Superconducting circuits

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Quantum thermodynamics for quantum computing

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Quantum thermodynamics has provided theoretical insights into the foundations of quantum and statistical physics. Now, a quantum thermal machine has found an application – cooling qubits in a quantum computer.

Quantum computers must operate at extremely low temperatures to reduce errors. These conditions are usually reached through the combination of several processes, starting with putting the qubits in a cold environment such as a dilution fridge. However, in practice, the fridge itself is not enough to eliminate all unwanted excitations, requiring methods that can pump energy out of individual qubits. Often, these methods require some kind of active process to ensure that qubits are correctly prepared in the ground state. Now, writing in *Nature Physics*, Mohammed Ali Aamir and co-authors have demonstrated how concepts from quantum thermodynamics can be used to implement an autonomous cooling method[1] that is competitive with state-of-the-art alternatives.

Most thermal machines do not operate autonomously. For example, cooling the food in our fridge requires electricity from an outlet. Autonomous machines, on the other hand, can operate without external control, drawing their energy supply directly from heat baths. A prime example is an absorption refrigerator, which uses heat – from solar energy, for example – as the primary input.

There has been significant theoretical research into absorption refrigerators that could operate in the quantum domain. The idea is rather simple (Fig. 1a). The process involves three bodies, with the goal of cooling one of the bodies while the other two each couple to a thermal bath.

The essential feature behind a quantum absorption refrigerator is a three-body interaction. According to the second law of thermodynamics, energy will usually flow from the body connected to a hot bath to the colder one. In an absorption refrigerator a three-body interaction is engineered so that this flow of energy between reservoirs only happens if some energy is extracted from the third body as well, producing the desired cooling process (see Fig. 1a). In quantum systems, this kind of interaction is possible owing to resonances between the transition frequencies of the three bodies.

Aamir and co-workers demonstrated an autonomous quantum refrigerator made of three superconducting qudits – generalizations of qubits with more than one excited state – coupled to separate hot and cold baths (Fig. 1b). The baths are realized by coupling each qudit to a waveguide whose temperature can be controlled by injecting thermal radiation. The three qudits are designed to interact through a nearest neighbour coupling between pairs of qudits. However, the team were able to tune the transition frequencies of the qudits to create an effective three-body interaction. They then controlled the temperatures of the hot and cold baths to cool one of the qudits to its ground state, ready to be used as a computational qubit.

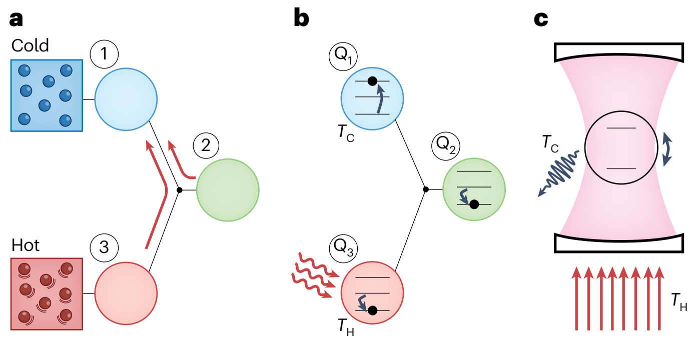

Fig. 1 | A superconducting qudit quantum refrigerator. a, Schematic of a quantum thermal refrigerator with bodies A (blue, coupled to cold reservoir), B (green, body to be cooled), and C (red, coupled to a hot reservoir). Heat flow is indicated by red arrows and the three-body coupling is indicated by black lines. Engineering of an appropriate three-body interaction means that heat flow from C to A also draws heat from B, cooling it. **b**, Qudit-based quantum thermal refrigerator as realized by Aamir and co-workers. Qudits Q_A and Q_C are coupled to cold (temperature T_C) and hot (temperature $T_H > T_C$) reservoirs, respectively. These reservoirs continually create a thermal population in the excited states of Q_C and extract excitations from Q_A. The energy structure of the qudits makes it possible to engineer a three-body interaction that cools qudit Q_B as energy flows from Q_C to Q_A. Once Q_B is cooled to its ground state, the first two energy levels can be used as a two-level qubit. **c**, In resonant sideband cooling, thermal light plays the role of the hot reservoir of the cavity mode (mode C), the cold reservoir comes from the spontaneous decay of an internal electronic transition (mode A), and the system that is cooled is the motional state of the atom (mode B).

There is a connection between this autonomous cooling process and resolved sideband cooling methods used in many atomic, molecular and optical systems[2]. An atom can be cooled with thermal light – for example, light from the sun – by placing it in a cavity to realize a three-body interaction that converts the thermal light into light resonant with the cavity by absorbing energy from the atom (Fig. 1c).

The performance of Aamir and co-workers' quantum thermal machine is characterized by the effective cooling temperature and the reset time. The team measured the reset time by tuning away from the three-body interaction resonance condition, thus turning off the cooling. They then measured the decay from the excited state after the refrigerator was turned on. Their thermal machine cooled the target qubit to its ground state within 1.6 μs which, crucially, is on the same timescale as a typical measurement in superconducting circuits. This means that the cooling process would not significantly slow down the operation of the processor. The effective temperature, which measures the probability that the qubit is incorrectly left in an excited state, was competitive with other state-of-the-art, non-autonomous qubit reset techniques[3,4].

Aamir and co-workers' demonstration of quantum thermal refrigeration for qubit reset marks the transition of quantum thermal machines from abstract ideas to practical application. The performance is already on a par with alternative methods, but a careful analysis of resources is needed before the technique can be widely adopted in quantum computers.

For example, a conventional measurement-based reset[3] may not be autonomous, but it can be implemented without adding more elements to a quantum processor, whereas Aamir and co-workers' realization of a quantum refrigerator triples the number of physical qubits. Furthermore, in the team's demonstration the temperatures of the hot and cold baths were controlled through artificially generated noise that was injected through additional wires at room temperature. However, the authors do suggest a solution where thermal baths are directly coupled to different temperature stages of the dilution refrigerator.

Ultimately, the work by Aamir and co-workers is a promising demonstration of a useful quantum machine, and it is natural to wonder whether it could address other practical problems in quantum information science. Beyond the task of resetting qubits, thermodynamics is an integral part of quantum information processing. For example, quantum error correction is essentially a process that extracts the entropy associated with environmental noise without disrupting quantum computation. Attempts to scale up quantum computers must manage the growing heat load from the quantum devices and associated control lines. Therefore, it would not be surprising if the answer to better quantum computers – at least partially – lies within quantum thermodynamics.

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Competing interests

The authors declare no competing interests.