**Cool Vibrations**
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PHYSICS

# Cool Vibrations

The ability to cool mechanical systems to ultralow temperatures will enable a new generation of sensitive detectors.

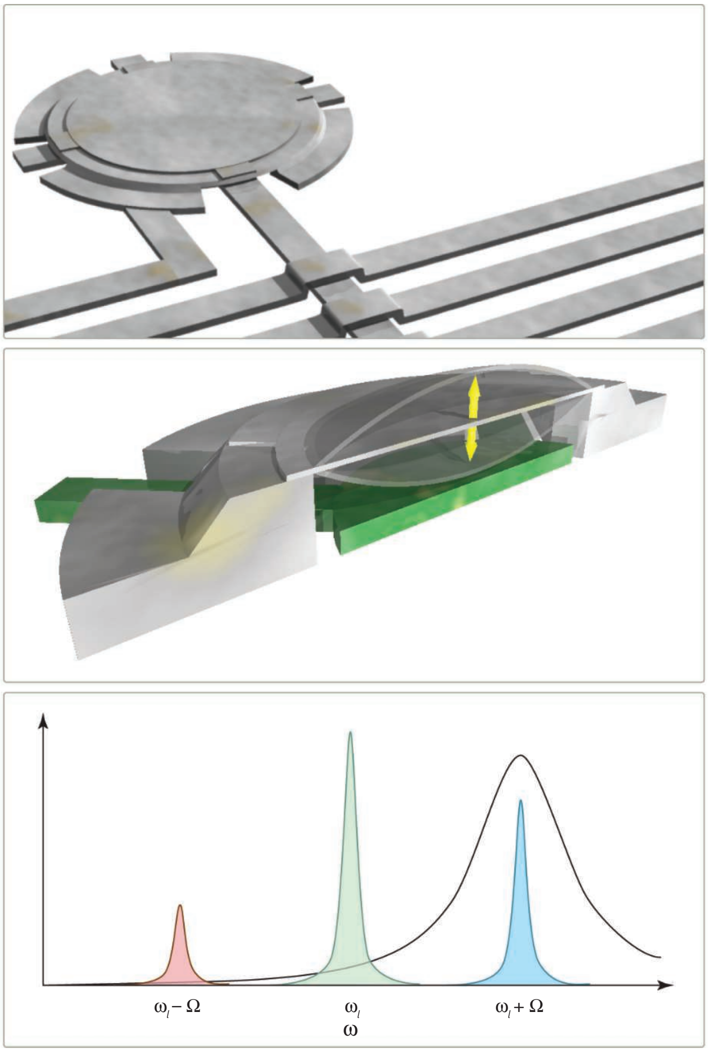
**Pierre Meystre**

Reaching for extremes in temperature has repeatedly proven to be a major route to transformational advances in fundamental and applied science. For example, the increasingly high temperatures attained in the realm of high-energy particle physics allow us to access the most fundamental constituents of the universe. At the other extreme, ultralow temperatures have led to discoveries such as superfluidity and superconductivity. Laser cooling has been a key technology in attaining the lowest temperatures ever achieved, with the record now in the tens of picokelvins range (*1*). These low temperatures allow exploration of subtle quantum mechanical effects such as the crossover between superconductivity and superfluidity and magnetic ordering. They also permit the realization of quantum simulators for the study of complex, strongly correlated many-body systems.

In parallel to these fundamental advances, ultracold temperatures are also critical in the development of mechanical sensors that operate in a regime where thermal noise is largely absent (*2*). A major step toward that goal was recently achieved by two groups at the University of California (UC)–Santa Barbara (*3*) and at the U.S. National Institute of Standards and Technology (NIST) (*4*). Both groups were successful in cooling macroscopic, mechanical oscillators to within a fraction of a phonon (a quantum of vibration) of their ground state of vibrational motion. The NIST system is particularly impressive in that researchers cooled the oscillator to such a low temperature that the average number of phonons in the system was only 0.34. This was achieved with sideband cooling by a microwave field (see the figure). This corresponds to a center-of-mass temperature of about 370 μK. By contrast, the UC Santa Barbara system has a much higher oscillation frequency of about 6 GHz, so that for all practical purposes it reaches its motional ground state when confined in a $^3$He cryostat at a few tens of millikelvin. Bringing such mechanical systems to their quantum mechanical ground state of motion is a major breakthrough that opens the way to a new generation of force and field detectors of unsurpassed sensitivity.

Much of the work that culminated in these recent results has its origin in the desire to detect the extremely weak signals expected in gravitational wave antennas [see, for example, (*5*)]. These signals are so feeble that their detection requires the elimination of all classical sources of noise, as well as a way of dealing with the back-action of quantum measurements on the dynamics of the antenna (*6*).

