per nucleon, the product ions would no longer be energetic enough to penetrate the window and reach the detector.

Recently the researchers have installed a new detector that doesn't require a window. That should enable them to work at energies as low as 5 MeV per nucleon. Further planned improvements to the apparatus could allow lower energies still. Reifarth also hopes to try replacing the H_2 target with a helium one to study alpha-induced reactions, also thought to have a role in nucleosynthesis.

Johanna Miller

References

1. G. Wallerstein et al., *Rev. Mod. Phys.* **69**, 995 (1997).
2. T. Rauscher et al., *Rep. Prog. Phys.* **76**, 066201 (2013).
3. B. Mei et al., *Phys. Rev. C* **92**, 035803 (2015).
4. J. Bork et al., *Phys. Rev. C* **58**, 524 (1998).

A quantum squeezed state of a mechanical resonator has been realized

Manipulating zero-point fluctuations may pave the way for ultraprecise measurements of forces and positions.

The uncertainties imposed by quantum mechanics, though unavoidable, take the form of a trade-off: It's always possible, at least in theory, to reduce the uncertainty in a parameter of interest (a particle's position, say) at the expense of increasing the uncertainty of something else (its momentum).

In optics, the trade-off gives rise to so-called squeezed states of light, which can be constructed, for example, with lower uncertainty in their amplitude and higher uncertainty in their phase, or vice versa. More generally, if the waveform is written as $X\cos(\omega t) + Y\sin(\omega t)$, where t is time and ω is the wave's frequency, then X and Y, called the quadratures, are the requisite pair of noncommuting quantities whose uncertainties can be manipulated. The ability to produce squeezed light using nonlinear optics enables greater sensitivity in optical measurements such as those made by large interferometers (see PHYSICS TODAY, November 2011, page 11, and the Quick Study by Sheila Dwyer in PHYSICS TODAY, November 2014, page 72).

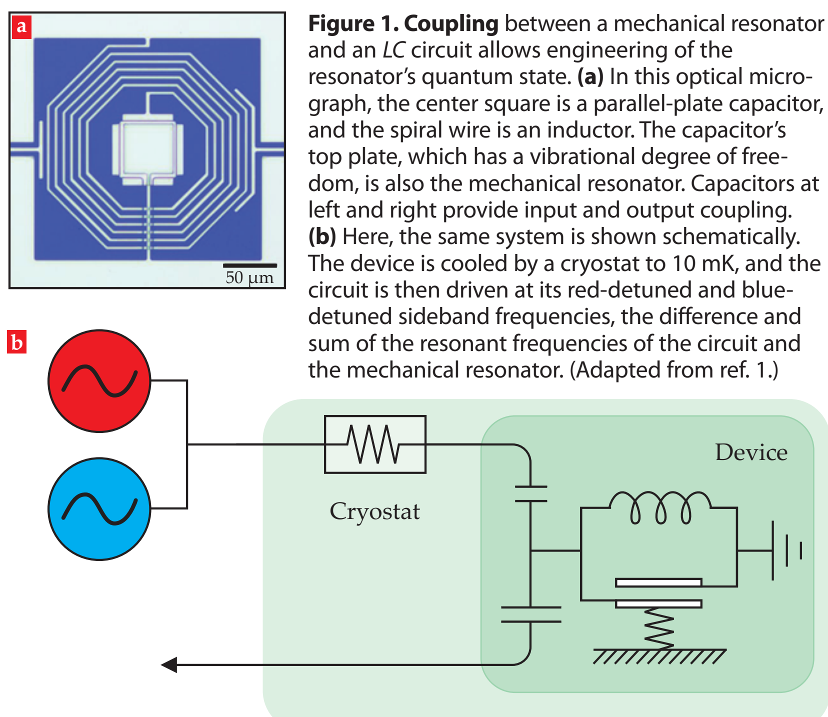

Figure 1. Coupling between a mechanical resonator and an *LC* circuit allows engineering of the resonator's quantum state. **(a)** In this optical micrograph, the center square is a parallel-plate capacitor, and the spiral wire is an inductor. The capacitor's top plate, which has a vibrational degree of freedom, is also the mechanical resonator. Capacitors at left and right provide input and output coupling. **(b)** Here, the same system is shown schematically. The device is cooled by a cryostat to 10 mK, and the circuit is then driven at its red-detuned and blue-detuned sideband frequencies, the difference and sum of the resonant frequencies of the circuit and the mechanical resonator. (Adapted from ref. 1.)

