Cooling a nanomechanical resonator with quantum back-action

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Recommended and Commentary by Steven M. Girvin, Yale University

Naik et al. have observed the quantum back action in the position measurement of a nano-mechanical oscillator. In addition, they have used this back action to cool the oscillator to a temperature of 300 mK, well below the 550 mK temperature of its bath.

The rules of quantum mechanics tell us that the act of measurement is generically accompanied by back action which affects the state of the system being measured. In the early days of quantum mechanics there were vigorous discussions of various gedanken experiments which elucidated the fact that acquiring information about the value of some observable necessarily implies that one's knowledge of the conjugate variable is decreased. For example in the Heisenberg microscope, one determines the position of an object by scattering light from it. Because light is a wave, the position resolution is limited by diffraction. Conversely, because light also has a particle nature, the random recoils from the scattering of photons off the object increase the uncertainty in momentum by an amount which increases as the wavelength (and hence the diffraction limited position uncertainty) decreases. By this mechanism, the Heisenberg uncertainty principle is enforced.

The problem of measuring the position of a harmonic oscillator is of fundamental importance on a wide variety of length scales ranging from the macroscopic scales of gravitational wave detectors to the nano-mechanical scale studied by Schwab's group. Because position does not commute with the Hamiltonian of an oscillator, position measurements are not quantum non-demolition (QND), that is, they are not repeatable. Random momentum kicks from the back action reappear a quarter cycle later as increased position uncertainty. This implies that, while there is no theoretical limit to the precision with which a single position measurement can be made (think of a diffraction limited Heisenberg microscope using gamma rays!), the power spectrum of position fluctuations at some definite frequency ω (and hence requiring repeated measurements at different times) is always increased (relative to the quantum ground state) by the act of measurement. For a damped simple harmonic oscillator (SHO) coupled to a zero temperature bath, this increase in noise power is not less than a factor of two. If one thinks of the back action noise as added noise in an otherwise perfect amplifier monitoring the SHO, the theoretical minimum noise energy of the amplifier (referred to the input) is $\frac{1}{2}\hbar\omega$. That is, the zero-point vacuum noise is at least doubled. This is referred to as the standard quantum limit (SQL) for position measurement.

A necessary, but not sufficient, condition for reaching the SQL is that the measurement be strong enough (relative to the oscillator damping and technical noise from the amplifier) that the back action noise is visible in the amplifier output. This condition was achieved by Naik et al.

Based on the above discussion, one might think that back action noise inevitably heats up the oscillator under observation. This is indeed true if the oscillator is close to zero temperature. If however it is at higher temperatures, back action noise can actually be used to cool the oscillator closer to (but not all the way to) its quantum ground state. This was also achieved by Naik et al. .

When dealing with quantum noise generated by a detector, one must distinguish noise at positive frequency, which corresponds to absorption of energy by the detector, and noise at negative frequency which corresponds to emission of energy by the detector. It turns out that the noise spectrum of a superconducting single electron transistor (SSET) is highly sensitive to the bias conditions and can correspond to positive or negative temperatures. The latter condition was demonstrated recently in the Schoelkopf group at Yale by the inversion of the polarization of a Cooper pair box being read out by a SSET. In appropriate circumstances, the charge transport through the SSET is controlled by resonant tunneling of Cooper pairs onto the island of the SSET. This occurs if the bias voltage has just the right value to compensate the finite charging energy required to place the Cooper pair on the island. If the bias voltage is smaller than this, then the SSET tends to make up the deficit by absorbing energy from the system being measured. Conversely if the voltage bias is too high, the SSET tends to heat the system being measured. Analogous effects occur in driven electrical and optical resonators. If the resonator is driven below resonance, the system to which it is parametrically coupled is cooled, while above resonance the system can be driven into spontaneous oscillations.

Naik et al. have succeeded in using the quantum asymmetry in the back action noise of a SSET to cool a nano-cantilever. The results are qualitatively in agreement with theoretical expectations but both the noise and the damping are mysteriously larger than expected (by factor of ~ 15) indicating that there is more to be understood about the noise processes in the SSET and/or how it couples to the cantilever.