Vectorial polaritons in the quantum motion of a levitated nanosphere

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The strong coupling between photons and bosonic excitations in matter produces hybrid quasiparticle states known as polaritons⁴. Their signature is the avoided crossing between the eigenfrequencies of the coupled system illustrated by the Jaynes–Cummings Hamiltonian⁴. It has been observed in cavity optomechanics, polariton modes originate from the quantum-coherent coupling of a macroscopic mechanical vibration to the cavity radiation field⁴. Here we investigate polaritonic modes in the motion of an optically levitated nanosphere⁵–⁷ in the quantum-coherent coupling regime. The particle is trapped in a high vacuum by an optical tweezer and strongly coupled to a single cavity mode by coherent scattering of the tweezer photons⁸–⁹. The two-dimensional motion and optical cavity mode define an optomechanical system with three degrees of freedom. In the strong-coupling regime, we observe hybrid light–mechanical states with a vectorial nature. Our results pave the way towards protocols for quantum information transfer between photonic and phononic components and represent a step towards the demonstration of optomechanical entangled states at room temperature.

The optomechanical coupling between a mechanical resonator and the cavity mode of the electromagnetic field leads to the thermalization of the former towards the temperature of the photonic bath. For weak coupling, the system dynamics can be effectively described in terms of a mechanical oscillator at angular frequency \( \Omega_m \) and an optical oscillator at frequency \( -\Delta = -(\omega_l - \omega_c) \), given by the detuning between laser angular frequency \( \omega_l \) and cavity resonance \( \omega_c \). Each of these oscillators is characterized by its own damping rate: mechanical damping \( \Gamma_m \) for the former and cavity decay rate \( \kappa \) for the latter.

In the strong-coupling regime, that is, when coupling rate \( g \) exceeds the damping (namely, \( 4g > \Gamma_m, \kappa \)), the optical and mechanical modes can no longer be treated as separate entities and form hybrid optomechanical states⁴. The eigenfrequencies of the system, which, without any coupling, would be degenerate at \( \Delta = -\Omega_m \), undergo avoided crossing with the maximum separation at resonance equal to the vacuum Rabi splitting \( 2g \). As the cavity detuning is varied, they define spectral curves consisting of two branches with complementary asymptotic behaviour: photon-like behaviour at low detuning and phonon-like behaviour at high detuning for the upper branch, and vice versa for the lower branch.

When the optomechanical coupling is larger than the phononic thermalization rate (\( 2g > \Gamma_m \)), the swapping time—the time at which individual photons and phonons exchange their energy—becomes shorter than the decoherence time. In this case, quantum-coherent coupling between the optical and mechanical modes is achieved⁴,⁵, and the collective excitations of the system can be meaningfully described in terms of quantized polariton states. This regime has

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Characterized by two avoided crossings centered at different frequencies give rise to polaritonic modes whose spectral curves are modified due to the 2D dynamics of the particle. We remark indeed that here the two mechanical modes represent the orthogonal combination of strong three-body interactions, have not been observed in whispering gallery mode resonators and cavity electromechanical systems.

In our experiment, we achieve and investigate regimes where optomechanical polaritons may emerge from the quantum-coherent coupling between a cavity mode and the two-dimensional (2D) motion of an optically levitated nanosphere. Particle dynamics occur on the plane orthogonal to the tweezer axis and can be decomposed into two independent mechanical modes oscillating along perpendicular directions defined by the linear polarization of the tweezer field. A particular mixture of the two modes thus identifies the orientation of the Cartesian axes used to describe the particle motion. Owing to the optical spring effect, the oscillation frequencies are shifted towards degeneracy and the two oscillators become correlated even for weak optomechanical coupling.

In this case, the system can be conveniently represented in terms of alternative states, given by linear combinations of the original mechanical modes, which are respectively well coupled (bright mode) and weakly coupled (dark mode) to the intracavity field. As we shall see, when achieving the strong-coupling regime, such states give rise to polaritonic modes whose spectral curves are characterized by two avoided crossings centred at different frequencies. Similar curves, which provide unambiguous evidence of strong three-body interactions, have not been observed in optomechanical experiments.

