|$, $\sigma_j^x = |r\rangle_j \langle g| + |g\rangle_j \langle r|$, and $U_{ij} = C_6/|x_i - x_j|^6$ is the van der Waals interaction strength between excited atoms at positions x_i and x_j . In the following, we indicate the number of atoms along $\mathbf{a}_x(\mathbf{a}_y)$ with $N_x(N_y)$, and the interaction strength between nearest neighbors with U .

In this Letter, we study the phase transition between the ordered phases at 1/3 and 2/3 filling [9]—hereafter referred to as the 1/3 and 2/3 phases for brevity—characterized by a nonzero staggered magnetization,

$$m = \frac{1}{N/3} \sum_j n_j e^{i\mathbf{Q} \cdot \mathbf{x}_j}, \quad (2)$$

with $\mathbf{Q} = (2\sqrt{3}/3, 2/3)\pi/a$ and $\mathbf{x}_j$ being the position of the j atom. In the 1/3 phase, the complex order parameter $m = |m|e^{i\phi}$ can point along $\phi = 0, 2\pi/3$, or $4\pi/3$, while in the 2/3 phase, it can point along $\phi = \pi/3, \pi$, or $5\pi/3$ [Fig. 1(b)]. The two ordered phases thus correspond to a spontaneous symmetry breaking of two distinct $\mathbb{Z}_3$ symmetries. In our Letter, to distinguish between the two, we use the real-valued order parameter $\langle m^3 + m^{3\dagger} \rangle = |m|^3 \cos(3\phi)$, which takes positive and negative values in the 1/3 and 2/3 phases. Since these phases are related by a $\mathbb{Z}_2$ inversion symmetry ($|g\rangle \rightarrow |r\rangle$), a transition is expected at the point of degeneracy $(\Delta/U)_c$, where the system exhibits a $\mathbb{Z}_3 \times \mathbb{Z}_2 \simeq \mathbb{Z}_6$ symmetry.

In the recent study of Ref. [35], the authors focus on the critical point $(\Delta/U)_c$ at fixed $\Omega/U \approx 0.33$, analyzing the phase transition as a function of temperature. They show that thermal fluctuations render the $\mathbb{Z}_6$ anisotropy irrelevant, resulting in an extended KT phase with quasi-long-range order and emergent continuous $U(1)$ symmetry, separated from the high-temperature disordered phase by a KT transition.

In our Letter, we focus instead on the zero-temperature quantum phase transition between the 1/3 and 2/3 phases as a function of Δ/U at fixed $\Omega/U = 0.33$. Unlike Ref. [35], which considers an isotropic 2D system, we study quasi-1D geometries: infinite cylinders (Fig. 2) and infinite ladders [Figs. 3(a) and 3(b)]. Specifically, the cylinders have periodic boundary conditions along $\mathbf{a}_y$, with circumference N_y —corresponding to l_y unit cells (of size 3×3) along $\mathbf{a}_y$. These geometries allow us to characterize the transition theoretically via an effective field theory, and we expect them to be effectively equivalent to isotropic systems at finite temperatures—connecting with the results in Ref. [35]—set by the inverse of the cylinder circumference, i.e., $k_B T \sim 1/l_y$ [45]. Infinite ladders, by contrast, have open boundary conditions along $\mathbf{a}_y$ and are infinite along $\mathbf{a}_x$, making them relevant to experimental Rydberg arrays. In our Letter, we show that in both cases the two ordered phases are separated by a DQCP with emergent $U(1)$ symmetry [see Fig. 1(b)]. Finally, we also

