PHYSICS

Microwave Cooling of an Artificial Atom

Quantum computers need to be isolated from environmental disturbances including the effects of thermal noise. A method has been found to cool a quantum computing element to low temperatures relative to its surroundings.

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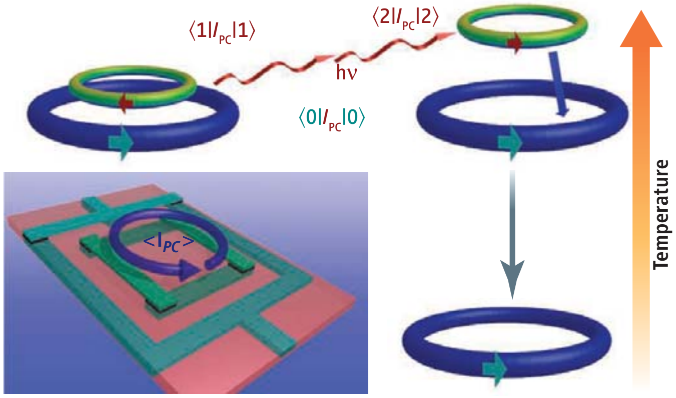
Quantum computers could potentially perform difficult calculations at unparalleled speeds. Instead of being based on conventional digital bits, however, such computers would use elementary units called quantum bits, or qubits. Owing to its quantum nature, a qubit can exist in states spanning any combination of two basic wavefunctions $|0\rangle$ and $|1\rangle$, whereas classical bits have values of either 0 or 1. Consequently, an operation on one qubit causes simultaneous operations on each of the combination's components, which can be used to speed up certain kinds of calculations. Likewise, a single operation on a multiqubit system can affect a huge amount of information, compared with just changing a single bit from 0 to 1. This property is called quantum parallelism and lies at the heart of quantum information technology. Coherence, the ability to protect the quantum operations from deterioration, is the primary challenge for scientists in this field.

Quantum information is very delicate and its manipulation with laboratory electronics often proves to be a tremendous challenge. Scientists are therefore constantly working on new methods to reduce the effect of noise and to preserve the coherence of a quantum bit. On page 1589 of this issue, Valenzuela *et al.* report a method to lower the temperature of a solid-state superconducting qubit by up to two orders of magnitude relative to the temperature of the surrounding electronics (*1*).

The technique they used was originally developed for atomic systems. Atoms are among the earliest and best studied quantum entities, and their application to the quantum information field is nowadays pursued with enthusiasm. At the same time, solid-state qubits—often called artificial atoms—have great prospects of being fabricated in large numbers on electronic chips by means of conventional lithographic techniques. Solid state artificial atoms therefore combine easy fabrication with our deep knowledge of quantum atomic physics.

There are several types of superconducting qubits, one of which is the persistent current qubit or flux qubit studied by Valenzuela *et al.* It consists of a superconducting loop interrupted by three Josephson junctions (black regions between the green strips in the figure). The Josephson junctions are engineered such that the loop's energy can be described by discrete energy levels (*2, 3*)—analogous to an atomic system—contained in a two-well potential. The relative position of levels can be selected by applying an external magnetic flux through the qubit loop. The $|0\rangle$ and $|1\rangle$ states of the qubit are the lowest levels and are localized in separated wells. They are characterized by opposite directions of the persistent current $I_{\rm PC}$, namely counterclockwise and clockwise, with average currents $\langle 0|I_{\rm PC}|0\rangle$ and $\langle 1|I_{\rm PC}|1\rangle$, respectively. A surrounding SQUID (superconducting quantum interference device) is able to identify the different flux states corresponding to different qubit states and is therefore used as a qubit readout. In the experiment of Valenzuela *et al.*, the device was noise-shielded in a superconductive cavity and cooled in a cryostat to minimize thermal effects.