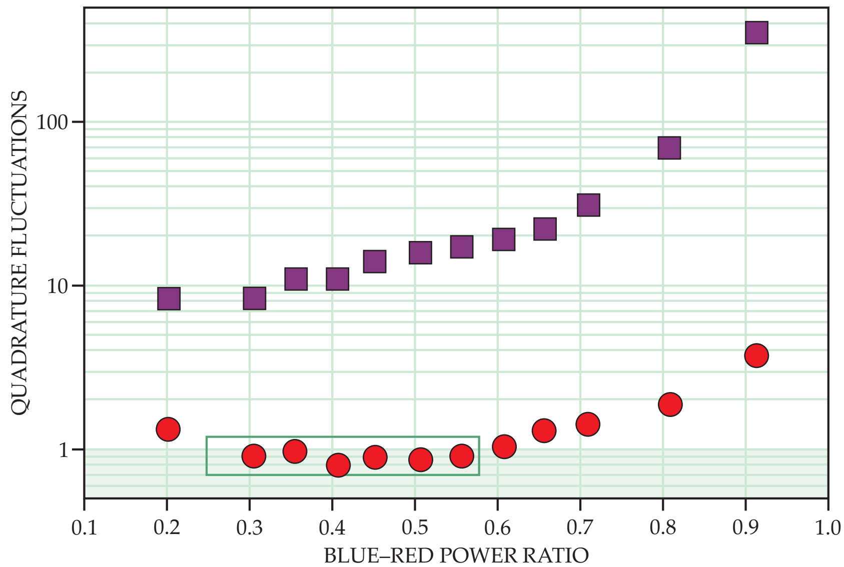

Figure 2. The resonator's two quadratures have vastly different uncertainties (shown here in units of the zero-point uncertainty) when the coupled circuit is driven at red-detuned and blue-detuned frequencies simultaneously. As highlighted by the green box, the lower-noise quadrature (red circles) is squeezed below the zero-point level for some ratios of the blue-detuned and red-detuned power. Fluctuations of the higher-noise quadrature (purple squares) are much greater. (Adapted from ref. 1.)

Now Caltech's Keith Schwab and collaborators have achieved the long-standing goal of similarly squeezing the quantum state of a micron-scale mechanical resonator.[1] In their device, shown in figure 1a, the center-square capacitor and the spiral-wire inductor form an *LC* circuit with a resonant frequency of 6.2 GHz. The top plate of the capacitor is free to move, with a vibrational frequency of 3.6 MHz. Through the coupling between the circuit and mechanical resonator, the researchers squeezed one quadrature of the mechanical resonator's motion down to 80% of the quantum zero-point level.

Fresh squeezed

A major obstacle to teasing out such a micromechanical system's quantum character is that even at a chilly 10 mK, thermal fluctuations in the mechanical motion overwhelm quantum fluctuations by two orders of magnitude. (In contrast, optical modes at room temperature are in their quantum ground state.)

That's where the coupled circuit comes in. As shown in figure 1b, motion of the mechanical resonator changes the capacitance of the parallel-plate capacitor. The circuit's resonant frequency ω_c thus acquires two sidebands at $\omega_c \pm \omega_m$, where ω_m is the mechanical frequency. (For a description of an equivalent system using an optical cavity instead of a circuit, see the article by Markus Aspelmeyer, Pierre Meystre, and Keith Schwab, PHYSICS TODAY, July 2012, page 29.)

Driving the circuit at the so-called blue-detuned frequency $\omega_c + \omega_m$ amplifies the mechanical oscillations: Each quantum of energy in the circuit can impart its excess energy to the resonator in the form of a phonon. Likewise, driving at the red-detuned frequency $\omega_c - \omega_m$ removes energy from the mechanical resonator.

In 2011 John Teufel and colleagues at NIST used that technique to cool a micromechanical resonator into its quantum ground state.[2] (See PHYSICS TODAY, September 2011, page 22.) Schwab and company went a step further by squeezing one quadrature of their cooled resonator's motion. They used a scheme devised by Andreas Kronwald and colleagues,[3] who had built on a decades-old idea that driving at both sideband frequencies at the same time affects the mechanical resonator's two quadratures differently.[4] Kronwald and colleagues worked out that by giving the two driving frequencies unequal intensities—with the red-detuned amplitude greater than the blue-detuned amplitude—one could cool and squeeze the motion simultaneously.

Verifying that the scheme works in practice was a challenge. Most techniques for probing the resonator's fluctuations risk destroying the delicately engineered quantum state. Schwab and company settled for an indirect approach whereby they deduced the fluctuations of the resonator's two quadratures through a theoretical analysis of the circuit's frequency output spectrum. The results, shown in figure 2, reveal that when the ratio of blue-detuned to red-detuned power is between 0.3 and 0.6, the quadrature with the lower noise (plotted in red) is squeezed below the zero-point level.

The next goals include measuring the quadrature fluctuations more directly and squeezing the mechanical motion of larger objects. The Caltech researchers' device, at 0.2 mm on a side, is big enough to see with the naked eye. It represents a step on the road to bringing quantum mechanics into the macroscopic world.

Johanna Miller

References

1. E. E. Wollman et al., *Science* **349**, 952 (2015).
2. J. D. Teufel et al., *Nature* **475**, 359 (2011).
3. A. Kronwald, F. Marquardt, A. A. Clerk, *Phys. Rev. A* **88**, 063833 (2013).
4. C. M. Caves et al., *Rev. Mod. Phys.* **52**, 341 (1980); V. B. Braginsky, Y. I. Vorontsov, K. S. Thorne, *Science* **209**, 547 (1980).

Slow-growing pebbles lead to fast-growing Jupiters

Planet-formation simulations produce the right number of gas giants in our outer solar system.

The planets in our solar system started out some 4.5 billion years ago as dust and gas in a protoplanetary disk surrounding the infant Sun. Radioactive dating of meteorites and other rocks indicates that Earth grew to its present size over a period of some 100 million years. (See the article by Bernard Wood, PHYSICS TODAY, December 2011, page 40.)

Ironically, the much larger solid cores of the gas-giant planets had to have formed much more quickly. Looking around the Milky Way at young star-forming regions, astronomers have found that gas disks surrounding young stars dissipate within the first 1 million to 10 million years. The cores of gas giants had to grow large enough—to 10 Earth masses—to be able to sweep up that nebular gas in time.

In the traditional picture of planet formation, dust in the protoplanetary disk clumps up to form pebbles that in turn collide and stick together to make rocks. The rocks then accrete to make boulders and so on to ever larger objects. But in planet-formation simulations, that mechanism works too slowly for the gas giants.

In 2012 Anders Johansen of Lund University in Sweden, together with his then graduate student Michiel Lambrechts (now at Nice Observatory in France), showed that the cores of gas giants could form much more efficiently if growing planetesimals fed on centimeter-sized pebbles rather than each other.[1] But that pebble accretion was perhaps too efficient. When Harold Levison and Katherine Kretke of the Southwest Research Institute in Boulder, Colorado, included pebble accretion in their simulations, they ended up with hundreds of Earth-sized objects rather than a few gas giants, like the four in our solar system.[2]

Now Levison, Kretke, and Martin Duncan of Queen's University in Canada have tweaked the model by adding as a control knob the rate at which pebbles form out of dust in the protoplanetary disk. Their new simulations show that slowing down pebble formation can produce the hoped-for handful of gas-giant cores.[3]

Meter barrier

A major stumbling block for planet-formation models is the so-called meter barrier. Electrostatic forces can make dust particles stick together. "That's why we get things like dust bunnies underneath our beds," Levison explains. For kilometer-sized objects, gravity can do the job. For sizes in between, neither force is strong enough to make things stick.

Even if objects could somehow grow to be bigger than pebbles, adds Levison, they face yet another fatal obstacle: aerodynamic drag from the gas in the disk. Dust can simply float around in the gas, and planet-sized objects feel the drag as a minor perturbation. However, for centimeter- to meter-sized objects, the situation is dire. The drag from the gas removes so much angular momentum from their orbits, they quickly spiral into the disk's central star.

Johansen and Lambrechts built on earlier work showing that turbulence in the protoplanetary disk could concentrate a population of pebbles into clumps. Those clumps become gravitationally unstable and collapse directly into 100- to 1000-km-sized planetesimals and thus bypass the need to grow intermediate-sized rocks and boulders.[4] "You go from things the size of coffee