Simulation of Projective Non-Abelian Anyons for Quantum Computation

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Fundamental particles in nature can be classified as bosons or fermions, which satisfy their correspondent statistics. However, quasiparticles of condensed matter physics may be neither bosons nor fermions, but can be named as anyons satisfying a generalized statistics. These anyons can be related with topological phases of matter. Interestingly, anyons can be used to encode qubits to perform quantum computations with specific advantages in which the corresponding qubits are naturally fault tolerant due to topological protection.[1,2] This approach is called topological quantum computation. However, its implementation based on natural systems still seems far from realization.

Quantum simulation is a powerful tool to demonstrate various characteristics of different systems. Particularly, digital simulation is universal in that different properties can be realized by the corresponding circuits with a universal set of quantum logic gates. However, digital simulation poses several challenges in achieving high fidelity with increasing number of qubits and layers of gates. Simulation of anyons can focus on different properties including their Abelian or non-Abelian statistics, fusion, and braiding operations, among others. Notably, a collaboration team of superconducting quantum computation, from Zhejiang University of Haohua Wang and Chao Song experimental group and Tsinghua University of Dongling Deng theoretical group, has simulated a series of building blocks for topological quantum computation based on anyons.[3] They used, individually, 68 and 30 qubits located on the square lattices of two superconducting processors to perform the experiments, where the use of 30 qubits was generally for verification.

Several kinds of anyons, such as electric and magnetic types of quasiparticles, are realized based on the toric-code model, corresponding to different excitations of ground state of the model created by circuits. Fundamental operations such as fusion and braiding with non-Abelian statistics are implemented by means of circuits and measurement of stabilizers. Single-qubit gates and a two-qubit controlled X gate are successfully realized through fusions and braidings among anyons to demonstrate the feasibility of quantum computation, where six twists of anyons are used to encode two qubits. Finally, logic two-qubit and three-qubit entangled states are realized by using these realized gates, with fidelity approximately 0.844 and 0.771, respectively. These results represent successful simulation of projective non-Abelian anyons for realizing topological quantum computation in future.

Notably, the Google quantum AI team has also digitally simulated non-Abelian braiding of anyons of the toric-code model.[4] The approaches used in Refs. [3,4] are similar. Additionally, the logic three-qubit entangled state encoded by six anyons has been prepared by the Google team using the braiding method for 25 superconducting qubits.

We know that topological logic qubits are still absent in natural systems. The highlight of the digital simulation is the promise of superconducting qubits for universal quantum computation. However, the characteristic of topological protection still seems challenging to be observed or realized in a simulation. However, the digital simulation of anyons paves the way for exploring various exotic properties of the quasiparticles in condensed matter physics and their control for advancement of quantum computation technologies.

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