

Nanoelectromechanical system approaches the quantum detection limit

Although a detector's effects on the object being measured add uncertainty to the measurement, they are not always bad. They can also cool the object.

What is the ultimate sensitivity with which one can continually measure an object's position? Sensitivity is often limited by thermal noise, and in some situations amplifiers set the noise floor. But classical physics argues that, with proper experimental design, the position uncertainty can be made arbitrarily small. Nearly 80 years ago, though, Werner Heisenberg posited his now-famous uncertainty relation, in which quantum mechanics places a fundamental limit on measurement precision: The product of the uncertainties in an object's position and momentum must be at least $\hbar/2$. A single position measurement will cast an object into a position eigenstate, but the resulting uncertain momentum will make the next position measurement uncertain.

Not only is the object being measured subject to quantum mechanics, so too are the measurement apparatus and the interaction between the object and the apparatus. And back action—the effect of the measurement system on the

object being measured—is inescapable. Quantum mechanics places further restrictions on measurement sensitivity by imposing a lower limit on the back action—which arises ultimately from the discrete nature of the photons, electrons, or other particles used to make the measurement. Some measurements can be configured so that the back action affects degrees of freedom other than the one being measured, but that's not always possible. For position measurements of a harmonic oscillator, for example, the back-action limit is comparable to the oscillator's zero-point fluctuations.

The quest to detect gravity waves prompted investigations more than 25 years ago into the quantum limits on position detection.¹ Growing interest in ultrasensitive detection in other contexts—single-spin magnetic resonance, magnetic resonance force microscopy, and weighing of individual atoms, among others—has reinvigorated interest in detection limits, this time at the other extreme of the size spectrum.

Such challenging experiments will require ultrasensitive detectors with sensitivities as close as possible to the ultimate quantum limit. Keith Schwab (Cornell University) and colleagues have recently succeeded in measuring the back-action effects in a nanoresonator—and have shown that they are very near the quantum mechanical detection limit.²

Schwab and company's experiments fall under the category of nanoelectromechanical systems (NEMS): They detect the motion of a nanoresonator by electrical means, namely a superconducting single-electron transistor (SSET).

(For more on NEMS, see the article by Schwab and Michael Roukes in *PHYSICS TODAY*, July 2005, page 36.) Optomechanical monitoring has been another area of active investigation, though better suited for devices on the micron scale than on the nanometer scale; recent results have reported the potential for quantum-limited measurements with that approach.³

The art of noise

In Schwab's NEMS experiments, done at the University of Maryland, the nanoresonator, shown in figure 1, is a bridge 8.7 μm long and a mere 200 nm wide, composed of 50 nm of silicon nitride covered by 90 nm of aluminum. It behaves like a mechanical oscillator with a resonant frequency of about 20 MHz. Located 100 nm away is the SSET. An exquisitely sensitive electrometer, the single-electron transistor consists of an island connected through tunnel junctions to source and drain leads. At very low temperatures, the Coulombic repulsion between electrons makes the current through the SET proceed one electron at a time. And that current depends acutely on the voltage applied to a nearby, capacitively coupled gate electrode.

In 2003, Robert Knobel and Andrew Cleland (University of California, Santa Barbara) covered a nanoresonator with a metal electrode, capacitively coupled it to the island of a normal (that is, non-superconducting) SET, and demonstrated the potential of SETs as displacement sensors.⁴ Fluctuations in the resonator's position had the same conductance-modulating effect as tweaking the SET's gate voltage, and like an ultrasensitive microphone, the SET turned the displacement of a nanoresonator into a measurable signal. That first effort at SET displacement detection achieved a sensitivity that was about a factor of 100 above the limits set by zero-point and back-action fluctuations.

Two years ago, Schwab's group achieved higher position sensitivity using an SSET.⁵ When the leads and island are superconducting, not only

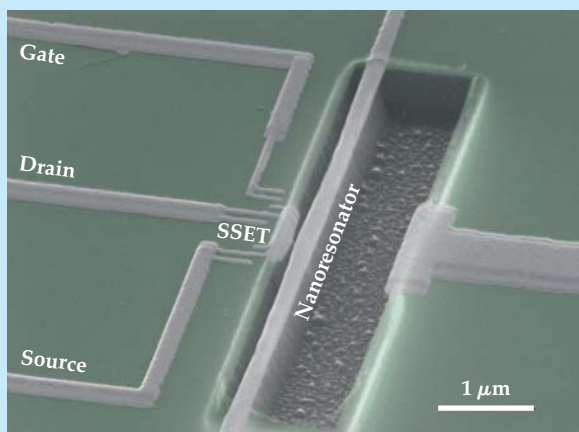


Figure 1. Nearly quantum-limited measurements of the position of this suspended nanoresonator are possible using the nearby superconducting single-electron transistor. The SSET is sensitive to tiny changes in the capacitance between it and the nanoresonator. The nanoresonator, in turn, is affected by back action caused by noise in the SSET. (Adapted from ref. 2.)

