[Strapline:] Quantum physics ***[OK as a strapline?]***

Feedback offers quantum control of nanoparticles

Measurement-based system provides quantum control of nanoparticles

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Precise measurements of the position of a levitating nanosphere have been used to control forces that damp the nanosphere's motion — potentially opening the way to quantum control of macroscopic objects. See p.XXX & YYY.

The uncertainty principle states that certain incompatible pairs of properties of a particle cannot be determined simultaneously with unlimited precision. It is often taught using a thought experiment: if the position of an atom is measured with light, the back-action of the scattered photons on the atom invariably disturbs the atom's momentum; the back-action can be reduced by using less-energetic or fewer photons, but this also reduces the precision of the measurement. More specifically, the Heisenberg uncertainty principle stipulates that the product of the uncertainties in measurements of position and momentum must be greater than or equal to half of Planck's constant. But this constant is so tiny (6.6 x10^{–34} joules per second) that the trade-offs between the back-action and imprecision can be observed only in carefully controlled experiments, typically using objects at the size scale of atoms. Whenever the product of uncertainties (not just for the position-momentum pair) attains the minimum we call them Heisenberg limited.

Writing in *Nature*, Magrini *et al.*[1] (page XXX) and Tebbenjohans *et al.*[2] (page YYY) report independent studies in which they were able to track the position not just of a single atom, but of a nanosphere that contains billions of atoms, with a precision close to the Heisenberg limit. This enabled them to use a technique called measurement-based quantum control to cool the nanosphere from highly excited thermal states down to average energies that are close to the quantum ground state of the particle — the state at which the nanosphere, were it a classical object, would come to a standstill. For the quantum case there is **always** a residual half quantum of motion called the zero-point motion as a quantum oscillator can never be perfectly still.

The results of the two studies are a breakthrough in optomechanics, the research field that aims to bring small mechanical oscillators into quantum regimes through their interaction with light. In the subfield of levitated quantum optomechanics, the oscillator is a silica particle about the size of a virus (100–200 nanometres in diameter), and is trapped and controlled by light. This minimizes both unwanted heating of the particle and decoherence

— the loss of the particle's quantum behaviour through interactions with the environment, a process that typically occurs much faster in experiments with oscillators directly tethered to their environment. After a decade of effort by several groups worldwide [3a,] cooling of a levitated nanoparticle by light to the quantum ground state was finally reported[3] in 2020. But that experiment relied on the quantum mode of light bouncing between two highly-reflective mirrors, a set-up known as an optical cavity. This approach comes with limitations -only narrow frequency ranges can be cooled in each setup— and technical difficulties- sufficiently controlled operation of an optical cavity to allow it to hold the particle stably and to cool it is challenging.

Magrini *et al*. and Tebbenjohanns *et al*. used a completely different approach, dispensing with the optical cavity, and thus evading the associated problems. Their technique might therefore offer a more robust and straightforward way to prepare quantum states of mesoscopic objects (between about 100 nanometres and a micrometre in size) in the future. The authors' approach is an extension of a method called termed feedback cooling, in which continuous measurement of an oscillator's position enables a force (the feedback) to be applied that counters and damps the oscillator's motion. Although feedback cooling has been extensively investigated, for some years there was considerable scepticism as to whether this approach alone, without cavity cooling, could reach the milestone result of cooling a levitated particle to an average energy that corresponds to less than single quantum of energy above the fundamental zero-point motion. The current studies both demonstrate that this milestone can indeed be reached in this way.

Several advances in have paved the way to this achievement. A feedback technique known as cold damping, which applies a force that is proportional to the velocity of the particle rather than to the particle's position, was shown in recent experiments [4a,4b] to yield highly efficient cooling. Importantly, the nanospheres are naturally charged, which means that the feedback force can be applied using an electric field[4], rather than light — thus avoiding extra photon back-action being exerted on the nanospheres. Moreover, the experimental set-ups in the two new studies operate at ultrahigh vacuum levels (about 10^{-12} of normal air pressure), largely eliminating heating of the nanosphere and decoherence associated with collisions with surrounding gas molecules. And both studies also benefitted from improvements in the efficiency with which scattered photons are collected to measure the position of the nanosphere[5].

Moreover, the two experiments employed a technique for measuring the energy of a particle [6] that is not only calibration-independent but is also a beautifully signature of the approach to the quantum regime: the spectra of the light scattered by the nanosphere have two peaks, one of which corresponds to the nanosphere absorbing a quantum of energy and the other to the particle losing one quantum; the precise ratio of the areas of the peaks corresponds to the ratio of n to n+1, where n is number of energy quanta of the nanosphere (n is 0 in the quantum ground state, for example). A version of this technique, often called sideband asymmetry, is used in optical-cavity optomechanics [3] but its applicability to experiments that use scattered light for measurements was not recognized until 2019 [6].

The recent LIGO expt did not show the above sideband asymmetry, that is visible for n<20 or so, although they claim n~11. So I emphasized the paragraph above.

There are also differences between the two experiments. Magrini *et al.* cooled their particle from room temperature, which corresponds to a state in which n is in the tens of millions, down to a measured average energy of n = 0.56 — which means that, although the particle is not exactly in the quantum ground state, it has more than a 50% probability of being in that state, and a sharply falling probability of being in successively higher quantum states (of n > 1). To achieve this cooling, they used a statistical algorithm called the Kalman filter[7] to optimize the feedback forces applied in real time to the nanosphere in response to a continuous measurement. The Kalman filter is especially well suited for controlling quantum systems that have states typical of mechanical oscillators[8].

By contrast, Tebbenjohanns *et al.* used a straightforward control system that relies on the harmonic (pendulum-like) nature of the nanosphere's motion to predict the velocity of the nanosphere from its measured position, and hence to drive the feedback force. They also immersed the trapped nanosphere in a cryostat that reduced the initial temperature from about 300 to 60 kelvin. This cryogenic cooling will fulfil a crucial function in future experiments: it will ensure that the internal temperature of the nanosphere is low, thus reducing the emission of thermal radiation from the nanosphere. Such radiation is a major source of decoherence, and can potentially be produced from the relatively hot interior of a nanosphere even when the centre-of-mass motion of the object is in the quantum ground state.

Measurement based control techniques similar to those employed here, coupled to the formidable precision possible with the huge 4 Km long optical cavities of the LIGO experiment -that can measure displacements a small fraction of an atomic nucleus- has now also enabled the strong damping of oscillations of a 10 Kg LIGO mirror to a little over n=10 quanta [9]. The big goal for the future is now to demonstrate quantum behavior with these cold oscillators whether levitated or not.

The optical trapping forces of the tweezer thus the degree to which they are tightly confined is fully controllable so that they may be guided in space or fully released. As they are highly decoupled from sources of decoherence they may retain their quantum coherence long enough to exhibit quantum wave interference effects. They may exhibit entanglement (what Einstein termed "spooky action at a distance"), possibly in experiments with multiple nanospheres. They could also be used as ultrasensitive force detectors, suitable for testing fundamental physics (such as quantum gravity), or for practical applications, such as accelerometry.

Hence this new generation of table-top optically levitated experiments are comparatively simple, less costly than LIGO and open up possibilities not available using tethered oscillators.

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