Dispersively coupled optomechanical systems: a new approach to quantum optics with radiation pressure

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Radiation pressure provides a unitary coupling between the electromagnetic field and the center-of-mass motion of macroscopic objects. In principle it should be possible to use this coupling to imprint the electromagnetic field's quantum fluctuations onto objects which, due to their large size and high temperature, would otherwise behave classically. Although this is a fascinating goal and progress in the past few years has been rapid, the technical challenges are considerable. In practice one must build a high finesse optical cavity which is coupled to an ultrasensitivie mechanical force sensor. The twin requirement of a delicate mechanical force detector and a high finesse cavity has proved to be a major barrier to observing quantum effects in optomechanical systems.

In my talk I will describe an optomechanical device in which a 50 nm-thick dielectric membrane is placed at the waist of a high-finesse optical cavity. In this ”membrane-in-the-middle” geometry, the coupling between the cavity mode and the membrane is closely analogous to the dispersive coupling between a cavity mode and an off-resonant atom. We demonstrate that even with the dielectric membrane inside the cavity it is possible to achieve a cavity finesse equal to 150,000. We also find that some membranes have a surprisingly large mechanical quality factor: $Q = 1,000,000(10,000,000)$ at a bath temeprature $T = 300$ K $(0.3$ K), leading to a near-world-record force sensitivity of 10^{-15} N/Hz$^{1/2}$ (10^{-17} N/Hz$^{1/2}$).

This combination of high finesse and high mechanical Q allows us to laser cool the 100 kHz vibrational mode of the membrane. Starting at room temperature, we achieve a laser-cooled temperature of 7 mK. Straighforward estimates indicate that if this device is placed in a cryostat at 0.3 K, the same cooling should bring the membrane to its quantum mechanical ground state.

I will also describe how the dispersive coupling in this device allows us to realize a novel type of readout in which light leaving the cavity only carries information about the square of the membrane's position. Such a ”position-squared” measurement has long been known to be a key requirement for making a phonon-resolving quantum nondemolition measurement of a mechanical oscillator. I will review the prospects for realizing such a measurement and observing real-time quantum jumps of a micromechanical device. Although challenging, it appears this goal could be reached using present-day technology.

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