OPTOMECHANICS

Push towards the quantum limit

Optomechanical set-ups use radiation pressure to manipulate macroscopic mechanical objects. Two experiments transfer this concept to the fields of superconducting microwave circuits and cold-atom physics.

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Johannes Kepler might have been the first to realize that light can produce mechanical effects. In his treatise *De Cometis* of 1619, Kepler suggested that the tail of a comet is deflected by the Sun's light. Today we know this is indeed true for the dust part of the tail, which points away from the Sun due to the radiation pressure. It took almost 300 years, however, until radiation-pressure effects were demonstrated in the laboratory, a feat first achieved at the beginning of the last century by Pyotr N. Lebedev and, independently, by Ernest F. Nichols and Gordon F. Hull.

One route to exploiting the tiny forces that light exerts on matter is to have them act on microscopic objects that are easy to push around. This has been done with great success in the field of optical atom cooling and trapping during the past twenty years. The effects can be increased by many orders of magnitude simply by introducing an optical cavity, where the light intensity is resonantly enhanced. In such a set-up, photons bounce around hundreds of thousands of times, each time transferring a small momentum kick to the end-mirrors. If one of those mirrors is attached to a flexible mechanical element — a cantilever, for example — it will start to move under the effect of the light-induced force (Fig. 1a). As soon as this happens, the light intensity also changes, as the incoming radiation is no longer in resonance with the optical mode. The resulting coupled dynamics of light and matter can be exploited to obtain both amplification and cooling of the mechanical motion.

Such cooling of macroscopic objects has been demonstrated recently in a series of remarkable experiments[1–7], giving rise to the field of optomechanics, which has joined nanoelectromechanical systems[8] in the race to cool a macroscopic object (such as a mirror with its many billions of atoms) down to the ground state of mechanical motion and perform quantum-coherent experiments. Such experiments would test quantum mechanics in a new regime and provide valuable insights into decoherence (and thus into the transition from the quantum regime to the classical world). Another, related, goal is to make ultrasensitive measurements, such as displacement detection or observing quantum jumps between single vibrational levels of a macroscopic object[7].

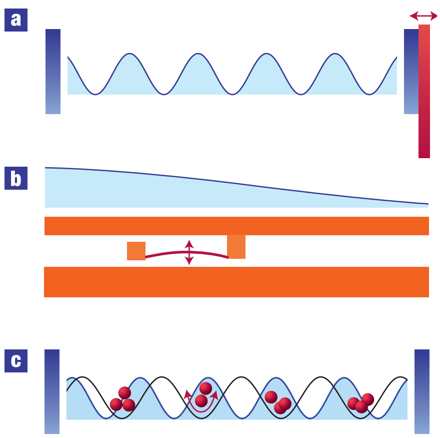

Figure 1 Approaches to observing mechanical effects of radiation. **a**, In the standard optomechanical set-up, light (represented as a blue wave) inside an optical cavity pushes against a mirror, mounted on a vibrating cantilever (red). **b**, The set-up of Regal *et al.*[9] uses a transmission-line microwave resonator instead of the optical cavity, with a capacitively coupled nanobeam. **c**, In the set-up of Murch *et al.*[10], the movable mirror is replaced by a cloud of cold atoms, vibrating in an optical lattice potential (black).

Two experiments reported in this issue now add new twists to this theme, and connect optomechanics to other research fields of current interest. Writing on page 555, Cindy Regal and co-workers[9] show how to replace the optical cavity by a microwave resonator on a chip. And on page 561, Kater Murch and colleagues[10] describe how the movable mirror can be substituted by a cloud of cold atoms trapped inside an optical lattice.

In the set-up developed by Regal *et al.*[9], a nanobeam is coupled capacitively to an on-chip transmission-line microwave resonator made from superconducting material (see Fig. 1b), such that the motion of the beam modulates the microwave resonance frequency — much in the same way that the optical resonance is shifted by the mechanical motion in the standard set-up (Fig. 1a). There are several advantages to the approach explored by Regal and colleagues. The on-chip assembly is easily cooled by standard bulk refrigeration techniques, and in principle the size of the mechanical resonator is no longer constrained to be larger than the wavelength of the radiation, unlike in optical experiments that work with reflection. In a first demonstration of their set-up[9], Regal *et al.* claim a near-record force sensitivity and a displacement uncertainty a factor of 30 above the standard quantum limit. (The quantum limit roughly corresponds to pinpointing the spatial coordinate down to the width of the ground state within one damping period, as dictated by the Heisenberg uncertainty principle.) In work performed since then[11], the same group has also shown radiation-induced cooling. One of the appealing prospects for such a set-up is to merge it with nonlinear circuit elements such as Josephson junctions or qubits, which have already been coupled to on-chip microwave resonators. These may afford sensitive measurements based on nonlinear techniques and offer a connection with quantum-information processing.

