Variational state preparation with noisy trapped-ion quantum computers

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Noise in quantum devices challenges implementation of quantum algorithms. Our study focuses on noisy trapped ion quantum computers, addressing the errors arising from residual entanglement between electronic and motional levels. We introduce a variational quantum state preparation algorithm for non-ideal ionic quantum computers, achieving in our numerical experiments fidelities in preparing GHZ states with 3-5 qubits up to 0.99. Additionally, we propose optimizing hardware requirements for mixed-state preparation by utilizing ion-specific motional modes as computational resources.

Noisy trapped-ion quantum computers

In ion quantum computing, ions of some substance are held in a particular configuration in an electromagnetic Paul trap [1]. Usually the ions are arranged in a one-dimensional lattice called an ion chain, which we assume further in our work. A selected pair of electronic levels of each ion are used to encode a qubit whose state is controlled by laser pulses.

At low temperatures, the motion of ions in the trap is quantized in motional modes. These modes are determined by the Coulomb interaction of ions among themselves and their interaction with the trap. The excitation of these modes corresponds to the collective motion of all ions in the chain, and this is used to realize entangling gates between arbitrary qubits. Such gates include the Molmer-Sorensen gate.

As the size of ion chains increases, it becomes increasingly difficult to disentangle the electronic and motional degrees of freedom by the end of the execution time of the entangling gate, leading to potential residual entanglement and decreased fidelity of the gate. The presence of such non-idealities is characteristic of modern noisy intermediate scale quantum (NISQ) devices and presents a challenge to the successful implementation of quantum algorithms.

Pure state preparation

In this work, we have considered noisy ionic quantum computers where the leading source of error is the residual entanglement between electronic and motional levels, which is created by non-ideal Molmer-Sorensen gates. We have developed a variational algorithm for preparing quantum states that accounts for this residual entanglement and yet can successfully prepare a given pure state with high fidelity. We numerically tested this state preparation algorithm by preparing GHZ states with 3, 4, and 5 qubits, achieving fidelity up to 0.99.

Mixed state preparation

The controlled preparation of arbitrary mixed states is a fundamental quantum subroutine [2], on which we shall also focus our attention. There are two main approaches to its solution. The first approach, called purification, proposes finding such a pure state in a Hilbert space of higher dimensionality that the reduced density matrix over the added subsystem is identical to the target state. This approach has a drawback in that, in the worst case, it requires doubling the number of qubits in the register for its realization. The second approach is related to the representation of the mixed state as a statistical ensemble of pure states and the subsequent preparation of pure states from this ensemble according to their probability distribution. A disadvantage of this approach is the need to prepare a potentially exponentially large set of different states.

We propose a solution to optimize the hardware requirements for mixed-state preparation on ion quantum computers, using platform-specific motional modes as a useful computational resource. We demonstrate that it is possible to prepare mixed states in a register without the use of ancilla qubits, exploiting the entanglement between the electronic and motional subsystems. In numerical experiments, mixed states were prepared for 2 qubits that differed from the target mixed states in terms of the Hilbert-Schmidt distance by no more than 0.01.

References

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