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# Real-Time Dynamics in a (2+1)-D Gauge Theory: The Stringy Nature on a Superconducting Quantum Simulator

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Understanding the confinement mechanism in gauge theories and the universality of effective string-like descriptions of gauge flux tubes remains a fundamental challenge in modern physics. We probe string modes of motion with dynamical matter using a digital quantum simulation of a (2+1) dimensional gauge theory on a superconducting quantum processor with up to 144 qubits, stretching the hardware capabilities with quantum-circuit depths comprising up to 192 two-qubit layers. We realize the $Z_2$-Higgs model ($Z_2$HM) through an optimized embedding into a heavy-hex superconducting qubit architecture, directly mapping matter and gauge fields to vertex and link superconducting qubits, respectively. Using the structure of local gauge symmetries, we implement a comprehensive suite of error suppression, mitigation, and correction strategies to enable real-time observation and manipulation of electric strings connecting dynamical charges. Our results resolve a dynamical hierarchy of longitudinal oscillations and transverse bending at the endpoints of the string, which are precursors to hadronization and rotational spectra of mesons. We further explore multi-string processes, observing the fragmentation and recombination of strings. The experimental design supports 300,000 measurement shots per circuit, totaling 600,000 shots per time step, enabling high-fidelity statistics. We employ extensive tensor network simulations using the basis update and Galerkin method to predict large-scale real-time dynamics and validate our error-aware protocols. This work establishes a milestone for probing non-perturbative gauge dynamics via superconducting quantum simulation and elucidates the real-time behavior of confining strings.

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