Murch *et al.*[10] stick with optical radiation, but they replace the mechanical element with a cloud of ultracold rubidium atoms. The atoms are trapped inside a fixed optical lattice made from a standing light wave in the cavity, where they vibrate independently in the troughs of the optical potential (see Fig. 1c). The cloud of atoms acts as a tenuous dielectric medium, and therefore the atoms' motion affects each optical resonance frequency of the cavity. The degree of these shifts depends on the detailed placement of the atoms with respect to the intensity maxima of a given optical mode. As a result, some properly chosen collective coordinate of the atomic cloud replaces the position of the end-mirror in the standard set-up. One of the benefits provided by this scheme is that there is no need to work hard to get to the ground state. In fact, in the direction along the cavity axis, the vibrational motion of the atoms is already in the ground state, at microkelvin temperatures. The atoms' vibrations have a rather low quality factor, but this is actually useful for observing measurement backaction, the central result of this work. These achievements point towards a potentially fruitful interplay of cold-atom physics with concepts known in nano- and optomechanics. Exciting avenues to be explored are the role of interatomic interactions (giving rise to truly collective modes) and the combination with atom-chip techniques.

Different as the two approaches[9,10] may be, they illustrate the rapid pace of progress in the young field of optomechanics. Breakthroughs such as cooling of massive objects to the ground state might, therefore, be just around the corner.

References

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KAVLI PRIZE

Science on all scales

How do you determine who does the best scientific research? For Fred Kavli — physicist, entrepreneur, philanthropist — the answer is clear: the most important science is that which benefits humanity. Established in 2000, the Kavli Foundation focuses on a few frontier areas of research that Kavli himself believes will make the largest impact on our quality of life. The Foundation funds endowed chairs as well as fifteen research institutes at top universities. And on 28 May 2008, the first recipients of the Kavli prizes in astrophysics, nanoscience and neuroscience were announced.

KAVLI FOUNDATION

On the smallest scale, the nanoscience prize went to Louis E. Brus of Columbia University and Sumio Iijima of Meijo University "for their large impact in the development of the nanoscience field of the zero and one-dimensional nanostructures in physics, chemistry and biology". Brus was working with colloidal suspensions of semiconductor particles when he noticed that the optical properties depended on their size and shape. These 'quantum dots' behave as artificial atoms with both fundamental and applied implications. Similarly, carbon nanotubes exhibit interesting physics and are useful for applications owing to their extraordinary strength. For his contribution to nanotube research, Iijima shares the nanoscience prize.

Further up the length scale is a single nerve cell, or neurone. In the human brain, each neurone is 'connected' to a thousand others, and there are 100 billion such neurones to coordinate. The circuitry is mind-boggling, but nonetheless, research has come a long way. Pasko Rakic of Yale University, Thomas Jessell of Columbia University and Sten Grillner of the Karolinska Institute were awarded the neuroscience prize "for discoveries on the developmental and functional logic of neuronal circuits". Rakic's work on neuronal development and Jessell's studies of neural circuitry have led to a framework for describing the assembly of neural circuits within the brain. Combined with the work of Grillner, mainly on the subtleties of motor coordination of nerve cells, we have a clearer understanding of the relationship between the structure and behaviour of the networks within the central nervous system.

Finally, at distances of billions of light-years from Earth are quasars. Through a small optical telescope, they are indistinguishable from local stars, and indeed, from their odd radio signals, they were considered to be 'quasi-stellar' objects in our Galaxy only fifty years ago. However, Maarten Schmidt of Caltech worked out that the spectrum of the quasar 3C273 only made sense if it was moving away at 47,000 km s^{-1} due to the expansion of the Universe. Consequently, it must be emitting 10^{12} times more energy than the Sun. The source of that power was eventually identified by Donald Lynden–Bell of Cambridge, building on the hypothesis of Edwin Salpeter and Yakov Zeldovich that quasars are powered by a central black hole. Lynden–Bell explained that the luminosity arose from frictional heating in the accretion disc surrounding a black hole. He also predicted that most massive galaxies harbour black holes, which has been verified. Schmidt and Lynden–Bell share the astrophysics prize for having "dramatically expanded the scale of the observable Universe [that has] led to our present view of the violent Universe in which massive black holes play a key role".

The three biennial prizes, jointly administered by the Norwegian Academy of Science and Letters, Norwegian Ministry of Education and Research, and the Kavli Foundation, each consists of a scroll, a medal and US$ 1 million. On 9 September 2008, the seven winners will collect their awards at the inaugural ceremony in Oslo, Norway. As public outreach is an important aspect of the Kavli prizes, the activities will include public-awareness lectures as well as scientific symposia.

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