QUANTUM COMPUTATION

Noise phased out

Environmental noise can severely hinder the storage and transmission of quantum information. Experiments now reveal that trapped ions are promising candidates for reliable quantum memories.

Shruti Puri

Quantum-error-correction protocols enable reliable computation even in the presence of unwanted noise in the underlying quantum hardware. One challenge in the path towards scalable quantum computing is the realization of a fault-tolerant quantum memory — a device that can store a unit of quantum information longer than any of its components. A promising resource-efficient proposal for achieving this is based on encoding quantum information in non-classical states of a harmonic oscillator. Now, as they describe in *Nature Physics*, Brennan de Neeve and collaborators[1] have demonstrated stabilization of an error-corrected state in the harmonic oscillator mode defined by the motional degree of freedom of a single trapped ion.

Every quantum computation starts with the fundamental unit of quantum information, the qubit. A qubit is a quantum object that can exist in two distinguishable states, and can be realized in a variety of ways. In this case, de Neeve and co-workers used two electronic pseudo-spin states of a $^{40}Ca^{+}$ ion to form the state-space of a physical qubit.

However, qubits necessarily interact with their surroundings — if they did not, we would not be able to control them. These interactions can cause the qubit to evolve in unpredictable ways, leading us to a kind of impasse: the interactions that enable our control also inhibit it. Fortunately, although quantum mechanics does not allow recovery of a general state of a quantum system coupled to its environment, it does permit recovery in a restricted state-space[2]. This forms the basis of quantum-error-correcting codes.

In a quantum-error-correcting code, a qubit is encoded in a two-state subspace of a larger quantum system, such as a system of several trapped $^{40}Ca^{+}$ ions. Perturbations or errors induced by common sources of noise are identified by detecting changes in some chosen quantum correlations in the qubit state. Once identified, reversing the effect of errors allows one to recover the original quantum state. This procedure is successful if the errors do not spread too rapidly to the global system state. Moreover, for an error-correction code to be fault-tolerant, the monitoring of errors must not introduce new perturbations beyond what the code can handle. Although there are many proposals to achieve this, the associated system requirements and resource costs are difficult to overcome in practice.

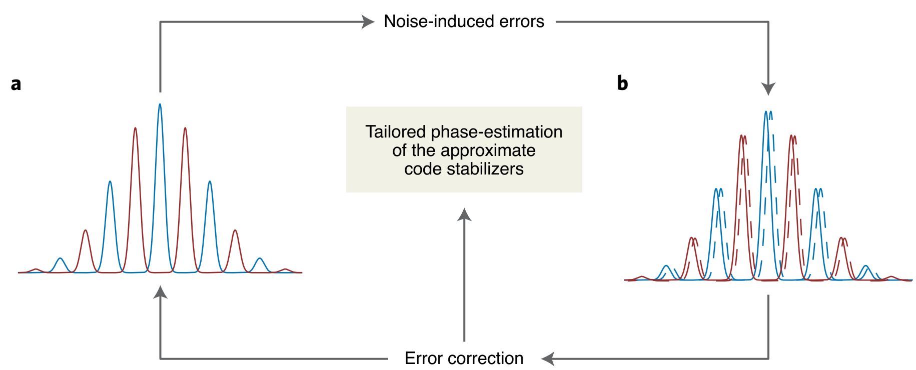

Fig. 1 | Error correction of the GKP code. Error-correction procedure in the GKP code. **a**, Schematic depiction of a typical wave-function envelope of a GKP qubit state, which is represented as a superposition of periodically displaced position eigenstates. **b**, Noise-induced errors result in momentum and position displacements that are detected and used for the correction procedure.

A strategy to ease these requirements is based on storing quantum information in non-classical states of a harmonic oscillator mode. One of the first of such encoding schemes was introduced by Daniel Gottesman, Alexei Kitaev and John Preskill in 2001 and is now known as the GKP code[3]. Compared with conventional codes, which rely on a large number of physical qubits and thus face scalability issues, the GKP code can be realized in the large state-space of a single harmonic oscillator mode. GKP code preparation has been demonstrated previously in trapped ion platforms[4], and its stabilization has been achieved in superconducting circuits[5]. Now, de Neeve and colleagues introduce two new techniques that are likely to be crucial for realizing a long-lived quantum memory with the GKP code. The theoretical ideas underpinning this experiment were also developed by other groups[6,7].

A quantum harmonic oscillator is described using two conjugate variables such as the position and momentum operators, related by canonical commutation relations. One possibility is to use the oscillator's lowest eigenstates, that is, the states with 0 and 1 quanta of excitation, to encode a physical qubit. If the dynamics of the oscillator is restricted to this subspace, error correction requires the introduction of several additional oscillator modes. Bosonic codes such as the GKP help to overcome this requirement, by harnessing the large state-space of a single harmonic oscillator to build a protected logical qubit, thus allowing error correction on a single physical entity. In their work, de Neeve and collaborators implemented the bosonic GKP code in the motional harmonic oscillations of a single $^{40}Ca^{+}$ in the trap.

Physical noise in a harmonic oscillator can be decomposed as displacements in position and momentum. The GKP code relies on the use of specific unitary operators, also referred to as stabilizers, which anti-commute with such displacements. As a result, position and momentum displacement errors lead to a phase shift of the eigenvalues of the stabilizers, which can be measured by a quantum phase-estimation protocol (Fig. 1). Thus, displacement errors can be unambiguously identified and any state in the logical GKP qubit space could be preserved indefinitely if the oscillator only suffers from errors smaller than a maximal threshold.

De Neeve and co-workers prepared an approximate logical GKP code-space and extended its lifetime by implementing error correction with the use of an auxiliary physical qubit, experimentally encoded in the internal electronic pseudo-spin state of the $^{40}Ca^+$ ion. The researchers used optical laser fields to activate the required conditional operation between the motional-harmonic-oscillator degree of freedom of the $^{40}Ca^+$ ion and its internal electronic states. The key innovation is the development and implementation of a modified phase-estimation algorithm, which brings two main advantages. First, it allows a more accurate estimate of changes in the eigenvalues of the stabilizers of the approximate GKP code. Second, it circumvents the problem of catastrophic errors introduced in the GKP code due to the unwanted interactions generated during the readout-cycle of the auxiliary electronic states.

The remarkable simplicity of the new protocol and its adaptability to other architectures make it particularly appealing. The introduction of error correction resulted in a three-fold improvement in the coherence of the GKP code compared to the case with no error correction. Despite some limitations in terms of the expected GKP lifetime, there is little doubt that the techniques developed in this work represent another step on the path towards the elusive fault-tolerant quantum memory. ❐

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References

1. de Neeve, B., Nguyen, T.-L., Behrle, T. & Home, J. P. *Nat. Phys.* https://doi.org/10.1038/s41567-021-01487-7 (2022).
2. Preskill, J. *Quantum Information and Computation* (Lecture Notes for Physics 229, California Institute of Technology, 1998); http://theory.caltech.edu/~preskill/ph229/
3. Gottesman, D., Kitaev, A. & Preskill, J. *Phys. Rev. A* **64**, 012310 (2001).
4. Flühmann, C. et al. *Nature* **566**, 513–517 (2019).
5. Campagne-Ibarcq, P. et al. *Nature* **584**, 368–372 (2020).
6. Royer, B., Singh, S. & Girvin, S. M. *Phys. Rev. Lett.* **125**, 260509 (2020).
7. Hastrup, J. & Andersen, U. L. *Quantum Sci. Technol.* **6**, 035016 (2021).

Competing interests

The author declares no competing interests.