In most quantum electrodynamics and optomechanical systems, the polarization of the cavity field plays a marginal role and polaritons are typically considered as scalar bosons. While polarization effects can be ignored even in our setup, the picture is deeply modified due to the 2D dynamics of the particle. We remark indeed that here the two mechanical modes represent the orthogonal components of particle motion. In contrast with most platforms, their linear superposition has, therefore, a clear physical meaning, representing a position vector that can be associated to a physical vibration direction on a plane. Due to the degeneracy of mechanical frequencies and the consequent strong correlation of modes, the 2D motion confers a kind of directionality to the associated phonons and—in the strong-coupling regime—a peculiar vectorial nature to the polariton field.

The nanosphere is positioned inside a nearly concentric Fabry–Pérot cavity (free spectral range, FSR = 3.07 GHz; linewidth, $\kappa/2\pi = 57$ kHz), orthogonal to the tweezer axis. A second, auxiliary Nd:YAG laser is frequency-locked to the optical cavity, and the tweezer laser is phase-locked to the auxiliary one with a controllable frequency offset equal to FSR $+$ $\Delta/2\pi$, thus accurately defining the detuning $\Delta$ of the tweezer radiation from cavity resonance. Light scattered by the particle on the cavity mode and transmitted by the output mirror is superimposed on a local oscillator beam, derived from the main Nd:YAG laser before launching it in the fibre, and shifted in frequency by $1.1$ MHz. The mixed beams are sent to a balanced detection unit to implement heterodyne measurement. The beat note between the local oscillator and scattered light allows the determination of location of the nanosphere inside the mode’s standing wave, and to place it on the optical axes, in correspondence of a node. In this position, the optical coupling between the particle motion and radiation field is due to the coherent scattering on the cavity mode and it is effective just for the projection of motion on the cavity axis (Supplementary Information provides additional details on the experimental setup).

The optomechanical coupling rates for the oscillations parallel ($Y$ direction) and perpendicular ($X$ direction) to tweezer polarization are $g_x = g \sin^2 \theta$ and $g_y = g \cos^2 \sin \theta$, where $\theta$ is the angle between the cavity and polarization axes. Our measured values are $\theta = 72^\circ$ and $g = 2 \times 30$ kHz. Gas damping rate $\Gamma_w$ is proportional to pressure $P$ (for a high Knudsen number, that is, below ~1 kPa); for our conditions (170-nm-diameter silica nanospheres in a pure nitrogen atmosphere), it is $\Gamma_w/2\pi \approx 10$ Hz $\times P$ (Pa). The coherent strong-coupling regime is expected to be achieved when $2g > \Gamma_w = \Gamma_{m} + \Gamma_{th}$, where $n_{th}$ is the mean occupation number of the thermal bath and $\Gamma_{m}$ is the decoherence rate in addition to gas damping.

In Fig. 2a, we show the spectra (high-frequency sideband) of the transmitted field when the pressure in the experimental chamber is about $6 \times 10^{-10}$ Pa, for varying detuning $\Delta$ of the tweezer light with respect to cavity resonance. The photonic component becomes evident for $-\Delta/2\pi = 160$ kHz, where the spectrum shows three peaks for one optical and two mechanical resonances. The $X$- and $Y$-mode peaks merge, forming dark and bright modes; at slightly smaller pressure, the two modes become degenerate due to the optical spring effect.
Fig. 3 | Spectra in coherent strong-coupling regimes. 

**a.** Area of the spectral peak corresponding to motion along the X direction (high-frequency sideband in heterodyne detection), measured for a tweezer light detuning of $-\Delta/2\pi = 260$ kHz as a function of background pressure. The spectra are normalized to the detection shot noise. The solid line shows the fit with a straight line, where the constant term is due to dipole scattering. The error bars reflect the statistical uncertainty (one standard deviation) on different consecutive time series. 

**b.** Spectra of the two motional sidebands, multiplied by the cavity filtering function $1 + \left(\frac{\Delta + \Omega}{\kappa/2}\right)^2$, acquired at $3 \times 10^{-5}$ Pa. The hot Y mode generates symmetric peaks around 118.7 kHz, while the broad peaks corresponding to the X mode show the expected asymmetry. 

