Intrinsic Noise Properties of Atomic Point Contact Displacement Detectors

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Recommended and Commentary by Steven M. Girvin, Yale University

There is great current interest in both the optics and condensed matter communities in attempting to approach the limits set by quantum mechanics on position sensing of nano-mechanical oscillators. Flowers-Jacobs et al. have developed a novel atomic point contact position (APC) sensing technique and used microwaves to read out the position sensor with a factor of 500 increase in the measurement speed that allows the high frequency cantilever oscillations to be followed despite the high tunneling impedance of the APC. In addition to representing progress towards quantum limited position measurements, the techniques developed in this paper point the way towards high bandwidth scanning tunneling microscopy.

Quantum limited position measurements have two key requirements which must be met. First the detector/transducer must have near perfect efficiency and must have sufficient gain that the primary source of noise in the measurement comes from the quantum fluctuations intrinsic to the system being measured (and to the quantum detector) and not from noise added by the following amplifiers. For example, the position of a mirror in a cavity or an interferometer can be measured using the *wave* nature of light via interference. In order to be quantum limited, the imprecision of measurement of the position must be limited solely by the *particle* nature of light, i.e. the photon shot noise, and not by photomultiplier quantum efficiency, dark counts or post amplification noise. This is fairly readily achieved in optical experiments, but had not previously been achieved via electrical measurements, e.g. with single electron transistors [1]. Flowers-Jacobs et al. do achieve this limit using a novel quantum point contact which measures position via the exponential dependence of tunnel resistance on the size of the gap between the nano-mechanical cantilever and the atomic point contact. This is because the large energy barrier of the atomic point contact junction allows large bias voltages to be applied so that the current shot noise $S_{II} = 2eI$ can be made larger than the post amplifier noise.

The second key condition to achieve a quantum limited measurement is that the coupling of the detector to the system must be adjustable so that it can be optimized. In particular one has to be able to achieve sufficiently strong coupling that the measurement *back action* begins to affect the system being measured. That is, the momentum uncertainty imparted by the measurement (through the back action force) has to be large enough that it affects the subsequent position measurements. If this is not the case, then Heisenberg uncertainty is not the limiting factor in the measurement. This second condition has never been achieved in an optical measurement, but it was recently achieved with a single electron transistor by the Schwab group at Cornell [1]. (However their measurement did not achieve the first condition of being shot noise limited because the SET works best at very low bias voltages.) In the experiment of Flowers-Jacobs et al. , the effective coupling to the detector is adjustable via the bias voltage and they were able to see the back action noise.

One important mystery is that the back action noise seems to be about an order of magnitude larger than expected theoretically. The origin of this is unknown, but there is suspicion that since the back action noise spectrum is white, it is exciting higher modes of the mechanical motion. If the system were perfectly harmonic, this would not matter, but in reality weak nonlinearities cause these other modes to indirectly heat up the mode being measured. That is, the cantilever is acting as a broadband bolometer (K. Lehnert, private communication). This point emphasizes one of the practical features necessary to reach the quantum limit: The back action noise should be limited to the vicinity of the frequency of the oscillation mode being measured and should only be vacuum noise at all other frequencies. In the end, pretty much every system is a bolometer.

References:

1. 'Cooling a nanomechanical resonator with quantum back-action,' A. Naik, O. Buu, M. D. LaHaye, A. D. Armour, A. A. Clerk, M. P. Blencowe and K. C. Schwab, *Nature* **443**, 193 (2006).