

QUANTUM MECHANICS

The surf is up

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Researchers have long wanted to be able to control macroscopic mechanical objects in their smallest possible state of motion. Success in achieving that goal heralds a new generation of quantum experiments.

Dead silence — and then roaring applause. I still remember that brief moment that revealed the astonishment of everyone in the audience. Andrew Cleland had just concluded his talk at the conference ‘Quantum Optics of Nano- and Micromechanical Systems’, which was held last July in Bad Honnef, Germany. He had taken us all by surprise. Andrew’s talk had begun as a review of recent results¹ of his and John Martinis’ team — they had achieved an unprecedented degree of control over individual electromagnetic quanta (photons) in a microwave resonator by coupling the resonator to a superconducting two-state quantum system, or qubit. But the awe came with his last slide: in it, he showed that if the microwave resonator could possibly be replaced with a mechanical oscillator of similar resonance frequency, then the same qubit device could be used to attain quantum control over individual mechanical quanta (phonons). Just eight months later, Cleland, Martinis and their colleagues (O’Connell *et al.*, page 697 of this issue)² report that they have done just that*.

Over the past few years, impressive progress has been made in studying nano- and micro-mechanical resonators, and the common aim of exploring the quantum regime of mechanical systems has generated a thriving field that continues to attract an eclectic mix of researchers³. O’Connell and colleagues’ results² are a remarkable achievement because they involved overcoming two outstanding challenges in the field. The first is bringing the mechanical device reliably to its quantum ground state of motion, and the second is coupling it strongly to a different quantum system. With these challenges met, the future is ripe to use these systems both to test the principles of quantum mechanics and in applications such as quantum information processing.

The difficulty in bringing a mechanical device to its quantum ground state lies in the environmental temperatures (T) needed. To suppress residual thermal phonons in the device requires $T < hf_m/k_B$, where f_m is the device’s resonance frequency and h and k_B are Planck’s and Boltzmann’s constants, respectively. Typical mechanical resonators involve the motion of the device’s centre of mass and have resonance frequencies smaller than hundreds of megahertz. The required ground-state temperatures of such devices are below those achievable with standard cryogenic

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refrigerators. One solution is to use additional cooling schemes analogous to the laser cooling of atoms. This technique has allowed the preparation of mechanical states of mean phonon occupation, n , close to the quantum ground state ($n=0$), for both nanomechanical⁴ ($n \approx 4$) and micromechanical^{5,6} ($n \approx 30$) resonators.

Another solution is simply to avoid the difficulty, as O’Connell *et al.*² do. Their micro-mechanical resonator consists of a suspended slab that, owing to its piezoelectric nature (it changes its volume when subjected to an external electric field), can undergo oscillations in its thickness when the two metal electrodes between which it is sandwiched are subjected to a voltage. This acoustic vibration does not involve any centre-of-mass motion and hence allows the authors to achieve ultra-high mechanical frequencies of $f_m \sim 6$ gigahertz, for which they could prepare their system’s ground state using a conventional dilution refrigerator: at temperatures of about 25 millikelvin they obtained $n < 0.07$.

After meeting the first challenge, the authors were set to meet the second: to couple a resonator and another quantum system sufficiently strongly for quantum effects to be observed. Recent experiments have demonstrated mechanical coupling to qubits⁷ and strong coupling to optical cavities⁸. However, decoherence mechanisms have thus far prevented quantum effects from being observed.

In their experiment, O’Connell *et al.*² overcome this problem. Their mechanical resonator is connected via a capacitor to a Josephson phase qubit, which consists of two superconductors coupled by an insulating (Josephson) junction. The qubit’s ground and excited states represent the two lowest energy states of the superconductors’ wavefunction phase difference across the tunnel junction. By using the piezoelectric nature of the resonator, the electromagnetic energy of the qubit can be converted into the mechanical energy of the resonator, or vice versa. In principle, this interaction allows the authors to coherently transfer an arbitrary state of the qubit to the resonator, and even to generate entanglement — a quantum effect in which the states of the qubit and the resonator are linked together in an inseparable way.

To demonstrate coherent quantum-state transfer, O’Connell *et al.* prepared the qubit in the excited state and switched on the interaction between the qubit and the resonator. They then

measured the occupancy of the qubit's excited state as a function of the interaction time. The observed oscillatory behaviour of this occupancy is a clear quantum effect and indicates reversible qubit-resonator exchange of a single quantum of energy. The typical transfer times for single quanta (the Rabi swap time) was 4 nanoseconds, which is smaller than the energy decay times of 17 ns and 6 ns for the qubit and resonator, respectively. The authors observed a similar oscillatory behaviour in the excited-state occupancy when they transferred a qubit's superposition state, one in which the system is in the ground and excited states at the same time, hence preparing a quantum superposition of the mechanical system. It is also worth noting that, after half the Rabi swap time, the authors' transfer interaction should create an entangled state between the qubit and the mechanical resonator. They point out, however, that their current experimental performance excludes a direct test of entanglement.

Although today it is routine to control the quantum-mechanical motion of individual atoms⁹, controlling that of a nano- or micro-metre-sized system is not. Quantum mechanics on such scales has been envisaged^{10,11} since the 1990s. With their experiment, O'Connell *et al.* have not only set foot firmly in this quantum regime but have also opened the door for quantum control of truly macroscopic mechanical devices. And the prospects are exciting. One in particular is quantum information processing. In this, a key ingredient is the coherent control of many quantum systems, ideally in a scalable architecture. There have been proposals^{12,13} to achieve such control by using arrays of mechanical resonators. Although actual implementations will require minimizing the effect of detrimental decoherence mechanisms, the authors² have undoubtedly set the stage for such a future.

Another long-term prospect is testing the foundations of quantum physics. For example, superposition states of massive mechanical objects may be used to test possible deviations from quantum mechanics, which have been suggested to eliminate the 'Schrödinger's cat' paradox (in which a cat concealed in a box can be both dead and alive in a superposition of states)^{14,15}. Such tests require quantum superpositions of macroscopic spatial separation between two states of an object, literally of an object being both 'here' and 'there'. In O'Connell and colleagues' experiment², access to this regime is still hampered by the resonator's high mechanical frequency: the actual displacement between the two motional states of the prepared superposition is on the order of 10^{-16} metres — that is, six orders of magnitude smaller than the size of the unit cells of the resonator's structural lattice.

Although future experiments will need to find a working regime at lower frequencies, O'Connell *et al.* have taken a decisive first step towards an exciting future in mechanical quantum physics. This reminds me of the closing

remark of another intriguing talk that was given at the same conference by Pierre Meystre, one of the early pioneers in the field: "Thirty years ago I thought that it was a dead field. Now I think that the surf is

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