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Neural Quantum State Study of the Toric Code under Heisenberg

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We employ convolutional neural network quantum states (NQS) to investigate the topological phase transition in the toric code when perturbed by isotropic Heisenberg interactions, a regime that has remained largely unexplored. Neural networks have recently demonstrated remarkable versatility in tackling quantum many-body problems, capturing volume-law entanglement and complex correlations [1]. The toric code, an exactly solvable model hosting topological order and anyonic excitations, serves as a benchmark for quantum memory architectures. While the impact of external magnetic fields on the toric code has been extensively studied, the role of intrinsic spin-spin interactions remains poorly understood [2-3].
In our approach, we use a translationally invariant convolutional ansatz that respects the underlying Hamiltonian symmetry. We further reinforce rotational symmetry by averaging network inputs over all lattice orientations.[4] By variationally optimizing this CNN-based NQS, we accurately compute ground- and first-excited-state energies on finite lattices, from which we extract the energy gap and ground-state fidelity as functions of the Heisenberg coupling strength. To pinpoint the critical point in the thermodynamic limit, we analyze the behave of Wilson loop operator.
Our results demonstrate clear signatures of a topological–trivial phase transition driven by Heisenberg interactions. This study not only extends the applicability of neural quantum states to interaction-driven topological phenomena but also provides new insights into the interplay between topological order and conventional spin interactions.

Reference

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