Quantum feedback of a nanomechanical oscillator

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In real-time quantum feedback protocols (1), the record of a continuous measurement is used to stabilize a desired quantum state. Recent years have seen spectacular advances in a variety of well-isolated micro-systems, including microwave photons(2) and superconducting qubits(3). By contrast, the ability to stabilize the quantum state of a tangibly massive object, such as a nanomechanical oscillator, remains a difficult challenge. The main obstacle is environmental decoherence, which places stringent requirements on the timescale in which the state must be measured. Using cavity optomechanical coupling(4, 5) we report on a position sensor that is capable of resolving the zero-point motion of a solid-state, 4.3 MHz frequency nanomechanical oscillator in the timescale of its thermal decoherence(6), a basic requirement for preparing its ground-state using feedback as well as (Markovian) quantum feedback. The sensor is based on evanescent coupling to a high-Q optical microcavity(7), and achieves an imprecision 40 dB below that at the standard quantum limit for a weak continuous position measurement(8), while maintaining an imprecision-back-action product within a factor of 5 of the Heisenberg uncertainty limit. As a demonstration of its utility, we use the measurement as an error signal with which to feedback cool the oscillator. Using radiation pressure as an actuator, the oscillator is cold-damped(9) with unprecedented efficiency: from a cryogenic bath temperature of 4.4 K to an effective value of 1.1 mK, corresponding to a mean phonon number of 5 (i.e., a ground state probability of 16%). The measurement reveals strong backaction-imprecision correlations, which we observe as quantum mechanical sideband asymmetries, as well as ponderomotive squeezing of the light field(10). Our results set a new benchmark for the performance of a linear position sensor, and signal the emergence of mechanical oscillators as practical subjects for measurement-based quantum control. We moreover demonstrate the existence of such quantum correlations due to the optomechanical interaction at room temperature (11) and demonstrate that the correlations enable quantum enhanced force sensing (termed “variational measurements”). This scheme, rather than utilizing squeezed vacuum, uses the quantum correlations produced in the interferometer for enhanced force sensing. Closing, we will describe recent progress which uses soft clamping and strain engineering, which has enabled to attain mechanical quality factor exceeding 800 million at room temperature, implying a mechanical oscillator undergoing more than hundreds of oscillations during the thermal decoherence time. These results signal the emergence of room temperature quantum feedback.

References: