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Two-dimensional lattice gauge theories with superconducting quantum circuits

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ABSTRACT

A quantum simulator of $U(1)$ lattice gauge theories can be implemented with superconducting circuits. This allows the investigation of confined and deconfined phases in quantum link models, and of valence bond solid and spin liquid phases in quantum dimer models. Fractionalized confining strings and the real-time dynamics of quantum phase transitions are accessible as well. Here we show how state-of-the-art superconducting technology allows us to simulate these phenomena in relatively small circuit lattices. By exploiting the strong non-linear couplings between quantized excitations emerging when superconducting qubits are coupled, we show how to engineer gauge invariant Hamiltonians, including ring-exchange and four-body Ising interactions. We demonstrate that, despite decoherence and disorder effects, minimal circuit instances allow us to investigate properties such as the dynamics of electric flux strings, signaling confinement in gauge invariant field theories. The experimental realization of these models in larger superconducting circuits could address open questions beyond current computational capability.

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1. Introduction

Since the pioneering experiments showing quantized coherent excitations in electrical circuits [1,2], superconducting circuits including Josephson junctions are playing a fundamental role to demonstrate quantum effects at a mesoscopic level and, remarkably, in quantum information processing. The enormous recent progress in this field comprises, for example, the realization of quantum teleportation [3] and complex two- and three-qubit algorithms, including number factoring and quantum error correction [4–8]. From the viewpoint of analog quantum simulation, the large coherence times and non-linearities achieved with superconducting qubits [9–12] have opened frontiers towards the simulation of Hubbard models with photonic excitations and, as a by-product, the emulation of classical static fields in circuit lattices [13–15].

A new perspective in quantum simulation is to mimic fundamental interactions, such as those arising in field theories [16], and in particular, lattice gauge theories [17]. In elementary particle physics, dynamical quantum gauge fields mediate fundamental interactions [18–20]. In condensed matter systems such as spin liquids, dimer models, and presumably in high-temperature superconductors, gauge fields emerge as relevant low-energy degrees of freedom [21–25]. Solving these theories is, however, fundamentally challenging. Classical simulations typically rely on Monte Carlo methods which may suffer from severe sign problems, which imply that real-time dynamics and certain exotic phases are so far out of reach. The quantum simulation of *dynamical* gauge fields is thus attracting a great deal of interest, giving rise to a variety of recent proposals, mainly based on cold atoms in optical lattices [26–37].

Here we show how different gauge invariant models can be simulated with superconducting circuits. This platform offers on-chip highly-tunable couplings, and local control over basic modules that can be interconnected, enabling – in principle – scalability. Specifically, in this work we focus our attention on two-dimensional $U(1)$ gauge theories, and show how ring-exchange interactions, present in dimer models, and plaquette terms arising in lattice gauge theories, can be engineered with quantum circuits under realistic dissipative conditions. We will illustrate this by constructing gauge invariant models in a superconducting-circuit square lattice. As we will show, even in the presence of excitation loss and disorder, distinctive features of the gauge theory, such as confinement and string dynamics, can be observed in relatively small circuit lattices. The implementation of these gauge invariant interactions generalizes previous proposals based on cold atoms [26–38], as well as pioneering studies in this area with Josephson-junction arrays [39], trapped ions [40], and superconducting circuits [41].

To quantum simulate dynamical gauge fields, we use the framework of quantum link models [42–44]. In this formulation, the gauge field is represented by quantum degrees of freedom residing on the links that connect neighboring lattice sites. In contrast to Wilson's lattice gauge theory [18,19], quantum link models have a finite-dimensional Hilbert space per link, and provide an alternative non-perturbative regularization of gauge theories. This, on the one hand, leads to new theories beyond the Wilson framework, and, on the other hand, allows us to address the standard gauge field theories relevant in particle physics. For example, quantum chromodynamics (QCD) emerges from an $SU(3)$ invariant quantum link model by dimensional reduction [45]. In this framework, continuously varying gluon fields are not put in by hand, but emerge dynamically as collective excitations of discrete quantum link degrees of freedom, and chiral quarks can be incorporated naturally as domain wall fermions. Quantum electrodynamics and other gauge field theories relevant in particle physics can be regularized with quantum links along the same lines. Here we focus our attention on the simplest $U(1)$ lattice gauge theories that can be realized with quantum links. While they are not directly connected with particle physics, they share qualitative features with QCD, including the existence of confining flux strings. In addition, they are of interest in the context of the condensed matter physics in strongly correlated electron systems.

For a $U(1)$ quantum link model, the link degrees of freedom may be represented by spin $S = \frac{1}{2}$ operators. Quantum dimer models have the same Hamiltonian as the $U(1)$ quantum link model, but operate in a static background of "electric" charges. Upon doping, quantum dimer models may realize Anderson's resonating valence bond scenario of high-temperature superconductivity [46]. In this case, confinement manifests itself in valence bond solid phases, while deconfinement is associated with