Coupling a silicon nitride membrane resonator with a gas of ultracold atoms offers a novel approach to controlling mechanical systems at the quantum level.

Subject Areas: Atomic and Molecular Physics, Optics

A Viewpoint on: Realization of an Optomechanical Interface Between Ultracold Atoms and a Membrane
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Physical Review Letters 107, 223001 2011 – Published November 21, 2011

Researchers have used laser fields for decades to achieve extraordinary control over the quantum states of atoms, molecules, and ions. Condensed-matter physicists have recently made fast progress in achieving a similar level of control over nano- and micromechanical oscillators, i.e., lithographically engineered structures. Among the opportunities that drive this effort is the possibility of detecting and controlling these devices at the quantum level. Reaching this quantum regime makes it possible to prepare the mechanical oscillator in pure quantum states and observe how it evolves under interaction with the environment, potentially revealing yet unobserved decoherence mechanisms. From an applied perspective, such studies may also enable researchers to create sensors with improved sensitivity.

What makes mechanical systems attractive in this context is the large mechanical quality factor of micro- and nanomechanical systems (that is, their ability to store energy in resonant states for very long periods). One especially interesting case is silicon nitride: membranes made of this material exhibit dissipation mechanisms that are surprisingly reduced and the subject of much research. Building upon this earlier work with silicon nitride, Stephan Camerer from Ludwig Maximilians University, Germany, and colleagues report in Physical Review Letters their progress in achieving atomic-mechanical coupling.

One method to achieve such control, which has recently been widely explored, consists of coupling the mechanical motion parametrically to an optical or microwave cavity mode, a technique first envisioned by Braginsky. Indeed, optomechanical coupling allows substantial control of the mechanical oscillator state, including quantum-limited readout of its position and the preparation of the oscillator with very low residual thermal motion. The result is a mechanical oscillator that spends a significant fraction of its time in the quantum ground state. Despite the impressive progress made in cavity optomechanics these schemes are approaching but not quite at the level of control that can be attained in atomic physics. In a different experiment, O’Connell et al. used a microwave field to mediate the coupling of a superconducting qubit to a high-frequency piezoelectric mechanical oscillator, enabling the intriguing observation of the swapping of quantum states between the qubit and the oscillator.

More generally, coupling the mechanical device to a fully controlled quantum system appears to be a promising route. Among the many proposals for such hybrid quantum systems, experiments that use ultracold atoms as the quantum “handle” on the mechanics are particularly attractive. Theorists have put forward a number of proposals of how atomic systems—such as a trapped ion, atom, Bose-Einstein condensate (BEC), or atomic ensemble—could be coupled to a mechanical device.

In the group of Theodor Hänsch, Philipp Treutlein and his colleagues at Ludwig Maximilians University have pioneered the practical implementation of such proposals. Recently, they have demonstrated the coupling of a BEC to a micromechanical cantilever via surface forces. On their handy “atom-chips,” they managed to probe the motion of a micromechanical cantilever with a BEC approached to its surface. The oscillations of the cantilever caused a clearly discernable loss of atoms when it resonated with modes in the BEC; however, the backaction on the mechanical motion could not be observed. The backaction in this case is the force that the atoms exert via the light field on the mechanical oscillator; it is precisely this backaction that mediates the mutual coupling between the two systems.

In the new work reported by Camerer et al., this group accomplishes the feat of seeing the backaction (see Fig. by elegantly implementing atomic-mechanical control...
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about membrane’s mass exceeding the mass of all atoms by
oscillators have dramatically different masses, with the
atoms and a nanomechanical oscillator, consisting of a
50-nanometer, thin silicon nitride membrane mounted like a drumhead on a 0.5-millimeter silicon frame. These
oscillators have dramatically different masses, with the
membrane’s mass exceeding the mass of all atoms by
about 8 orders of magnitude. It is a surprisingly sim-
ple trick that allows coupling these two oscillators: The
optical standing wave that provides the atoms’ lattice
trapping potential is created by (partially) reflecting a
laser beam from the membrane instead of a fixed mir-
ror. From an experimentalist’s point of view, this is an
intriguing arrangement [13], as the light used for cou-
pling can be shuttled over a long optical path to connect
the two subsystems, which can consequently be held in
completely different environments.

