SPs[8], and the transport of these SPs to the Ge detector.

The analysis of the far-field fluorescence from individual QDs or from a cluster of QDs revealed that, in some cases, there is a time lapse between two consecutive photon detections. This property, known as 'photon antibunching', is characteristic of single-photon emitters, which require a finite re-excitation time after photon emission. Thus, in accordance with previous work[9], the authors suggest that these QDs also act as single-plasmon sources. However, up to now, the existence of single plasmons has been based on indirect measurements made on photons. An intriguing possibility could be to test the quantum nature of SPs through the noise spectrum of the induced electrical current — just as the sound of rain falling on a roof gives us information on the discreteness and size of water drops.

It must be noted that in the device presented by Falk *et al.*, the existence of an electrical current relies on asymmetries in the directions defined by the arms of the Ge nanowire with respect to the Ag nanowire axis. A cylindrically symmetric SP cannot excite electrons in a symmetric wire crossing at 90° because the SP electric field points to the left at the left-hand arm of the detector, and to the right at the right-hand arm. The existence of a substrate does not break this left–right symmetry. The asymmetry in the reported study was largely uncontrolled, although it depended on the bias voltage applied between the metal pads; it would therefore be beneficial in the future to have a method of controlling and optimizing the coupling between the Ag and Ge nanowires.

Although the present work represents another step in the direction of an electrically and locally addressable plasmonic circuit, the excitation of the SPs still relies on optical methods. The combination of the present proposal with existing devices for the electrical excitation of SPs[10] (or, perhaps, using as an emitter a nanowire made from a direct bandgap semiconductor or a p–n structure) could finally create the much-sought-after 'dark' optical circuits in the nanoscale region. ❐

Luis Martin-Moreno is at the Instituto de Ciencia de Materiales and Departamento de Fisica de la Materia Condensada at the CSIC-Universidad de Zaragoza, C/Pedro Cerbuna 12, 50009 Zaragoza, Spain.
e-mail: lmm@unizar.es

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OPTOMECHANICS

Photons refrigerating phonons

Optomechanics is a promising route towards the observation of quantum effects in relatively large structures. Three papers, each discussing a different implementation, now combine optical sideband and cryogenic cooling to refrigerate mechanical resonators to fewer than 60 phonons.

Andrew Cleland

Quantum mechanics provokes much popular interest, due to its highly non-intuitive predictions and its unsettling contradictions of everyday experience. Ironically, quantum mechanics has never really been needed to understand mechanical systems. This is because mechanical systems are typically dominated by thermal effects, which destroy the coherence that distinguishes quantum behaviour. Over the past two decades it has become apparent that it should be possible to reach the quantum limit for some mechanical systems[1], driven by developments in nanoelectromechanical systems[2–4], and more recently in optomechanics, in which light is coupled to a mechanical system, enabling use of the full panoply of optical control techniques[5].

The experimental focus is on mechanical resonators, with resonance frequencies f_M typically between a few kilohertz and a few hundred megahertz. Cooling to the quantum ground state, which is one way to reach the quantum limit, requires reduction of the resonator's thermal energy k_BT to below the energy quantum hf_M. At 1 kHz, this requires temperatures below an astounding 50 nK, whereas at 100 MHz this requires $T < 5$ mK. Conventional cryogenic techniques can be used to lower the resonator's physical temperature towards these values, but typically further reduction is needed, especially for the lower resonator frequencies.

There are a number of optical techniques that can be used to cool a mechanical mode — similar to those used to cool the motion of atoms. One way is to parametrically couple the mechanical resonator to an optical cavity, with optical frequency f_O. The parametric coupling is achieved by construction; for example, the optical cavity can be formed by placing two mirrors so that they face one another, and trapping light between them. One of the mirrors is made very small, and placed on the mechanical resonator, so that the mechanical motion changes the spacing of the mirrors and thus changes the optical cavity's resonance frequency (Fig. 1).