**c, d.** Enlarged views of the heterodyne spectra for detuning values of $-\Delta/2\pi = 170$ kHz (c) and $-\Delta/2\pi = 100$ kHz (d), showing the narrow dark-mode and broad phonon-like polariton. The zero frequency is set at the difference between tweezer light and local oscillator (that is, 1.1 MHz). The spectra are normalized to shot noise, which was then subtracted, and a moving average with a width of 600 Hz is applied. Solid lines show the model prediction. The agreement in the area of the dark-mode peak between the experiment and theory, underlined by the moving average, indicates that no un-modelled extra force noise is present in this spectral region. On the low-frequency sideband, the dashed line shows the prediction in case of classical, symmetric noise spectrum, that is, the high-frequency sideband multiplied by $\frac{(\kappa/2)^2 + (\Delta - \Omega)^2}{(\kappa/2)^2 + (\Delta + \Omega)^2}$. 

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detuning, the bright mode strongly mixes with the photon field, forming hybrid modes, which are identified as polaritons in a quantum formalism (the following description will be used hereafter even if the quantum-coherent coupling is just reached at lower pressure). At $-\Delta/2\pi \approx 140$ kHz, we can clearly distinguish the photon-like polariton (on the high-frequency side of the dark-mode peak) and phonon-like polariton (on the opposite side). For $-\Delta/2\pi \approx 120$ kHz, both polaritons are almost equally composed of phononic and photonic components and, as we will see, the minimum occupation number is achieved. The corresponding resonances have a width of $\sim \kappa/2$ and are separated by $\sim 2\gamma$. Between them, we see narrow resonance attributable to the dark mode. For smaller detuning, the relative position of the photon-like and phonon-like polariton peaks are swapped.

The corresponding spectral curves are shown in Fig. 2b. The polaritonic branches are separated by an energy gap (attributable to an upper and lower avoided crossing) and asymptotically approach the correspondent-free mechanical frequencies. This situation is strongly reminiscent of phonon polaritons in ionic crystals, where the asymptotic frequencies are those of longitudinal and transverse optical phonons. Inside the gap, the curve of the dark mode occurs, similar to what is observed in the spectra of two-qubit states interacting with microwave photons.

The Hamiltonian of the three interacting oscillators (one optical and two mechanical) is

$$H = -\hbar \Delta a^\dagger a + \hbar \Omega_1 b_1^\dagger b_1 + \hbar \Omega_2 b_2^\dagger b_2 + \hbar g_1 (a^\dagger + a)(b_1^\dagger + b_1) + \hbar g_2 (a^\dagger + a)(b_2^\dagger + b_2),$$

(1)

where $a$ ($b_i; i=1,2$) denote the bosonic operators of the optical (mechanical) oscillators and $\Omega_i$ denote the mechanical angular frequencies. A quantum Langevin model is derived from the Hamiltonian by adding the input terms. In particular, for the mechanical degrees of freedom, we take into account coupling with the thermal bath by means of gas damping and heating due to the shot noise in dipole scattering, which is relevant in a high vacuum. From the Langevin model and the input/output relation for the transmitted field, we calculate the heterodyne spectra (Fig. 2), which display excellent agreement with the experimental data (Supplementary Information provides additional details on the theoretical model). Even if a direct measurement of the nanosphere motion is not possible, since we only have access to the strongly interacting optical meter, the agreement between theory and experiment justifies the assumption that the system is well modelled and consequently the trust in the theoretical calculations. The phonon occupation numbers for the $X$ and $Y$ mechanical modes are calculated from the integral of the respective displacement spectra, as produced by the model. The minimum values are achieved for a detuning of 120 kHz and are around 200 and 1,500, respectively. The coldest oscillation is not, however, along the $X$ direction, but at about $15^\circ$—close to the cavity axis, and its effective occupation number is as low as 100.

The effective temperature of particle motion is further reduced by decreasing the background pressure and consequently the gas damping. This is well characterized by the spectra at large detuning (for our purpose, it is set at $-\Delta/2\pi \approx 260$ kHz, where the peak of the $X$ mode remains clearly distinguishable. Its area linearly decreases with pressure in the mid-vacuum range (Fig. 3a); from the slope, we deduce $\Gamma_{\text{in}}/2\pi P = 13$ Hz Pa$^{-1}$, in agreement with expectation. In a high vacuum, pressure-independent decoherence terms become relevant, particularly the shot noise in the dipole scattering that is calculated to be $\Gamma_{\text{in}}/2\pi = 8.9$ kHz for the $X$ mode and 4.8 kHz for the $Y$ mode (ref. 45). The experimental data extend down to $3 \times 10^{-11}$ Pa without showing effects of possible technical noise (such as parametric heating or mechanical vibrations). This is also testified by the slight asymmetry in the motional sidebands (Fig. 3b), whose ratio for the $X$ mode is $0.96 \pm 0.01$, giving a phononic occupation number of $25 \pm 5$, which is in agreement with the value of $\sim 20$ calculated by taking into account gas damping and dipole light scattering. At this point, the optomechanical coupling rate $2\kappa_0 = 2\pi \times 54$ kHz well exceeds the total decoherence rate $\gamma_{\text{th}}/\Gamma_{\text{in}} = 2\pi \times 38$ kHz, in spite of the room-temperature operation.

