Critical quantum metrology robust against dissipation and non-adiabaticity

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Critical systems near quantum phase transitions were predicted to be useful for improvement of metrological precision, thanks to their ultra-sensitive response to tiny variations of the control Hamiltonian. However, realizing criticality-enhanced quantum metrology is experimentally challenging, mainly owing to decoherence and critical slowing down associated with the corresponding quantum state preparation. We here circumvent these problems by making use of the critical behaviors in the Jaynes-Cummings model, to which the signal field is coupled. The information is encoded in the qubit's excitation number, which displays a divergent changing rate at the critical point, and is extremely robust against decoherence and non-adiabatic effects. We demonstrate such a metrological protocol in a superconducting circuit, where an Xmon qubit, interacting with a resonator, is used as a probe for estimating the amplitude of a microwave field. The measured quantum Fisher information exhibits a critical quantum enhancement, confirming the potential for quantum metrology.

Gutzwiller-Projected State Preparation: Linking Quantum Search Algorithms to Extremely Correlated Fermions

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A guiding state with non-trivial overlap with the ground state is essential for preparing the ground state of a many-body Hamiltonian. The Gutzwiller-projected state, one of the candidates for quantum spin liquid, serves as a physically motivated and promising non-trivial guiding state. We reformulate the Gutzwiller projection problem as a multi-target search problem and develop an algorithm to prepare the Gutzwiller-projected state of a given trial state, uncovering a nontrivial correspondence between quantum search problems and extremely correlated fermions. By employing quantum amplitude amplification, the algorithm achieves a runtime proportional to the inverse square root of the overlap, providing a quadratic speedup over classical algorithms, but it overlooks the potentially useful structures in the trial state. Furthermore, we propose alternative approaches using the imaginary-time evolution, developing both a probabilistic algorithm with structural similarity to the quantum search circuit and an approximate method whose accuracy depends on the system's correlation length. However, both algorithms have exponentially large circuit complexity in the sense that the numbers of gates are exponential functions of the system size. Additionally, we investigate algorithms based on Hamiltonian simulation for preparing the Gutzwiller-projected state, such as adiabatic quantum computing. When the adiabatic Hamiltonians are projectors, the well-known two-level approximation is applied, resulting in the quadratic speedup. We also find that constructing a counter-diabatic quantum computing method gives constant or logarithmic scalings, but it is hindered by the discretization error and limited access to arbitrary rotation axes. Our results highlight the challenge of preparing Gutzwiller-projected state on quantum computers, and provide useful insights for future studies about this state preparation problem of correlated fermions.

Nonstabilizerness entanglement entropy: A measure of hardness in the classical simulation of quantum many-body systems with tensor network states

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Classical and quantum states can be distinguished by entanglement entropy, which can be viewed as a measure of quantum resources. Entanglement entropy also plays a pivotal role in understanding computational complexity in simulating quantum systems, especially in tensor network states related methods. However, stabilizer states formed solely by Clifford gates can be efficiently simulated with the tableau algorithm according to the Gottesman-Knill theorem, although they can host large entanglement entropy. In this work, we introduce the concept of nonstabilizerness entanglement entropy which is basically the minimum residual entanglement entropy for a quantum state by excluding the contribution from Clifford circuits. It can serve as a new practical measure of difficulty in the classical simulation of quantum many-body systems, which takes both entanglement and nonstabilizerness into consideration. We discuss why it is a better criterion than previously proposed metrics such as stabilizer Rényi entropy when measuring the difficulty in the classical simulation with tensor network states related method. We also show numerical results of nonstabilizerness entanglement entropy with concrete quantum many-body models. The concept of nonstabilizerness entanglement entropy expands our understanding of the “hardness” in the classical simulation of quantum many-body systems.

Ergotropy of quantum many-body scar

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The quantum many-body scar constitutes a weak violation of the eigenstate thermalization hypothesis, which exhibit quantum correlation resembling the low energy ground states obeying the area law entanglement. While its quantum correlation has been well studied, the role of scar in the quantum thermodynamics remains largely unexplored. Here we show that its violation of thermalization results in extensive ergotropy, the maximal amount of work that can be extracted from a subsystem by unitary operations, in contrast to the thermal states that are passive and can not be used to extract extensive work. Moreover, this is also holds for a family of states with finite overlap with the scars, which threshold is obtained by charting out an ergotropy phase transition between the scar and thermal states with exact numerical simulation. Our results show that the quantum many-body scars, despite the tiny fraction in the Hilbert space, can be efficiently exploited for storing extractable energy, and scarring a many-body system as a promising route for engineering quantum many-body battery.

Embedding computationally hard problems in triangular Rydberg atom arrays

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Rydberg atom arrays are a promising platform for quantum optimization. They encode computationally hard problems by reducing them to independent set problems with unit-disk graph topology. For example, integer factoring, QUBO, and independent set problems on arbitrary graphs have been efficiently encoded into a special unit-disk graph: the King's subgraph. However, King's subgraphs are not optimal candidates in two dimensions. Due to the polynomial decay of interaction strengths, their approximation to unit-disk graphs is poor, leading to the necessity of post-processing that lacks explainability. In this work, we show that triangular lattice subgraph can also universally encode computationally hard problems, based on our innovative gadget search strategy. Triangular lattices feature a higher ratio between minimum disconnected distance and maximum connected distance, which is crucial for the robustness of the embedding. Numerical simulations show that this scheme reduces independence-constraint violations by multiple orders of magnitude, alleviating the need for post-processing in experiments.

Robust and efficient estimation of global quantum properties under realistic noise

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Measuring global quantum properties—such as the fidelity to complex multipartite states—is both an essential and experimentally challenging task. Classical shadow estimation offers favorable sample complexity, but typically relies on many-qubit circuits that are difficult to realize on current platforms. We propose the robust phase shadow scheme, a measurement framework based on random circuits with controlled-Z as the unique entangling gate type, tailored to architectures such as trapped ions and neutral atoms. Leveraging tensor diagrammatic reasoning, we rigorously analyze the induced circuit ensemble and show that phase shadows match the performance of full Clifford-based ones. Importantly, our approach supports a noise-robust extension via purely classical post-processing, enabling reliable estimation under realistic, gate-dependent noise where existing techniques often fail. Additionally, by exploiting structural properties of random stabilizer states, we design an efficient post-processing algorithm that resolves a key computational bottleneck in previous shadow protocols. Our results enhance the practicality of shadow-based techniques, providing a robust and scalable route for estimating global properties in noisy quantum systems.

Critical Evaluation of QBER in a Cross-Exchange Quantum Key Distribution Protocol

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This study investigates the performance of a novel quantum key distribution protocol that uses cross-exchange of superpositioned qubit pairs with concealed rotation angles, contributing to the advancement of secure quantum communication. The purpose is to assess the protocol's reliability through Quantum Bit Error Rate (QBER) analysis under various conditions. We employed detailed simulations of quantum channels to test QBER across different attack scenarios and noise levels. Findings show QBER values ranging from 0.287 to 0.534, with a strong correlation ($R^2 = 0.97$) between attack intensity and error rate increases. Critically, the baseline QBER of 0.287 ± 0.045 exceeds the 11% security threshold by 2.6 times even without attacks, revealing inherent protocol vulnerabilities. A weak correlation ($r = 0.23 \pm 0.08$) between paired qubits further indicates flaws in the key agreement process, undermining secure key establishment. These results highlight that QBER alone cannot ensure protocol security and stress the need for thorough validation of quantum cryptographic systems. This work offers valuable insights for researchers and practitioners, emphasizing robust design principles for quantum key distribution to enhance secure communication technologies.