A logical magic state with fidelity beyond distillation threshold realized on superconducting quantum processor
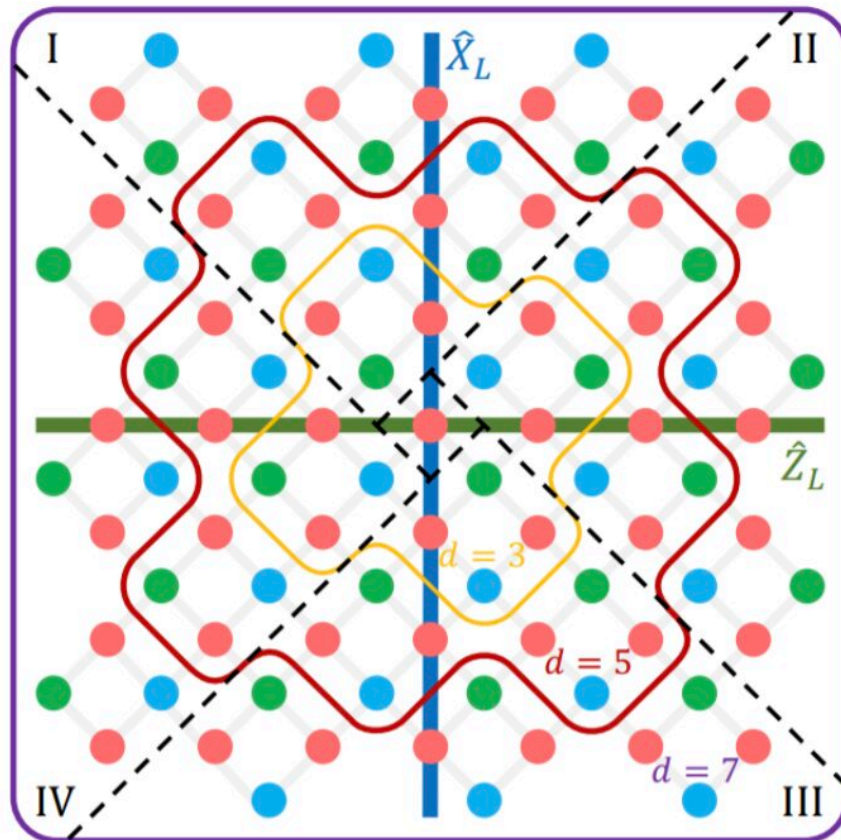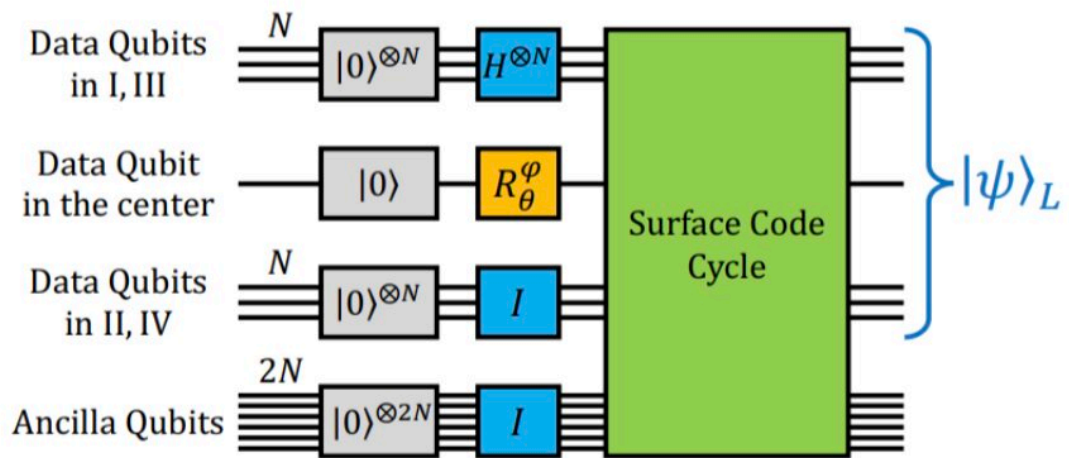
December 27 2023, by Ingrid Fadelli

I $\hat{X}_L$ II

$d = 3$

$d = 5$

$\hat{Z}_L$

IV $d = 7$ III

🔴 Data qubit   🟢 Z-type ancilla qubit   🔵 X-type ancilla qubit

Data Qubits in I, III — N — $|0\rangle^{\otimes N}$ — $H^{\otimes N}$ — Surface Code Cycle