By trapping light in the optical cavity, the mechanical motion of the resonator can be cooled by the radiation pressure of the photons trapped in the cavity. This type of radiation pressure damping has been successfully demonstrated[6,7], but the minimum mechanical energy is ultimately limited by the quantum uncertainty of the energy ΔE in the cavity, related to the cavity's optical lifetime τ (the average time a photon is trapped in the cavity) by $\Delta E \sim h/\tau$. If the cavity lifetime is too short, this prevents cooling of the mechanical mode to its quantum ground state.

To cool to the quantum ground state of the resonator, clearly the cavity's optical lifetime needs to be large; if the lifetime can be made to satisfy $\tau f_M >> 1$, meaning that a photon will stay in the cavity much longer than the oscillation period of the resonator, one can operate in the resolved-sideband limit of the resonator–cavity system. The minimum achievable resonator energy is then well below the energy quantum hf_M; that is, the resonator can in

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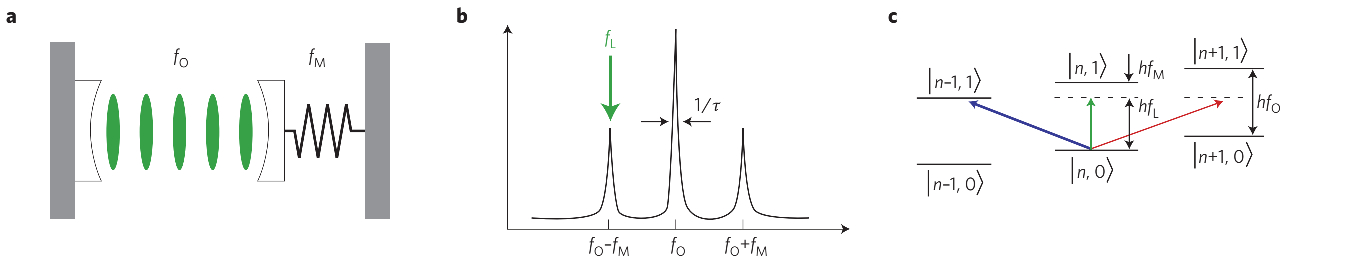

Figure 1 | Resolved-sideband cooling of an optomechanical resonator. **a**, Fabry–Pérot optical cavity with one mirror attached to a mechanical resonator. **b**, Optical cavity excitation spectrum in the resolved-sideband limit. Laser illumination (green arrow) is tuned to lower sideband. **c**, Energy level diagram for sideband-cooling. $|n,m\rangle$ represents mechanical resonator phonon state *n* with optical cavity photon state *m*. Laser transition at f_L (green arrow) is accompanied by strong transitions where one phonon is absorbed to generate a cavity photon (blue arrow), cooling the resonator. Transitions where one phonon is emitted (red arrow) are very rare.

principle be cooled to its quantum ground state. In this issue of *Nature Physics*, three papers[8–10] report an important step in this direction.

In the resolved-sideband limit, the motion of the mechanical resonator appears directly in the optical excitation spectrum of the cavity. For small harmonic motions of the mirror placed on the resonator, at frequency f_M, the spectrum of the optical cavity will develop split sidebands at $f_O \pm f_M$. When the natural cavity width $1/\tau$ is smaller than this splitting, these sidebands appear as peaks in the excitation spectrum (Fig. 1b). Cooling of the mechanical resonator is achieved by illuminating the system with a laser, tuned to the lower sideband of the coupled resonator–cavity system, at $f_L = f_O - f_M$. How this works to cool the resonator is best understood by studying the energy-level diagram shown in Fig. 1c. The laser excites virtual vertical transitions with energy hf_L, which can excite a cavity photon with energy hf_O if the mechanical resonator provides the additional energy hf_M. This energy is available if the resonator makes a transition from a state with *n* phonons to a state with $n-1$ phonons, adding the phonon energy to the laser photon, and generating a blue-shifted photon in the cavity with energy hf_O. Each process of this type removes one phonon from the mechanical resonator; the rate for this process is determined by the laser power, the cavity lifetime, and the optomechanical coupling strength between the mechanical resonator and the cavity.