Cooling a qubit. At lower left, the qubit (green) is surrounded by a readout SQUID (blue) able to detect changes in the average persistent current (blue curved arrow). At equilibrium with surrounding electronics (the "bath"), the ground-state current (blue rings) is countered by a small current (in green) caused by an undesired thermal population of the qubit first excited state $|1\rangle$. Cooling of the qubit is achieved by driving the thermal population of $|1\rangle$ to $|2\rangle$ with photons (red). State $|2\rangle$ (shown as a persistent current in the same direction as the ground state one) decays quickly toward state $|0\rangle$, which leads to qubit temperatures much lower than the bath temperature.

Further cooling of the qubit is achieved by a clever manipulation of its quantum states, analogous to the method called optical sideband cooling used to slow down vibrational degrees of freedom of atoms (*4*). Consider the state $|0\rangle$ as the ground state and $|1\rangle$ as the first excited state. The method requires the use of an ancillary state (hence the term "sideband")—for instance, the second excited state $|2\rangle$ of the superconducting loop. The undesired thermal population of state $|1\rangle$ is driven into state $|2\rangle$, which is then followed by a fast decay to the ground state $|0\rangle$. By repeating the cycle a number of times, the thermal population of state $|1\rangle$, and therefore the qubit's temperature, is decreased considerably.

There is one trick, though: The $|0\rangle$ to $|1\rangle$ equilibration rate and the $|2\rangle$ to $|1\rangle$ decay rate have to be considerably smaller than the $|2\rangle$ to $|0\rangle$ relaxation rate (indicated by the blue arrow in the figure). In the case of the persistent current qubit, the applied flux bias is such that state $|1\rangle$ and states $|0\rangle$ and $|2\rangle$ are localized in different wells (with different current directions but flowing inside the same loop, as illustrated in the figure). Thus, the intrawell relaxation rate dominates the dynamics and active cooling of the qubit is possible. Here, $|0\rangle$, $|1\rangle$, and $|2\rangle$ refer to qubit states, whereas in optical sideband cooling they refer to atom states coupled with the confining trap states.

Valenzuela *et al.* achieve activation of state $|2\rangle$ by applying classical electromagnetic fields via an on-chip antenna located near the SQUID-qubit structure. With this configuration they identify three regimes. At high frequencies, several subgigahertz photons are used to resonantly activate the $|1\rangle$ to $|2\rangle$ transition (the red arrows in the figure). At intermediate frequencies, the electromagnetic field shifts the qubit levels nonadiabatically and modulates the resonant activation. At low field frequencies below 10 MHz, levels $|1\rangle$ and $|2\rangle$ exchange adiabatically their position

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and population. Optimized cooling occurs when the electromagnetic field's amplitude is such that states $|1\rangle$ and $|2\rangle$ are in resonance at full swing in their oscillatory motion.

Despite the large size of the structure—compared with the optical cooling of atoms—Valenzuela *et al*. attain a remarkably low qubit temperature of just 3 mK above absolute zero. The procedure is robust when repeated at various bath (i.e., the substrate and surrounding electronics) temperatures ranging between 30 and 400 mK. Depending on the frequency regime, the qubit effective temperature is found to range between 3 and 50 mK. The adiabatic (low-frequency) regime is particularly attractive for cooling because it results in a constant 3 mK qubit temperature, independent of bath temperature. Qubit cooling is remarkably fast, it takes only about 1 µs and the effect persists for ~300 µs at 30 mK. This equilibration time decreases drastically, however, when bath temperature is increased. As a figure of merit, the ratio of equilibration and cooling times ranges between one and several hundreds, depending on bath temperature. Such a figure of merit could give an indication of the effectiveness of the process. If it would take longer to cool the qubit than it takes to warm it back up, the process would not be efficient.

