SUPERCONDUCTING QUBITS

Atomic physics with a circuit

Inspired by ideas and techniques for cooling atomic gases, an experiment demonstrates how the temperature of micrometre-scale electronic devices can be lowered using solid-state quantum circuits.

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Laser light can exert forces on atoms. Among other things, these forces allow the velocity of atoms to be decreased, and therefore provide an effective route for cooling atomic gases. Laser-cooling techniques[1–3] have become a centrepiece of modern atomic physics, and have found many applications, including atom optics, atom interferometry, atom lithography, atomic clocks, optical tweezers, optical lattices, Bose–Einstein condensation, and high-resolution spectroscopy. Reporting on page 612 of this issue, Miroslav Grajcar and colleagues[4] now describe the adaptation of a laser-cooling technique known as Sisyphus cooling for lowering the temperature not of atoms, but of a solid-state electronic circuit. These experiments provide a fine example of the parallels between 'artificial' atoms made of mesoscopic superconducting circuits, and 'real' atoms, as well as how these parallels can inspire new applications.

Using lasers to cool a gas of atoms seems counter-intuitive; at first sight, you would expect a laser to heat things up, rather than cool them down. Indeed, lasers can cool atoms only under very special conditions and when the laser frequency is near resonance to an atomic transition. For instance, when an atom moves towards a laser, momentum can be transferred from the photons to the atoms[1,2]; this is used in set-ups with two counter-propagating laser beams to slow down the motion of an atom confined between these two laser beams.

One laser-cooling technique is Sisyphus cooling[1–3], where the atoms move in one of two sinusoidally modulated energy potentials (see Fig. 1). When the atoms reach the top of a potential-energy hill, the incident light pushes the atoms down to the bottom of a valley, thus reducing the velocity of the moving atom (shown in Fig. 1b in red, purple and blue, as it loses speed in three consecutive snapshots). Therefore, the atoms always travel uphill, and then fall down to the bottom. This is reminiscent of the task given to Sisyphus, the Greek mythological character who must always push a stone uphill; as soon as the hilltop is reached, the stone rolls down again.

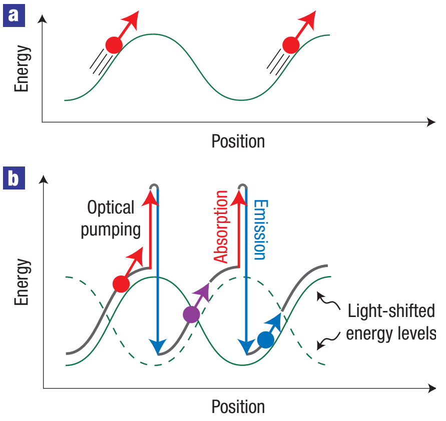

Figure 1 Sisyphus cooling of atoms. **a**, An atom moving on a periodic potential converts potential into kinetic energy and *vice versa*, while keeping its total energy constant. After each period, the atom velocity, shown by the red arrow, remains constant. **b**, The atom must lose energy in order to cool. This can be achieved when the atom interacts with two counter-propagating laser beams. In the interference pattern produced by these lasers, the two ground-state energies (shown in green) of the atom vary sinusoidally with position. By choosing a suitable laser frequency, the atom can absorb an incoming photon, and make a transition (indicated by the red vertical arrows) to an excited state, but only at the top of the potential energy hills[1–3]. The atom in the excited state can emit a photon (blue downward arrows), and then decay to the bottom of the valley. In the process, it loses an amount of energy equal to the energy difference between the absorbed and emitted photons, resulting in an energy loss leading to a successive slow-down after each cycle.

Grajcar *et al.*[4] now take the concept of Sisyphus cooling from the realm of atomic, molecular and optical physics to the condensed-matter physics context. Rather than laser light and atoms, they use 'quantum circuits' driven by a tank circuit. There is a deep analogy between natural atoms and the artificial atoms made of electrons confined in small superconducting components in quantum circuits. Both have discrete energy levels and exhibit coherent quantum oscillations between those levels. However, whereas natural atoms are controlled using visible or microwave photons that excite electrons from one state to another, the artificial atoms (qubits) in the circuits are driven by currents, voltages and microwave photons.

Differences between quantum circuits and natural atoms include how strongly each system couples to its environment; the coupling is weak for atoms and strong for circuits, and the energy scales of the two systems differ. In contrast to naturally occurring atoms, artificial atoms can be lithographically designed to have specific characteristics, such as a large dipole moment or particular transition frequencies (see, for example, refs 5–8). With a view to applications, this degree of tunability is an important advantage over natural atoms.