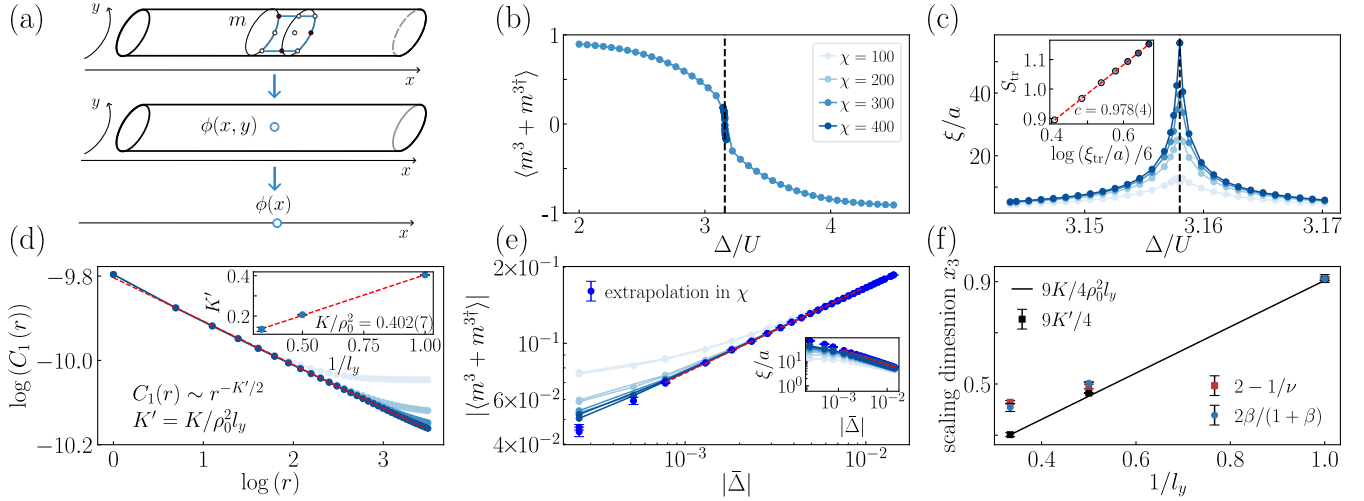


FIG. 2. (a) Mapping from a 2D cylindrical lattice to a 1D field theory model. The phase of the magnetization m [Eq. (2)] in each unit cell (of size 3×3) is mapped to a 2D field $\phi(x, y)$ and by dimensional reduction to a 1D field $\phi(x)$. (b)–(e) Analysis of an infinitely long cylinder ($N_x = \infty$) with circumference $N_y = 6$ ($l_y = 2$ unit cells) for increasing bond dimension χ [see legend in panel (b)]. (b) The order parameter changes continuously from positive to negative as a function of Δ/U , passing through zero at the critical point at $(\Delta/U)_c \approx 3.158$ (dashed vertical line). (c) The correlation length ξ/a as a function of Δ/U shows a peak at $(\Delta/U)_c$, which diverges with χ . Inset: extraction of the central charge c from the scaling $S_{tr} = c \log(\xi_{tr}/a)/6$ at $(\Delta/U)_c$. (d) Power-law decay of the two-point correlation function $\langle m(r)m(0) \rangle \approx C_1(r) = \rho_0^2 \langle e^{i\phi(r)} e^{-i\phi(0)} \rangle$ at $(\Delta/U)_c$, where m is evaluated on unit cells of size $3 \times 3l_y$. Inset: Luttinger parameter K' as a function of the cylinder circumferences l_y , extracted from the power-law decay of $C_1(r)$ [Table I]. (e) Linear fit of the order parameter and the correlation length (inset) in log-log scale as a function of $\bar{\Delta} = \Delta/U - (\Delta/U)_c$, used to extract the critical exponents β and ν , respectively. (f) Dependence of the critical exponents on l_y . We compare the scaling dimension x_3 estimated from (red) $2 - 1/\nu$ and (blue) $2\beta/(1 + \beta)$ to the theoretical prediction (black dots) $x_3 = 9K'/4$ and (black line) $x_3 = 9K/(4\rho_0^2 l_y)$, with coefficient K/ρ_0^2 obtained from the fit in the inset of (d).

propose a finite-size array that can be experimentally realized, in which the emergent U(1) symmetry can be observed [Figs. 3(c)–3(f)].

In the following, we truncate the interactions to the third-nearest neighbors [Fig. 1(a)]. This approximation is justified for a small Rydberg radius—the characteristic distance where the interaction strength is dominant and satisfies $U_{ij} = \Omega$. For $\Omega/U = 0.33$, this yields $R_b = 1.203a$, supporting the neglect of interactions beyond a distance of $2a$. In Supplemental Material (SM) [45], we show how our results, in particular the presence of a DQCP with an emergent U(1) symmetry, remain unaffected by the presence of longer-range interaction terms and persist for a broad range of parameters up to $\Omega/U \approx 0.4$.