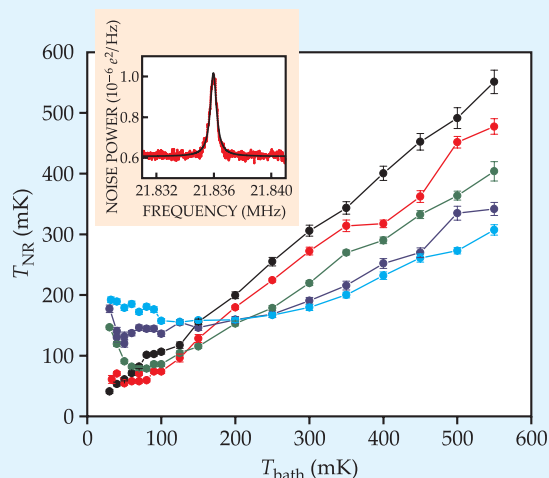


Figure 2. Back action manifests itself, among other ways, in the temperature of the nanoresonator, T_{NR} . That temperature is proportional to the area under the peak in the noise spectrum (like that in the inset) of microwave signals reflected off the SSET. Here T_{NR} is plotted against the surrounding temperature T_{bath} for resonator–SSET couplings from weak (black) to strong (blue). At the weakest coupling, T_{NR} matched T_{bath} . At stronger couplings, the resonator is heated at low temperatures and cooled at high temperatures, approaching the SSET’s effective temperature. (Adapted from ref. 2.)

singly charged electrons (or, more properly, quasiparticles) but also doubly charged Cooper pairs can tunnel. The combination of dissipative quasiparticle tunneling and resonant, dissipationless Cooper-pair tunneling can lead to a variety of current-carrying processes through the SSET. Biasing their SSET near a process combining Cooper-pair and quasiparticle tunneling, Schwab and colleagues could capitalize on the Cooper pairs’ resonant nature and achieve a substantial decrease in noise, getting to within a factor of 4.3 of the quantum detection limit.

To achieve high position sensitivity, it’s critical to have high gain, that is, strong coupling between the resonator and the detector. Otherwise, the signal will get lost amid the noise from the detector and downstream amplifiers. But as the coupling is increased, the detector’s back-action effects on the resonator strengthen. There is thus an optimum coupling for which the sensitivity is maximized.

In neither of the earlier nanoresonator–SET experiments was the coupling strong enough for back-action effects to be visible, but it was sufficiently strong in the new work. The back action, arising from charge fluctuations on the SSET island, manifested itself in three ways: a shift in the resonator’s frequency, an increased resonator damping rate,

and additional fluctuations in the resonator position.

When Schwab and colleagues used the SSET to perform noise thermometry on the nanoresonator, the resonator’s position fluctuations were apparent in the reflected noise spectrum, which peaked at the resonant frequency (see the inset of figure 2). The area under the peak is proportional to the resonator temperature, plotted in figure 2 as a function of the surrounding substrate temperature for various coupling strengths. When the coupling between the SSET and the nanoresonator was weak, the back-action effects were minimal, and the resonator’s temperature matched that of the substrate. For stronger coupling, though, the back action had a pronounced temperature effect.

Cooling off

While Schwab’s group was setting up the recent experiments, theorists were also getting busy. In studying the coupling between a quantum mechanical resonator and both normal SETs and quantum point contacts, Dima Mozyrsky, Ivar Martin, and Matthew Hastings (Los Alamos National Laboratory) had shown that the mesoscopic conductors interact with the resonator as if they were thermal reservoirs with a temperature proportional to the drain–source voltage.⁶ Theorists Miles Blencowe (Dartmouth University) and Andrew Armour (University of Nottingham), two long-term collaborators with Schwab and coauthors on the new back-action paper, had found the same behavior at higher temperatures, for which the resonator behaves classically.⁷

As Armour and Blencowe changed their focus from a normal SET to a superconducting SET coupled to a resonator, a third coauthor on the new work, Aashish Clerk (McGill University)—whose background was in the noise properties of SSETs—approached the same problem from a different perspective. In two papers published at the same time,⁸ the three theorists and their colleagues reported the same result: Near Schwab’s bias point, an SSET, too, acts like a thermal reservoir, but with the effective temperature determined not by the drain–source voltage but by the detuning from the Cooper-pair resonance. The effective temperature of the SSET in the recent experiments was

about 200 mK, as inferred from the resonator’s limiting temperature in the strong-coupling regime.

