A quantum Szilard engine that can achieve two-level system hyperpolarization

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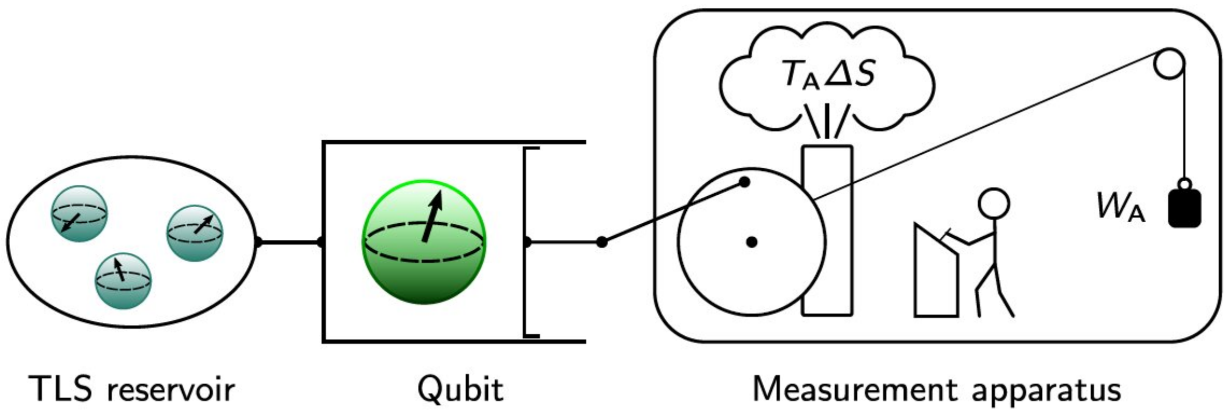

Credit: *Nature Physics* (2023). DOI: 10.1038/s41567-023-02082-8

Quantum computers, machines that perform computations exploiting quantum mechanical phenomena, could eventually outperform classical computers on some tasks, by utilizing quantum mechanical resources such as state superpositions and entanglement. However, the quantum states that they rely on to perform computations are vulnerable to a phenomenon known as decoherence, which entails the loss of quantum coherence and shift to classical mechanics.

Researchers at Karlsruhe Institute of Technology in Germany and Quantum Machines in Israel have recently carried out an experiment aimed at better understanding how environments could be improved to prevent the decoherence of quantum states, thus enhancing the performance of quantum computing hardware. In their paper, published in *Nature Physics*, they demonstrated the use of a quantum Szilard engine, a mechanism that converts information into energy, to achieve a two-level system hyperpolarization of a qubit environment.

"One of the biggest challenges of quantum superconducting circuits is preserving the coherence of quantum states," Ioan Pop and Martin Spiecker, two of the researchers who carried out the study, told Phys.org. "This is quantified by the energy relaxation time T_1 and the dephasing time T_{phi}. While doing T_1 energy relaxation measurements, we noticed that the qubit relaxation was not the same for different initialization sequences, similar to the observations of Gustavsson et al, published in Science in 2016. This motivated us to design and implement the quantum Szilard heat engine sequences presented in the paper."

A Szilard engine resembles the so-called Maxwell daemon, a hypothetical machine or being that can detect and react to the movement of individual particles or molecules. However, instead of operating on classical particles, as a Maxwell daemon would, the quantum Szilard engine operates on an individual quantum bit (i.e., a qubit).

Pop, Spiecker and their colleagues realized that the Szilard engine they created induces a hyperpolarization of a qubit environment. In addition, they were surprised to observe a very slow relaxation time of this environment, consisting of two-level systems (TLSs), which outlive the qubit by orders of magnitude.

"By continuously measuring the qubit and flipping its state in order to stabilize either the state 1 (or 0), the engine essentially uses information acquired from the qubit to heat (or cool) its environment," Pop and Spiecker explained. "By running the engine for sufficiently long, we can prepare the environment of the qubit in a hyperpolarized state, far from thermal equilibrium. Moreover, by monitoring the qubit relaxation we can learn about the nature of the environment and the qubit-environment interaction."

Via their quantum Szilard engine, the researchers were able to reveal the coupling between a superconducting fluxonium qubit and a collection of TLSs, which exhibited an extended energy relaxation time above 50 ms. This system could be cooled down to reduce the qubit population below the 20 mK temperature of the cryostat and heated to create an environment with a qubit population of approximately 80%.

"The before hidden TLS environment turned out to be the main loss mechanism for the qubit, while, almost paradoxically, the TLSs themselves are virtually lossless," Pop and Spiecker said.

"This is a crucial subtlety, because it implies that the qubit T_1 is independent on the TLS population, and strategies to improve T_1 relaxation times that are based on TLS saturation are not viable. Last, but not least, our experiments uncovered an up-to-now unknown TLS environment, with orders of magnitude longer relaxation times compared to the commonly measured dielectric TLSs."

The recent work by Pop, Spiecker and their colleagues could have valuable practical implications. For instance, their findings highlight the need to include environmental memory effects in superconducting circuit decoherence models. This key insight could help to improve quantum error correction models for superconducting quantum hardware, models that can help to mitigate the adverse impact of noise in quantum processors.

"One of the open questions is the physical nature of these long-lived TLSs, which might be electronic spins, or trapped quasiparticles (broken Cooper pairs) or adsorbed molecules at the surface, or something entirely different," Pop and Spiecker added. "We are currently performing experiments to measure the spectral density of these TLSs and gain some knowledge on their nature. Of course, the ultimate goal is to remove all TLSs from our environment and improve qubit coherence. In our case this would quadruple the qubit T_1."

More information: Martin Spiecker et al, Two-level system hyperpolarization using a quantum Szilard engine, *Nature Physics* (2023). DOI: 10.1038/s41567-023-02082-8