Silica Whispering-Gallery-Mode Microresonators

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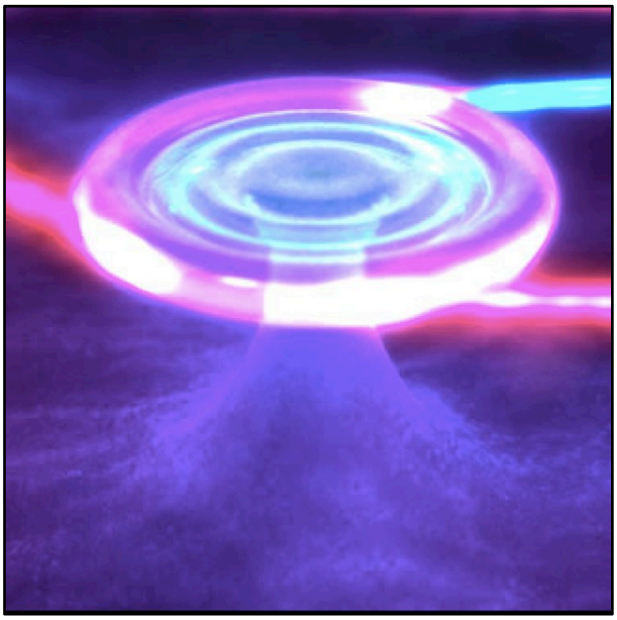
Optical forces have been harnessed to cool the motion of atoms and ions to the quantum regime. Recent experiments in the field of cavity optomechanics have demonstrated techniques enabling a similar level of control over much larger objects, such as nano- and micromechanical oscillators.

Radiation pressure has played an important role in many branches of physics. Already in the 17th century, Kepler conjectured that sunlight exerts a force on matter from his observation that comet tails always point away from the sun. Maxwell put this conjecture on solid theoretical grounds some 250 years later. But it was the advent of the laser that suddenly offered unprecedented opportunities to researchers. With laser light, it became possible not only to trap and manipulate small dielectric particles, but also to cool and control atoms and ions in a regime where their motion can only be understood in quantum mechanical terms.



A micromechanical oscillator. A toroid made of glass, with a diameter of a human hair, simultaneously hosts very high quality optical and mechanical modes. A laser coupled to the optical modes can be used to detect mechanical displacements at the attometer level. At the same time, its radiation pressure acts on the mechanical mode, and can be harnessed to cool its motion close to the quantum ground state.

In contrast to atoms and ions, larger mechanical systems – such as nano- or micromechanical oscillators – are still considered completely classical objects. In the emerging field of cavity optomechanics, researchers aim to study the quantum regime of these oscillators' motion by using radiation pressure to harness the interaction between their optical and mechanical degrees of freedom.

Silica microtoroids, in particular, have proven to be particularly well-suited vehicles for cavity optomechanics. They simultaneously host optical whispering-gallery modes (WGMs) as well as high-frequency mechanical radial breathing modes (RBMs). Due to their high optical quality, laser light coupled to a WGM orbits along the rim of the glass toroid millions of times. It is therefore ultrasensitive to a "breathing" mechanical oscillation of the resonator's radius. Indeed, oscillations with attometer-scale amplitudes – roughly a thousand times smaller than the radius of a proton! – induce a modulation of the cavity field's phase that can be measured within just a second of averaging time [1].

However, this is only one side of the medal, the presence of light also influences the mechanical motion – due to the radiation pressure exerted by the light. As the toroids store large amounts of light in a microscopic volume, the force can significantly alter the dynamics of the mechanical mode. This "dynamical back-action" of light has been predicted by the Russian theorist Vladimir Braginsky long ago, but had eluded experimental observation for more than three decades.

Under particular conditions, dynamical back-action can reduce the random thermal agitation of the mechanical oscillator's displacement, effectively cooling this individual degree of freedom. Such effect was first demonstrated with silica mirco-resonators [2]. Interestingly, this phenomenon can be viewed in close analogy to laser cooling of atoms or ions.

From this analogy, it can be understood that a micromechanical oscillator like a toroid's RBM can be cooled down to the quantum regime just as well. As a precondition, it is however necessary to rule out that the noise of the radiation pressure force – both technical and quantum – reheat the mechanical device. This can be accomplished only by cooling in the so-called resolved-sideband regime demonstrated first with silica microtoroids [3].

On the other hand, the mode of interest must be decoupled sufficiently from its hot reservoir constituted by the other mechanical modes. An engineered device geometry [4] does reduce the coupling, however, to enter the quantum regime, cryogenic pre-cooling is virtually inevitable. Although technically challenging, that's feasible, by thermalizing the samples to a cold helium buffer gas prior to laser cooling [5]. With a lighter 3He buffer gas at 800mK, we could recently demonstrate a micromechanical oscillator residing in the quantum ground state more than 10% of the time [6].

Laser cooling is now applied to a vast variety of opto- (and electro-) mechanical systems, paving the way towards the quantum control of nano- and micromechanical oscillators. Which role exactly these mechanical "quantum machines" will play in the future has yet to be seen – as transducers, memories or others. Without doubt, however, a new compartment can be added to the quantum toolbox.

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