The experiments bore out another theoretical prediction: In the case of strong coupling, the SSET can cool the resonator to temperatures below the substrate temperature. Such cooling is evident in figure 2. The resonator is, in effect, coupled to two thermal reservoirs—the substrate and the SSET. Its temperature will thus be somewhere between the two, at a point that depends on the relative thermal couplings. The cooling observed in the experiments is not especially large—the nanoresonator temperature is reduced by only about 25%—but the team expects that the cooling ability can be improved by increasing the resistance of the SSET tunnel junctions.

Cooling mechanical oscillators has a longer history on the macroscopic, classical scale: An experiment nearly 30 years ago demonstrated cooling via coupling to a cold, dissipative load.⁹ And on the micron scale, Constanze Hühberger Metzger and Khaled Karral (Ludwig Maximilians University) have recently demonstrated cooling of a microresonator by almost two orders of magnitude using light-induced viscous damping.¹⁰

The SSET cools the nanoresonator only when the drain–source voltage is set below a Cooper-pair resonance. In that situation, the Cooper pairs need a boost of energy to tunnel through the SSET, and they absorb that energy from the resonator. The behavior is similar—both qualitatively and quantitatively—to Doppler cooling of atoms and to laser cooling of an optical cavity with a movable mirror. Martin and coworkers have proposed a cooling scheme analogous to a different laser-cooling technique—side-band cooling—that they suggest could cool a nanoresonator down to its ground state.¹¹

If the SSET is blue-detuned—that is, tuned to the other side of a resonance—tunneling Cooper pairs will tend to emit energy to the resonator, thereby heating the resonator and possibly driving it into a nonlinear regime similar to a laser.¹² Schwab’s experiments hinted at nonlinear behavior, and he is planning further work to examine the effect.

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Collision between galaxy clusters unveils striking evidence of dark matter

The nonbaryonic matter generally assumed to dominate large aggregates of stars and gas almost always shares a common center of mass with the ordinary matter we can see. But a titanic collision can force them apart.

Cosmology's widely accepted "concordance model" presumes that some still unknown form of dark matter overwhelms the cosmic abundance of ordinary baryonic matter by a factor of about six. Powerful evidence of dark matter has been accumulating since the 1930s from an impressive variety of observational realms: gas temperature and the random motion of galaxies in large galaxy clusters, galaxy rotation, the distribution of clusters, the abundances of the lightest elements, the anisotropy of the microwave background, and the redshifts of distant supernovae.

In all those cases, the reasoning that leads to dark matter assumes that gravitation on galactic and larger scales is correctly described by general relativity and, in the nonrelativistic limit, by Newtonian gravity. But some cosmologists argue that imagining modifications of general relativity on large scales is no more speculative than postulating dark matter in the absence of laboratory evidence. Mordehai Milgrom's 23-year-old phenomenological modification of Newtonian dynamics (MOND) has had considerable success in describing the rotation of galaxies without requiring them to be enveloped in dark-matter halos. And two years ago, Jacob Bekenstein incorporated MOND into a full-blown covariant field theory.¹

Now however, dark-matter skeptics must contend with what appears to be a persuasively iconic manifestation of dark matter (see figures 1 and 2). Douglas Clowe (now at Ohio University) and coworkers have analyzed new optical and x-ray observations to conclude that the dominant dark matter in a pair

of large galaxy clusters emerging from a recent collision is clearly offset from the hot, ionized intergalactic gas that dominates the clusters' baryonic mass.² Furthermore, they find that the dark matter, unlike the gas, seems unaffected by the titanic collision. That is—just as the concordance model would have it—dark-matter particles hardly ever scatter off one another.

In a large cluster, hot intergalactic plasma, visible in x rays (figure 2), is known to exceed the stellar mass of the largely gasless constituent galaxies themselves (seen in figure 1) by a factor of about six or seven. But how would one trace the dark matter, which trumps both stars and gas but shines at no wavelength? That's done by noting its gravitational-lensing distortion of the background galaxies in figure 1, far behind the two clusters emerging from their head-on encounter.

The virtues of collision

Ordinarily in a cluster, as in an individual galaxy, the dark and baryonic matter share a common center of mass. But colliding clusters offer a unique prospect of seeing the two pulled apart. The cluster pair studied by Clowe and company is especially well suited to the purpose. It was discovered first in 1995 as an extended x-ray source in the southern constellation Carina and named 1E0657–558.

At a distance from us of about 5 billion light-years, the two cluster centers have separated by 2 million light-years since they passed through each other "only" 100 million years ago. The well-defined bow shock front visible on the