Effective field theory—We aim to characterize the transition on infinitely long cylinders with increasing circumference and to develop a field theory that both captures the nature of the transition and connects the results across different cylinders. We begin by presenting the results for the infinitely long cylinder with circumference $N_y = 6$ ($l_y = 2$). Further details on other geometries can be found in SM [45]. Here, the order parameter changes continuously from positive (1/3 phase) to negative (2/3 phase), vanishing at the transition point $(\Delta/U)_c \approx 3.158$ [Fig. 2(b)]. This smooth behavior signals a continuum quantum phase transition beyond the conventional LGW paradigm. This is

further corroborated by the growth of the correlation length ξ as the bond dimension χ increases in our DMRG simulations [Fig. 2(c)]. In particular, at the critical point, the scaling of the von Neumann entanglement entropy at half cylinder with the correlation length, $S_{tr} = c \log(\xi_{tr}/a)/6$, is consistent with the emergence of a CFT with central charge $c = 1$ [53–55]. Further evidence for critical behavior is provided by the power-law decay of the two-point correlation function of the magnetization between unit cells separated by distance r , $\langle m(r)m(0) \rangle$ [Fig. 2(d)].

To capture these numerical findings, we formulate an effective field theory by mapping the discrete microscopic model onto a continuous field description [Fig. 2(a)]. In the limit of quasi-1D systems ($l_y \ll l_x$), we associate a complex field $\psi(x) = \rho(x)e^{i\phi(x)}$ to the staggered magnetization m evaluated in a unit-cell of size $3 \times N_y = 3 \times 3l_y$. Neglecting amplitude fluctuations and setting $\psi(x) = \rho_0 e^{i\phi(x)}$, we can effectively describe the system via the 1D theory [45]:

$$S = \int dt dx \left[\frac{(\partial_\mu \phi)^2}{2\pi K'} + g'_3 \cos(3\phi) + g'_6 \cos(6\phi) \right], \quad (3)$$

where the parameters K' , g'_3 , and g'_6 depend on l_y and ρ_0 . In particular, $K' = K/(\rho_0^2 l_y)$, where K is a constant. This

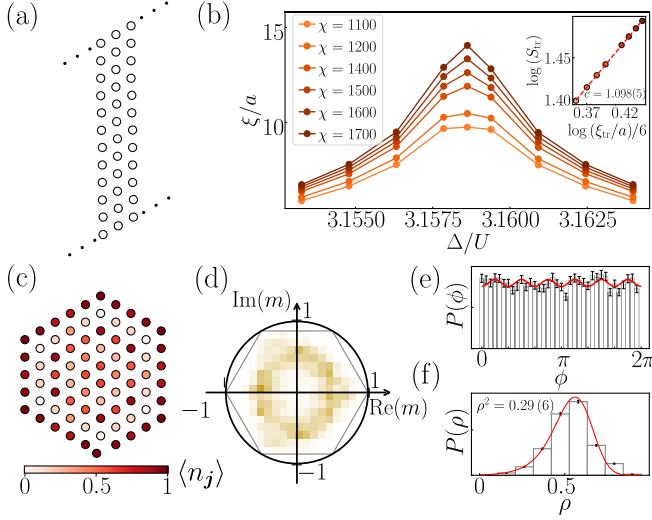


FIG. 3. (a) Unit cell of the infinite ladder ($N_x = \infty$) with $N_y = 3l_y = 12$ atoms along $\mathbf{a}_y$. (b) Correlation length ξ/a as a function of Δ/U for the infinite ladder shown in (a) and increasing bond dimension χ . Inset: extraction of the central charge c from the scaling of $S_{\text{tr}} = c \log(\xi_{\text{tr}}/a)/6$ at $(\Delta/U)_c \approx 3.1586$, corresponding to the maximum of the correlation length. (c)–(f) Experimentally feasible system. (c) Lattice and occupation number $\langle n_j \rangle$ for $\chi = 200$ and $\Delta/U = 2.94$. (d) Distribution of the staggered magnetization m [Eq. (2)] of the state considered in (c) over 10^4 snapshots in the occupation basis when restricting the sites to the “bulk” (i.e., excluding the last two “rings” of atoms). (e) Angular distribution of m , consistent with a weak potential $V(\phi)$ due to finite size effects [45]. (f) Radial distribution of m , consistent with a potential $V(\rho)$.

theory captures the phase diagram of the Rydberg model in Eq. (1) as a function of Δ/U (which we assume controls g'_3) and temperature T (proportional to $1/l_y$ and thus to K') [45]. In particular, it allows for a quantitative characterization of the continuous transition between the two $\mathbb{Z}_3$ -ordered phases, including predictions for the critical exponents, as detailed below.