Data Qubit in the center — $|0\rangle$ — R_θ^φ — Surface Code Cycle

Data Qubits in II, IV — N — $|0\rangle^{\otimes N}$ — I — Surface Code Cycle

Ancilla Qubits — $2N$ — $|0\rangle^{\otimes 2N}$ — I — Surface Code Cycle

$\}\, |\psi\rangle_L$

Arbitrary logical state preparation protocol. Top panel: The surface code is divided into 5 regions, the central data qubit, regions I, II, III, and IV. The logical operators $Z^_L$ and $X^_L$ intersect at the central data qubits. Bottom panel: The circuit of the protocol. All qubits are reset to $\vdash\ \dashv0\dashv\rangle$ state at the beginning of the circuit. Then the data qubits in the regions I and III are prepared to $\vdash\ \dashv+\dashv\rangle$ by Hadamard gate, and the central data qubit is prepared to the target state $\vdash\ \dashv\psi\dashv\rangle$ by rotation gates. One round of surface code cycle is applied afterwards, projecting the data qubits state into the logical state space. Credit: Yangsen Ye et al

Quantum computers have the potential to outperform conventional computers on some tasks, including complex optimization problems. However, quantum computers are also vulnerable to noise, which can lead to computational errors.

Engineers have been trying to devise fault-tolerant quantum computing approaches that could be more resistant to noise and could thus be scaled up more robustly. One common approach to attain fault-tolerance is the preparation of magic states, which introduce so-called non-Clifford gates.

Researchers at University of Science and Technology of China, the Henan Key Laboratory of Quantum Information and Cryptography and the Hefei National Laboratory recently demonstrated the preparation of a logical magic state with fidelity beyond the distillation threshold on a superconducting quantum processor. Their paper, published in *Physical Review Letters*, outlines a viable and effective strategy to generate high-fidelity logical magic states, an approach to realize fault-tolerant quantum computing.

"We have a long-term plan in the field of quantum error correction," Prof. Xiao-Bo Zhu, co-author of the paper, told Phys.org. "Following the

completion of our previous work on a distance-3 surface code for repeated error correction, we consider the next focus to be on the preparation of logical magic states."

The ultimate objective of the recent research by Prof. Zhu and their colleagues is to realize robust, fault-tolerant, universal quantum computing. The preparation of logical magic states is a key step to implement non-Clifford logical gates, which in turn lead to the attainment of fault-tolerant quantum computing.