By decreasing the detuning, the system fully enters the quantum-coherent strong-coupling regime. Around $-\Delta/2\pi \approx 130$ kHz, where the phonon-like and photon-like polaritons have similar strength in the output field, their spectral feature is too flat and close to the detection shot-noise level to provide reliable quantitative information. As a consequence, we focus here on two values of detuning, namely, $-\Delta/2\pi = 170$ and $100$ kHz, where the peaks of the phonon-like polariton are clearly visible at lower and higher frequency, respectively, with respect to that of the dark mode (Fig. 3c,d) and belong to different branches of the spectral curves. The asymmetry in the spectra of the motional sidebands is a signature of non-classicality. The phonon-like polariton is 78% (76%) phononic and 22% (24%) photonic at $-\Delta/2\pi = 170$ kHz (100 kHz). In the coldest direction, the inferred occupation number is 5.0 and 2.5, respectively (with an uncertainty of a few tens of percentages), and it decreases to $\sim 1.5$ for $-\Delta/2\pi \approx 120$ kHz. We notice that single-mode occupation numbers do not fully describe the thermal state of the system, which instead requires the complete correlation matrix. Even in view of applications to sensing, the usual definition of imprecision and back-action is not straightforward.

We finally comment on the perspectives opened by our results. We demonstrate regimes where quantum polaritons can form. The latter are a prerequisite for transferring quantum information between the photonic and phononic components. The dark mode—weakly interacting with both photonic field and (at low pressure) thermal bath—is suitable for its long-term storage. The system eigenfrequencies, when varying the detuning, display two avoided crossings, as typically observed in tripartite quantum systems. Notably, each avoided crossing acts as a quantum beam splitter of wavefunctions, driving an input quantum state into a coherent superposition of two output states evolving independently in time$^{46,47}$. Beam splitters are basic components to realize a number of quantum operations, such as entanglement$^{48}$ and teleportation$^{49}$. The realized system thus paves the way to novel protocols for the quantum-coherent control of phononic and photonic modes and represents a key step towards the demonstration of optomechanical entangled states at room temperature. Furthermore, phonon polaritons form a useful basis for developing nonlinear quantum optomechanics$^{50,51}$.

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Methods
We load a silica nanosphere (diameter, 170 nm) in the first vacuum chamber on the first optical tweezer mounted on the tip of a moveable rod. The trapped particle is then moved to the experimental chamber, where it is transferred to the second tweezer, formed by the light of a Nd:YAG laser delivered in a vacuum by an optical fibre. The photograph in Fig. 1c shows the nanosphere during transfer between the two tweezers. About 300 mW power is focused to an elliptical shape with waists of 1.02 and 0.93 μm, where the tighter focus occurs in the direction orthogonal to the axis defined by the linear polarization of the tweezer light. The corresponding typical oscillation frequencies of the nanosphere in the optical potential of the tweezer are 27 kHz (Z direction, along the tweezer axis), 120 kHz (Y direction, along the polarization axis) and 130 kHz (X direction). The second tweezer is mounted on a three-axes nanometric motorized linear stage. After the transfer, the moveable rod is retracted, the two chambers are isolated and the experimental chamber is pumped to a high vacuum.

Data availability
Source data are provided with this paper. All other data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Code availability
Codes to analyse the data and perform numeric calculations are available from the corresponding author upon reasonable request.

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Author contributions
F. Marin conceived the experiment. All the authors constructed the setup. A.R., P.V., F. Marino and F. Marin performed the experiment and analysed the data. F. Marino and F. Marin wrote the manuscript.

Competing interests
The authors declare no competing interests.

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