Here, we focus on the regime $2/9 < K' < 8/9$, where the $\mathbb{Z}_6$ anisotropy is irrelevant under the renormalization-group flow, while the $\mathbb{Z}_3$ anisotropy is relevant. A detailed discussion of the remaining parameter regimes is provided in SM [45]. In this range, the system spontaneously breaks the $\mathbb{Z}_3$ symmetry: $\cos(3\phi) = 1$ for $g'_3 < 0$ and $\cos(3\phi) = -1$ for $g'_3 > 0$, corresponding to the $1/3$ and $2/3$ phases, respectively. At the critical point, i.e., $g'_3 = 0$, the model reduces to a Luttinger liquid with an emergent $U(1)$ symmetry. Therefore, as g'_3 changes sign, the system undergoes an unconventional continuous phase transition between two distinct ordered phases, which are separated by a DQCP with $U(1)$ symmetry. We further predict the dependence of the critical exponents on the cylinder width l_y , as summarized in Table I [45].

We numerically verify the validity of this 1D model in Figs. 2(d)–2(f). First, we compute the two-point correlation

TABLE I. Correlation function and critical exponents for the field theory in Eq. (3) in the regime $2/9 < K' < 8/9$. The two-point correlation function $C_n(r) = \rho_0^2 \langle e^{in\phi(r)} e^{-in\phi(0)} \rangle$ at criticality decays algebraically with distance r . The correlation length ξ and the order parameter $\rho_0^3 \langle \cos(3\phi) \rangle$ scale as power laws in the perturbation parameter g'_3 . The associated critical exponents depend on the cylinder circumference l_y through the effective Luttinger parameter $K' = K/(\rho_0^2 l_y)$.

Observable	Scaling	Exponent
$C_n(r)$	r^{-2x_n}	$x_n = (n^2 K'/4) = (n^2 K/4\rho_0^2 l_y)$
ξ	$ g'_3 ^{-\nu}$	$\nu = (1/2 - x_3)$
$\rho_0^3 \langle \cos(3\phi) \rangle $	$ g'_3 ^\beta$	$\beta = (x_3/2 - x_3)$

function of the staggered magnetization evaluated for unit cells of size $3 \times 3l_y$ (with $l_y = 1, 2$, and 3 in units of $3a$) as a function of distance $\langle m(r)m(0) \rangle$, which corresponds to the field-theoretical correlation $C_1(r) = \rho_0^2 \langle e^{i\phi(r)} e^{-i\phi(0)} \rangle$. From its algebraic decay, we extract the effective Luttinger parameter K' and find that, as predicted, it displays a linear dependence on $1/l_y$ [Fig. 2(d)].

The critical exponents ν and β are related via the scaling dimension $x_3 = 9K'/4$ of the perturbation $\cos(3\phi)$, according to the relation $x_3 = 2 - 1/\nu = 2\beta/(1 + \beta)$. We test this relation by extracting the critical exponents ν and β from fits of the correlation length and order parameter, respectively, as a function of the distance from the critical point, $\bar{\Delta} = \Delta/U - (\Delta/U)_c$, which plays the role of the perturbation strength g'_3 , i.e., $\bar{\Delta} \propto g'_3$ [Fig. 2(e)]. The exponents obtained for different circumferences l_y agree with the theoretical predictions based on the Luttinger parameter K' for small l_y , with deviations that increase as l_y becomes larger [Fig. 2(f)]. In SM [45], we further corroborate the effective model on finite cylinders by performing a finite-size scaling analysis with respect to the cylinder length and analyzing the statistics of the staggered magnetization near criticality.

Finally, we note that the $\mathbb{Z}_6$ anisotropy becomes relevant in the 1D model when $K' < 2/9$, a condition met for large l_y . In particular, for $l_y = 3$, we numerically find $K' \sim 0.1$ [Fig. 2(d)]. The deviations observed for this cylinder may therefore originate either from the growth of the $\mathbb{Z}_6$ anisotropy or from the breakdown of the effective 1D description. The relevance of the $\mathbb{Z}_6$ anisotropy could be inferred from the saturation of the correlation length ξ as the bond dimension χ increases at criticality. Indeed, when relevant, the anisotropy leads—depending on the sign of g'_6 —either to a first-order transition or to an intermediate phase with spontaneously broken $\mathbb{Z}_6$ symmetry separating the $1/3$ and the $2/3$ phases [45]. However, our numerical results for $l_y = 3$ show that ξ continues to grow with increasing χ , albeit at a slower rate, suggesting that the system remains critical and that the 1D approximation may be breaking down. To definitely rule out the relevance of

the $\mathbb{Z}_6$ anisotropy, simulations at larger bond dimensions ($\chi > 2000$) would be necessary. The fate of the transition in the infinite-circumference limit is of particular interest for quantum simulations on experimental platforms, as we discuss now.