Although the microwave cooling method reported by Valenzuela *et al*. is acting on the qubit only and not on the noise sources of its surroundings, the study is an important advance for quantum computing. It provides a means to improve qubit readout, initial state preparation, and resetting of the qubit. The active cooling technique demonstrated here could be used to lower the temperature of any oscillator-like part of a chip. Moreover, the method is in principle applicable to ^{3}He refrigerators working at ~250 mK, to bring the essential parts of the chip to millikelvin temperatures. And finally, techniques developed in quantum optics could be blended with the rich physics of solid-state systems, yielding great benefits in the long run.

References

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ASTRONOMY

A Ghostly Star Revealed in Silhouette

One class of binary stars, in which white dwarfs accrete material from low-mass companions, has long been predicted, but their dimness has made observations difficult. Evidence that they exist now comes from the Sloan Digital Sky Survey.

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If our current understanding of the evolution of binary stars is correct, the Galaxy should be littered with the remains of stars that have been reduced to about 5% of the Sun's mass ($0.05M_{\odot}$) by extensive mass loss onto their white dwarf companions. White dwarfs are the small, dense collapsed cores of deceased stars. A binary star system in which a white dwarf accretes material from a companion (see the figure) is called a cataclysmic variable (CV). Every kilogram of material that falls onto the white dwarf gains the energy equivalent of a few kilotons of TNT. Much of this energy is released as ultraviolet or x-ray radiation. Many CVs have been identified from this highly variable, short-wavelength light produced by rapid mass transfer onto the white dwarf. However, most CVs should have evolved through this violent phase to become a "dead CV" with a low-mass companion that can support only weak mass transfer. Extensive efforts to confirm this long-standing prediction have failed to identify any CVs that have clearly survived the rapid mass transfer phase of their evolution. Now, on page1578 of this issue, Littlefair *et al.* (*1*) report the unambiguous detection of a dead CV from a direct mass measurement of the low-mass companion in the CV SDSS 103533.03+055158.4 (SDSS 1035 for short). Why has it taken more than 20 years to find a dead CV, and why does it have such a dull name? The answer lies inside your digital camera.

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Digital cameras use charge-coupled devices (CCDs) to detect light. CCDs have revolutionized astronomy because they detect up to 90% of the light falling on them, versus a few percent at best for photographic film. Large-format CCDs are now relatively inexpensive, so it has become possible to build instruments that use arrays of CCDs to survey large areas of the sky. The Sloan Digital Sky Survey (SDSS) is the most ambitious sky survey undertaken to date. Researchers in the SDSS consortium have used a 120-megapixel camera to measure the brightness of more than 200 million celestial objects over a quarter of the sky at five wavelengths. Interesting objects are then followed up by means of spectrographs fed by optical fibers that can observe hundreds of objects simultaneously. The first phase of the SDSS obtained spectra for almost 1 million objects, including more than 150 new CVs. It is clearly not possible to make up interesting names for all 200 million stars and galaxies, so each object is named after its position on the sky.

The CVs identified by the SDSS are typically fainter by a factor of 100,000 than stars visible to the naked eye—much fainter than most known CVs (*2*). This is only partly due to their being, on average, farther away than known CVs; they are also intrinsically less luminous than known CVs (i.e., they have low mass-transfer rates). The sample of CVs selected from the SDSS is also much less affected by sampling bias than existing samples, so it is a good place to search for a missing population of dead CVs. The challenge is to find a technique that can reliably measure the mass of an almost invisible companion to a very faint star. Littlefair *et al.* have used CCDs, a large telescope, and a bit of luck to meet this challenge.

A typical CV is smaller than the Sun, so there is a good chance that the orientation of the binary is such that the companion eclipses the white dwarf once every orbit as seen from Earth. This will lead to an apparent dimming of the CV every orbit during the few minutes that the companion blocks the light from the white dwarf. SDSS 1035 is an eclipsing CV, so there is a wealth of information to be gleaned from the changes in brightness during the eclipse. These show, for example, that the mass transferred from the low-mass companion forms a disc around the white dwarf with a bright spot on its outer edge due to the inflowing material. The geometry of the binary can be determined by measuring the times at which different

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