The essence of measurement back-action can be understood most simply in the case of a free mass $m$ by recalling the Heisenberg uncertainty relation, $\Delta x \Delta p > h/4\pi$, where $x$ and $p = mv$ are the position and momentum of the mass, with $v$ its velocity, and $h$ is Planck's constant. This relationship between the uncertainties in $x$ and $p$ also holds for any pair of so-called conjugate variables $A$ and $B$ in quantum mechanics. Consequently, the more precisely one parameter is determined, the more the uncertainty in the other. With subsequent measurements, the uncertainty on its conjugate variable feeds back into the parameter to be measured, an effect known as measurement back-action. That back-




**The beat of a quantum drum.** An illustration of the microwave optomechanical circuit of (*4*). The capacitor element is formed by a 15-μm-diameter membrane lithographically suspended 50 nanometers above a lower electrode. The middle panel is a cut through that capacitor showing the oscillating membrane oscillations at frequency Ω that modulate its capacitance, and hence the resonance frequency $\omega_l$ of the circuit. The bottom figure provides a schematic of sideband cooling. Because of the membrane oscillations, the coherent microwave field driving the circuit acquires frequency sidebands at $\omega_l \pm \Omega$ due to the membrane oscillations. The high-frequency sideband arises from the transfer of phonons from the membrane to the microwave field, whereas the lower sideband is due to the reverse process, that is, the amplification of the membrane oscillations. Sideband cooling results when the upper sideband frequency is resonant with the microwave resonator. It then dissipates faster than the lower sideband, resulting in a net decrease in phonon occupation of the vibrating membrane and cooling.

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action limits how precisely the parameter can be determined—the so-called standard quantum limit.

There are tricks, however, that can be performed so that the standard quantum limit can be circumvented. These back-action-evading, or quantum nondemolition (QND), techniques (*6*, *7*) typically involve the measurement of an observable *A* with strongly suppressed noise, most famously perhaps a quadrature (related to the phase of an optical signal) of a squeezed state, and the unavoidable quantum noise being therefore in the conjugate variable *B*, the other quadrature of the squeezed state (the conjugate variables *A* and *B* that characterize an electromagnetic field are called its quadratures). The measurement of *A* is then performed in such a way that the increased uncertainty in *B* does not feed back into *A*. Such QND measurements have been demonstrated in a number of quantum optics experiments but, so far, have been largely limited to electromagnetic fields. This is because a number of exquisite techniques have been developed to generate and characterize the types of quantum optical fields, such as squeezed states, that are required for back-action-evading measurements.

The recent breakthrough experiments open the way to the extension of these techniques to mechanical sensors. The successful cooling of macroscopic mechanical systems to their motional ground state is an exciting and essential step toward that goal, but it is "beyond ground state" physics that promises to be most exciting in bringing the emerging field of quantum acoustics to the level of sophistication of quantum optics. The demonstration of phonon lasers, squeezed and other nonclassical phonon states, entangled states, state transfer between phonon and photon fields, and much more, are already on the horizon, with an explosion of new results expected soon.

This bright future results from a cross-fertilization between quantum optics, laser cooling, nanotechnology, gravitational wave detection, and quantum measurement science and engineering—demonstrating the power of interdisciplinary science at its best.


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EVOLUTION

# Altruistic Wasps?

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Is the widely invoked theory of kin selection necessary to explain the apparent altruism in social wasp colonies?

*Polistes dominulus* is one of the most common social wasps in Europe and is an invasive species in the United States. Its wide prevalence has made it one of the best-studied social wasps. In most social wasps, the female wasps live in a colony and organize themselves into a behavioral dominance hierarchy such that only the dominant alpha individual (the queen) reproduces while the rest function as apparently altruistic, sterile subordinates (workers), building the nest, foraging for food and pulp, and feeding and caring for the brood. Why should workers invest their time and energy helping to rear the queen's brood, rather than found their own nests and rear their own brood—something they are quite capable of? On page 874 of this issue, Leadbeater *et al.* (*1*) show that the subordinates indeed produce their own offspring and this raises interesting questions about the links between altruism, direct reproduction, and the evolution of social behavior.

Using nine microsatellite markers to genotype pupae from 228 natural nests of *P. dominulus* from Spain, the authors measured the reproductive success of 1113 foundresses, including dominants (queens), subordinates (workers) and solitary nest foundresses (not in a multifemale nest). They found that subordinate foundresses produced more offspring per capita than an average solitary foundress who reproduced (and reared her brood) on her own. Thirty-two percent of the subordinates' offspring came from "sneaking" eggs into the joint nest (the queen usually prevents subordinates from laying) while the dominant was still alive, and 68% came from inheriting the dominant's position in the nest after the latter had died. Thus, the behavior of the subordinates is not altruistic at all. Subordinates that nest with a queen in a cooperative manner stand to inherit the nest and thereby produce their own offspring. What does this mean for theories about the evolution of social behavior that were built upon the assumption that

**Helping themselves.** Subordinate female wasps (*P. dominulus*) share a nest with a dominant queen, rearing the queen's brood. This behavior also benefits the subordinates, who stand to inherit the nest, or use the nest themselves for their own eggs, and increase the ability to rear their own brood.

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