Finite ladders and experimental proposal—Apart from probing the fate of an isotropic 2D system at zero temperature, we now argue that current Rydberg experiments could be readily used to observe a DQCP in an accessible quasi-1D geometry. This also represents an interesting direction as various experimental proposals have been advanced for observing DQCPs in 1D systems [42–44], yet none have been realized so far. Previously, we have shown that the transition on quasi-1D cylinders is unconventional. However, realizing cylindrical geometries in experiments is challenging. To address this, we now consider “infinite ladders”—systems that have open boundary conditions along $\mathbf{a}_y$ and are infinite along $\mathbf{a}_x$ [Fig. 3(a)]. Open boundaries play an important role, giving rise to an intermediate phase for small ladder widths ($l_y < 4$). However, for $l_y = 4$ we recover the continuous transition between the 1/3 and 2/3 phases. In particular, at criticality, both the entanglement entropy and the correlation length increase with bond dimension, consistent with a CFT with $c = 1$ [Fig. 3(b)].

As an experimentally feasible setup to observe this DQCP, we consider the finite array shown in Fig. 3(c), where the six classical configurations at 1/3 and 2/3 filling are exactly degenerate in energy in the limit $\Omega = 0$. We note that similar geometries were realized in Ref. [9]. Remarkably, even for such a small system, we find that an approximately U(1)-symmetric angular distribution emerges between the 1/3 and 2/3 phases [Fig. 3(d)], signaling the presence of deconfined quantum criticality. In particular, the angular probability distribution $P(\phi)$ and the radial probability distribution $P(\rho)$ agree with the field-theory predictions [Figs. 3(e) and 3(f)] and remain unaffected by the presence of longer-range interaction terms [45]. The distribution $P(\phi)$ is consistent with a weak potential of the form $V(\phi) = g_6 \cos(6\phi)$, such that $P(\phi) \propto e^{-V(\phi)}$, while the distribution $P(\rho)$ is compatible with a simple local effective potential $V_{\text{eff}}(\rho) = \mu\rho^2 - \lambda\rho^4$, with $\rho_0^2 = \mu/2\lambda$, such that $P(\rho) \propto e^{-V_{\text{eff}}(\rho)}$ [45].

Scaling up this geometry in one direction would allow for an experimental probe of the critical properties of the quasi-1D ladder depicted in Fig. 3(a). In particular, the DQCP can be identified through the progressive suppression of oscillations in the angular distribution $P(\phi)$ as the system size is increased in one direction. Whether or not the emergent U(1) symmetry is spontaneously broken in the 2D thermodynamic limit remains an open and interesting question that cannot be definitely answered from our numerics. This question could also be addressed experimentally by scaling up this geometry in both directions.

Conclusion and outlook—In this Letter, we have shown that quantum fluctuations render the phase transition between the 1/3 and 2/3 ordered phases of a triangular Rydberg array continuous in quasi-1D geometries, for both periodic and open boundary conditions. The transition point corresponds to a DQCP, which cannot be captured by the standard LGW formalism. Furthermore, our results demonstrated that the emergence of a continuous U(1) symmetry at criticality is captured by a 1D conformal field theory and can be experimentally probed in accessible finite geometries. This opens several exciting directions for future research.

An important open question is whether the DQCP persists down to zero temperature in isotropic 2D systems. This question could also be addressed experimentally—as Rydberg atom arrays enable access to system sizes and geometries beyond current numerical capabilities—by adiabatically preparing the U(1)-symmetric ground state at the transition in systems of increasing size. However, adiabatically preparing a critical state requires a preparation time that grows (polynomially) with system size, imposing limits due to finite coherence times and experimental imperfections (see discussion in SM [45]). Possible future directions include performing numerical analyses of adiabatic state preparation to identify optimal laser sweep protocols to prepare the U(1)-symmetric angular distribution demonstrated in Figs. 3(b)–3(e), as well as dynamically probing the DQCP via the quantum Kibble-Zurek mechanism [7,56,57].

Tensor network calculations were performed using the TeNPy Library [51].

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Data availability—The data that support the findings of this article are openly available [58].

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