Strong coupling is a hallmark of light–matter interaction, resulting in a hybrid state that cannot be described by considering the light and matter components individually. For example, an optomechanical system enters the strong coupling regime when the light in an optical cavity exchanges quanta with the vibrations of a mechanical system faster than it loses energy to the environment. The dynamics of this joint system — whether classical or quantum — represents a hybrid of both phononic and photonic character. If, in addition, the exchange of quanta is faster than the decoherence time of the quantum dynamics, the system reaches a quantum coherent coupling regime, which allows the swapping of quantum information between the cavity field and the mechanical motion — at least in principle.

Writing in Nature Physics, Andrea Ranfagni and co-workers report that they have now attained regimes that are both quantum coherent and strongly coupled, using an optomechanical system comprising a single silica nanosphere levitated and tightly trapped in an optical tweezer trap within an optical cavity[1]. They achieved this by exploiting an idea pioneered by atomic physicists seeking to cool atoms by coherently scattering photons from a laser into a cavity[2]. Remarkably, the technique worked beautifully even for a silica sphere, yielding very strong light–matter coupling while minimizing decoherence. Although Ranfagni et al. did not explicitly investigate quantum coherent phenomena in quantum strong coupling regimes, their work demonstrates that it will in principle be possible.

In condensed-matter physics, this hybridization between phonons, excitons or other quasiparticle modes with the photons of a laser yields polariton states. In the cavity optomechanical experiment, the polariton label is used in analogy with the condensed-matter quasiparticle. In fact, the authors dub the motions 'vectorial polaritons' because the hybridization is not between light and the centre-of-mass motion of the nanosphere along a single axis (say, x in Fig. 1), but rather betweenthe light and the motion on an entire plane (x–y plane in Fig. 1). One of the first proposals for achieving quantum control using polarizable nanoparticles — about the size of a virus — trapped in an optical cavity sparked speculations that it might be possible to prepare living organisms in quantum superposition states[3]. Such exciting prospects launched a generation of experiments aimed at quantum optomechanical levitation. But technical bottlenecks slowed progress for years. A key problem was the need to operate at ultrahigh vacuum to avoid collisions with the background gas, the major source of heating and decoherence. In addition, the requirement for strong optomechanical coupling between light and matter necessitated high cavity photon occupancy numbers, achieved by driving the cavity with sufficient power, while stabilizing its field. The recoil from scattered photons also represented a source of noise. These deleterious effects led to particle heating, or worse, escape of the nanosphere from the cavity as the background gas was pumped out to achieve the vacuum conditions. After almost a decade of effort, the simple modification inspired by atomic physics experiments[2] offered the key breakthrough. It still relies on a tweezer-cavity set-up but the cavity is undriven. Instead, it is populated solely by photons scattered from the tweezer, so the standing wave in the cavity contains very few photons — provided the particle is placed at a node of the standing wave. The dipole forces arising from the interference between the tweezer and the cavity's standing-wave fields yields very strong optomechanical coupling rates, but in an almost empty cavity, which suppresses photon recoil heating: a little like a 'something for nothing deal'. Such coherent scattering set-ups were demonstrated in 2019[4,5] and in turn enabled the cavity cooling of a levitated nanosphere from room temperature (around 10^7 phonons) to very near the quantum ground state (phonon number below 1)[6].

Ranfagni and co-workers also used a coherent scattering set-up for their experiment, but with an intracavity field with an optical decay rate over three times slower than that previously used[6]. This modification allowed them to take the optomechanical motion into the strong coupling regime, even though the quantum cooperativities were somewhat lower than in the earlier set-up6. As a result, most mechanical motions remained a few quanta above the ground state (rather than below 1).

However, Ranfagni et al. then went one step further and coupled the intracavity field to the mechanical motion in the x and y directions by adjusting the polarization of the tweezer light. For all tweezer polarization angles except 0 and π/2, the experiments were affected by x–y hybridization, particularly if the coupling of the motion along one direction to the cavity field was strong enough to be quantum cooled. In this case, the other direction of motion, which was only weakly coupled, remained hot. This shows that motional hybridization must be considered in measurements of quantum cooling7. But what happens if both directions of motion reach the strong-coupling regime?

This is the case for polarization angles like π/4, which might cool the motion on the entire x–y plane to a quantum state. In fact, this regime yields a curious effect: the light-mediated hybridization leads to the formation of a dark mode that cannot be cooled and two bright modes that are a three-way hybridization of light and motion in the x and y directions. Such hybrid bright–dark modes have been observed in optomechanics with vibrational modes of membranes 8, but in classical regimes with little cooling. For a levitated particle, though, they are associated with a spatial directionality in the two orthogonal motions, which is especially interesting in the quantum regimes investigated here. This is why Ranfagni and co-workers call them vectorial quantum polaritons. This vectorial character might even have future applications in quantum sensing of weak forces or the generation of entangled states of motion, provided the problems that hybrid bright–dark modes pose to two-dimensional quantum cooling9 can be overcome. ❐

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