But how does it work? In the first place, the standing
wave, in whose antinodes the atoms are held, moves along
with the membrane (Fig. 1). Therefore, if the membrane is
moving, a force is exerted on the atoms proportional to
the membrane’s displacement. At the same time, atomic
motion does act back on the membrane: By its very na-
ture, the optical trap forces each atom back to its equi-
librium position if it moves out of the trap center. Impor-
tantly, however, the origin of this force is a redistribu-
tion of photons between the running-wave components that
form the standing wave. As a consequence, the optical
power propagating towards the membrane is modulated,
and so is the radiation-pressure force on the membrane.
Indeed, if optical losses and the finite transmission of the
membrane are neglected, the forces experienced by the
displaced atom and the membrane are exactly equal in
magnitude, following the action-reaction principle.

The mutual coupling of membrane and atomic motion
resulting from these forces becomes particularly clear if
only the atomic center-of-mass mode—in which all atoms
move in unison in (ideally) identical trapping poten-
tials—is considered. The atomic motion and the mem-
brane’s displacement then form a pair of optically cou-
ped harmonic oscillators, with the coupling forces en-
hanced by the number N of atoms in the lattice.

In their study, the authors could detect this coupling
by investigating the damping induced upon the mem-
brane by the atoms. As the atoms are cooled by another
laser field (and additionally undergo dephasing), their
motion is damped at a much higher rate (130 kilohertz)
than the oscillations of the membrane (0.2 hertz). By
tuning the two oscillators into resonance (choosing the
appropriate optical power), an increase of the membrane
damping was clearly observed, following the expected lin-
ear dependence on the atom number N. A more elabo-
rate model, taking into account the finite temperature of
the atoms and the different trapping frequencies of atoms at different locations, could also fully reproduce
the damping measured when the trapping frequency is
tuned away from this degeneracy resonance.

In a second set of experiments, the researchers switched
off the laser cooling of the atoms, and the mechanical
mode of the membrane was excited by a piezoelectric
transducer. The resulting heating of the atoms—with exci-
tations of the center-of-mass mode quickly redistributed
among their motional degrees of freedom—was measured.
Again, resonant heating was observed when the “oscilla-
tors” were degenerate.

In future work, larger coupling would allow the full
quantum control made possible by the atoms, which can
be prepared in nonclassical states. Stronger coupling may
be realized by using more atoms, placing the membrane in
a cavity, or by using a different coupling arrangement,
which overcomes the scaling with the square root of the
mass ratio [11]. Moreover, the mechanical decoherence,
i.e., the rate at which one quantum is lost to the en-
vironment, can be reduced. This rate, given by the en-
ergy damping multiplied by the mean phonon occupancy,
can be decreased for silicon nitride by cryogenic precool-
ing. The remote coupling demonstrated by Camerer et
al. could be an enabling step in this context. It may then
become possible to fully exploit the quantum coherent
coupling between an atomic cloud and a micromechan-
ic oscillator, and allow quantum control of solid-state
systems.

References

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FIG. 1: A hybrid atom-nanomechanical interface used by
Camerer et al. [3]. The mechanical oscillator (a thin silicon
nitride membrane) is coupled to a cold atomic sample (right)
by an optical field. Importantly, the coupling via the standing
wave laser fields allows the researchers to entirely separate the
physical locations, which may prove highly versatile in future,
cryogenic experiments. (Adapted from S. Camerer et al. [3]).

DOI: 10.1103/Physics.4.97
URL: http://link.aps.org/doi/10.1103/Physics.4.97
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