There are a number of factors that limit the effectiveness of sideband cooling. The mechanical resonator is physically attached to a thermal reservoir, so if the mechanical mode temperature is reduced, thermal energy will 'leak' back in; this happens at a rate inversely proportional to the mechanical quality factor (Q) of the resonator. The optical resonator needs to have very low optical absorption, which otherwise could cause heating from the illuminating laser. Finally, the laser can itself inject noise, so a stable, low-noise laser is needed. Effective sideband cooling therefore requires a long cavity lifetime, high mechanical Q, low optical absorption, and a low-noise laser. Measuring the resonator's temperature, achieved by looking at its noise spectrum, is also highly challenging; a second laser, with very good noise performance, is typically used to measure the fluctuations in the cavity resonance frequency, from which the mechanical motion can be inferred.

Cooling in the resolved-sideband limit has been achieved[4,11], but has been limited by noise in the laser or by energy absorption in the cavity. In the three papers appearing here, all of the requirements for sideband cooling are met simultaneously, and all three report a substantial reduction of the mode temperature of a mechanical resonator, starting from a cryogenic physical temperature close to that of liquid helium. The flavour of the three papers is however somewhat different. In the paper by Simon Gröblacher and co-workers[9], micromachining is used to fabricate a doubly clamped beam that includes a Bragg mirror on its top surface, which forms one side of a Fabry–Pérot optical cavity. The fundamental 1-MHz flexural mode of the beam (with $Q \sim 30{,}000$) is cooled from an initial cryogenically achieved 5 K to about 1.5 mK, a reduction by a factor of about 4,000; at the minimum temperature, achieved by the balance of thermal load, noise and coupling strength, the authors estimate there are about 30 thermal phonons remaining in the mode.

The papers by Young-Shin Park and Hailin Wang[10] and by Albert Schliesser and colleagues[8] use similar, somewhat less 'engineered' optomechanical structures. Schliesser *et al.* use a toroidal microresonator, fabricated by micromachining a ~100-μm-diameter silica disc supported on a pedestal, which is then reflowed with a high-temperature laser process. The resulting toroidal structure supports extremely long-lifetime optical whispering-gallery modes. The toroids also exhibit a number of mechanical vibrational modes; the researchers use the high-Q radial breathing modes, which modulate the path length of the optical modes. Park and Wang instead laser-fuse two silica microspheres together, to generate a ~40-μm-diameter deformed microsphere, a structure that also supports long-lifetime whispering-gallery modes that can be efficiently excited by a free-space-coupled laser. The deformed microspheres exhibit bulk vibrational modes, and the researchers couple to, and cool, a mechanical mode with both radial and azimuthal components. The mechanical quality factors of the mechanical modes in both the toroidal and deformed spherical structures are somewhat lower than for those of Gröblacher *et al.* (with Q of a few thousand), but the mechanical resonance frequencies are substantially higher, in the range $f_M \sim 60$–120 MHz. Starting at a cryogenic temperature of around 1.5 K, each of these two groups is able to cool their respective mechanical modes by a factor of 3 to 6, resulting in a reduction of the mechanical energy to about 30 to 60 quanta. The larger bulk mechanical frequencies of the structures used by these authors makes reaching the resolved-sideband limit somewhat easier, as well as reducing the cooling needed to approach the quantum ground state. However, the coupling strength between the mechanical mode and the optical cavity is substantially smaller, so the rates of sideband cooling are correspondingly reduced. Interestingly, in spite of the factor of 100 difference in the mechanical resonance frequencies, the three efforts all achieve roughly the

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same performance in terms of mechanical quanta, and approximately match the best performance achieved to date in nanoelectromechanical systems.

The effective sideband cooling of macroscopic mechanical systems, as demonstrated in these three reports, coupled with similar advances using nanomechanical resonators, demonstrate that a number of quite different physical systems will probably soon be operating in the mechanical quantum regime. There may be surprises waiting in the quantum behaviour of these very large (observable to the naked eye) systems, and furthermore the potential impact of mechanical quantum instrumentation on measurement science is tremendous, applications that may further reveal new secrets of nature. Mechanics was the foundation for much of physics; it continues to provide promise for the future as well. ❐

Andrew Cleland is in the Department of Physics, University of California, Santa Barbara, California 93106, USA.
e-mail: anc@physics.ucsb.edu

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QUANTUM PHASES OF MATTER

Room for one more

In $YbRh_2Si_2$, the transitions to a heavy Fermi-liquid state and to a magnetic phase occur at a single quantum critical point. But under chemical pressure, these transitions separate, and a new phase of matter appears in between.