This tunability is now used by Grajcar and colleagues[4] to lower the temperature of a tuned circuit. Their experiment is schematically presented in Fig. 2. In the cycle $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$, a current first pushes the energy of the qubit uphill, until it reaches the resonance between the qubit and a microwave source. There, a mid-energy photon (represented in green), coming from a microwave source, is absorbed, and the qubit is promoted to its higher-energy state. Once there, the circuit's current drives the qubit uphill once more. Because the qubit is coupled to the environment, the qubit energy eventually decays to its lower-energy state emitting a high-energy photon. As in the Sisyphus myth, the qubit is doomed to fall to the bottom of the hill, after climbing to the top. The energy of the emitted photon is higher than the energy of the absorbed photon, and this energy loss cools the circuit, and makes it behave like a damped oscillator.

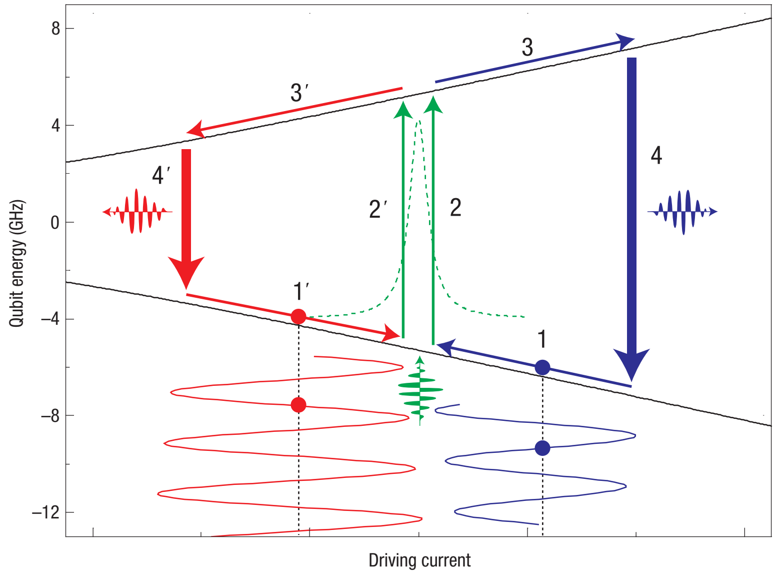

Figure 2 Sisyphus cooling of amplification of mesoscopic circuits[4]. The two energy levels of a quantum two-level system (a qubit) are shown versus the current of the circuit, which drives the qubit. The cycle 1 → 2 → 3 → 4 on the right side mimics Sisyphus cooling in atomic physics, and Sisyphus' fate in Greek mythology. The current plays the role of Sisyphus and the qubit plays the role of the rock. Initially, Sisyphus pushes the rock uphill (blue uphill arrows 1 and 3), but the rock eventually falls down to the bottom of the valley (blue downwards arrow 4). Sisyphus then starts the process all over again by pushing the rock uphill. The cycle 1′ → 2′ → 3′ → 4′ on the left side represents 'Sisyphus amplification', where the rock always rolls downhill. Animations illustrating these cycles are available online at http://dml.riken.jp/cool.

The same idea can be also used for 'Sisyphus heating', and, more significantly, for signal amplification akin to lasing (see the cycle 1′ → 2′ → 3′ → 4′ in Fig. 2). This cycle could be described as that of a 'happy Sisyphus' because the rock is always rolling downhill, and eventually it is lifted up by the applied microwave photons — the rock is now pushing Sisyphus downhill, instead of Sisyphus pushing the rock uphill. The qubit now amplifies the circuit current (and this amplification is related to lasing) by pushing the current downhill until it reaches the resonance, where the microwave photon is absorbed, promoting the qubit to its higher-energy state, where the qubit again pushes the circuit current. The qubit energy eventually decays to its lower-energy state emitting a low-energy photon. The energy loss, due to this emitted photon, is lower than the energy gain from the microwave, and therefore the microwave energy is now used to slowly amplify the current of the circuit.

The mechanisms demonstrated by Grajcar *et al.*[4] can be used for cooling and lasing, both of which are subjects of great interest in the field of superconducting qubit circuits[9–12]. A particularly intriguing perspective is to apply these techniques to cooling mechanical resonators at the nanoscale; this might provide opportunities to observe the transition between classical and quantum resonant behaviour.

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QUANTUM ELECTRONICS

Hybrid electron control

The ability to change the degree of hybridization of a donor electron between the coulombic potential of its donor atom and that of a nearby quantum well in a silicon transistor has now been achieved. This is a promising step in the development of atomic-scale quantum control.

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Doping is a crucial process in semiconductor electronics. The introduction of even a few parts per billion of dopant atoms into a semiconducting material can significantly change its electrical and optical properties. In conventional electronics, the key effect that dopants have is to contribute free charge and thereby to modify a semiconductor's conductivity. But as semiconductor devices become smaller, and ever more functionality is demanded of them, other properties, such as spin and even the precise nature of the quantum wavefunctions of dopants, can become important. Exploiting such properties not only promises to improve the speed and performance of future electronic devices, but could enable the development of solid-state quantum computing. Achieving the latter, however, requires the ability to exert full quantum control over the wavefunctions of donor electrons, and ideally over those of individual electrons. On page 656 of this issue, Lansbergen and colleagues demonstrate the ability to identify and manipulate the state of an individual