"In simple terms, the basic idea of our protocol is to first inject the state to be prepared into one of the qubits in the surface code, and then 'propagate' the state information to the entire surface code, thereby achieving a logical state preparation," Prof. Zhu explained. "In this protocol, the choice of the inject position of the state to be prepared and the initialization states of other qubits is important."
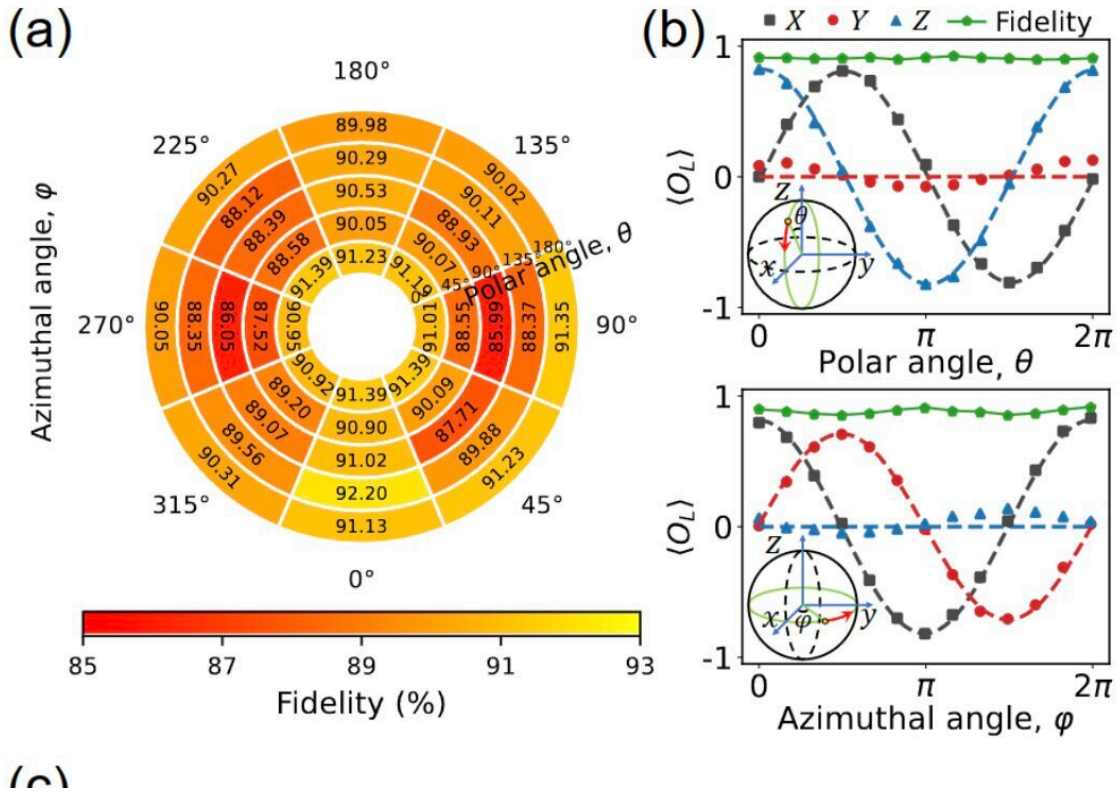
Experimental results of the prepared different logical states. (a) Logical state fidelity with post-selection in Bloch sphere. The fidelity of the preparation of different logical states is represented as a circle, which is divided into multiple annular sectors, each representing a point on the Bloch sphere, with the radial direction representing the polar angle θ and the tangential direction representing the azimuthal angle φ. The obtained average logical fidelity is 0.8983. (b) Logical measurement results of $\hat{X}_L$, $\hat{Y}_L$, $\hat{Z}_L$ as a function of polar angle θ or azimuthal angle φ. The colored dashed curves are the result of fitting with trigonometric function. (c) The logical density matrices of the magic states. Real and imaginary parts are represented separately, and the transparent wireframes represent the difference from the ideal density matrix. Credit: Yangsen Ye et al

The protocol proposed by this team of researchers outlines a simple, experimentally viable and scalable strategy to prepare high-fidelity raw magic states in superconducting quantum processors. As part of their

recent study, Prof. Zhu and his colleagues applied this protocol on Zuchongzhi 2.1, a 66-qubit quantum professor with a tunable coupling design.

"This processor's design allows us to manipulate the interaction between any two adjacent qubits, ensuring that our quantum gates be sufficiently high fidelity despite a high degree of parallelism," Prof. Zhu said. "This design is also conducive to expanding the scale of qubits on one processor."

When the researchers implemented their protocol on the Zuchongzhi 2.1 processor, they achieved very promising results. Specifically, they non-destructively prepared three logical magic states with logical fidelities of 0.8771 ± 0.0009, 0.9090 ± 0.0009, and 0.8890 ± 0.0010, respectively, which are higher than the state distillation protocol threshold, 0.859 (for H-type magic state) and 0.827 (for T-type magic state).

"We have achieved a critical milestone in the development of fault-tolerant computing based on the surface code by successfully preparing a distance-three logical magic state with fidelity surpassing the distillation threshold," Prof. Zhu said. "This outcome implies that we can feed low-fidelity magic states into the magic state distillation circuit, undergo multiple distillations to obtain sufficiently high-fidelity magic states, and subsequently employ them to construct fault-tolerant non-Clifford logical gates."

In the future, the protocol developed by Prof. Zhu and his colleagues could be used by other research teams to realize high-fidelity raw logical magic states, utilizing a broader range of superconducting quantum processors. Ultimately, it could contribute to the realization of robust fault-tolerance quantum computing, which could in turn enable the development of larger-scale quantum computers.

"In the field of quantum error correction, we plan to continue exploring two main research directions," Prof. Zhu added. "First, we aim to enhance the performance of a logical qubit (or error-corrected quantum memory) by reducing the physical manipulation error rate and increasing the number of encoded qubits, thereby suppressing the logical error rate to practical levels. Second, we conduct experimental research on error-corrected logical operations, such as lattice surgery, for application in future fault-tolerant quantum computing."

More information: Yangsen Ye et al, Logical Magic State Preparation with Fidelity beyond the Distillation Threshold on a Superconducting Quantum Processor, *Physical Review Letters* (2023). DOI: 10.1103/PhysRevLett.131.210603