T. Senthil

In the past two decades, the standard theory of metals — known as Landau's Fermi-liquid theory — has increasingly come under attack because of a variety of experimental discoveries. Particularly intriguing is the observed breakdown of Fermi-liquid theory in certain rare-earth alloys poised at the brink of a phase transition to magnetism. Previous work had led to the idea that the onset of magnetism goes hand-in-hand with a more fundamental reorganization of the electronic states, suggesting a rather unusual form of phase transition. On page 465 of this issue, Sven Friedemann and co-workers[1] provide very suggestive evidence that the reorganization of the electronic structure is a phenomenon that occurs independently of the magnetism. Remarkably, the experiments support the possibility of a zero-temperature metallic phase of matter that is not a Fermi liquid.

Mobile electrons inside a metallic solid must be described as a degenerate interacting quantum fluid of fermions. Landau's Fermi-liquid theory posits that a good starting model is simply the familiar non-interacting Fermi gas, and leads to a number of specific predictions for the properties of metals. Although remarkably successful in a large number of metals, a growing number of exceptions to Fermi-liquid behaviour have been discovered[2]. The most notorious of these is the mysterious metallic state of the high-temperature 'cuprate' superconductors, reached by heating them above their superconducting transition temperature. The class of rare-earth alloys known as heavy-fermion metals provide other good examples. Many others are also being found.

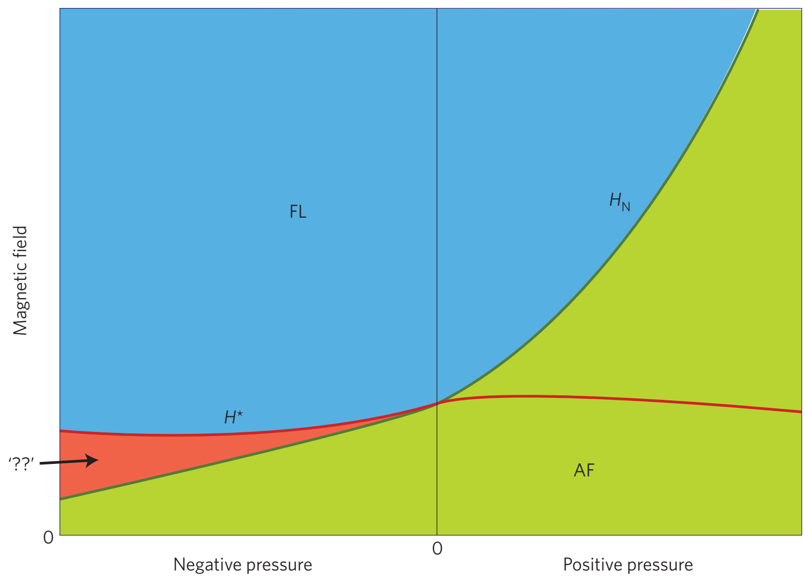

Figure 1 | Suggested phase diagram of $YbRh_2Si_2$ as a function of chemical pressure and magnetic field. H^* is associated with a reconstruction of the Fermi surface and H_N with the onset of Néel magnetic order. The coincidence of H^* and H_N for stoichiometric $YbRh_2Si_2$ apparently does not hold under chemical pressure. Most intriguing is the new, possibly non-Fermi-liquid phase (marked as '??') that is revealed at negative pressure.

At the microscopic level, the heavy-fermion systems possess a periodic array of localized magnetic moments (arising from atomic *f* orbitals) and a separate set of mobile conduction electrons. The localized moments interact with the spin of the conduction electrons through the usual 'exchange' process. This coupled system may thus be viewed as a lattice analogue of the celebrated Kondo problem, which studies the fate of a single localized magnetic moment immersed in a metallic host. The solution of the Kondo problem shows that such a localized moment 'dissolves' into the host Fermi sea at low energies.

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