

Ultrastrong linear optomechanical interaction

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(Received 26 May 2023; accepted 19 September 2024; published 25 October 2024)

Light-matter interaction in the ultrastrong coupling regime can be used to generate exotic ground states with two-mode squeezing and may be useful for quantum-enhanced sensing. Current demonstrations of ultrastrong coupling have been performed in fundamentally nonlinear systems. We report a cavity optomechanical system that operates in the linear coupling regime, reaching a maximum coupling of $g_x/\Omega_x = 0.55 \pm 0.02$. Such a system is inherently unstable, which may in the future enable strong mechanical squeezing.

DOI: [10.1103/PhysRevResearch.6.L042025](https://doi.org/10.1103/PhysRevResearch.6.L042025)

Cavity quantum electrodynamics in the weak coupling regime, where the light-matter coupling is significantly weaker than other characteristic energy rates in the system, is one of the most well-studied areas of quantum optics. Most interactions are described remarkably well by applying the rotating-wave approximation that preserves only the number-conserving terms, resulting in the notable Jaynes-Cummings Hamiltonian [1]. Once the coupling rate g becomes comparable to the main transition frequency ω ($g \gtrsim \omega/10$), the quantum system enters the so-called ultrastrong coupling regime where the rotating-wave approximation fails to fully describe the system dynamics [2,3]. Perhaps the most interesting consequence is that the ground states of ultrastrongly coupled systems become entangled as the counter-rotating terms that create pairwise excitations now contribute significantly to the system dynamics [4–7]. To gain access to these exotic ground states, it is generally required to observe symmetry breaking of the quantum vacuum [8] or to instantaneously tune the coupling rate [9–11]. This has been challenging to implement in experiments that have demonstrated operation in the ultrastrong coupling regime [12–23]. As the coupling rate is further increased to above $g = 0.5\omega$, a quantum phase transition may occur [2,3]. At this point, the resulting nonclassical states of the quantum system become highly sensitive to external forces, which is why such systems have been proposed as a resource for critical metrology and quantum sensing [24–27]. Intrinsically nonlinear systems will recover stability for coupling rates $g > 0.5\omega$ as the nonlinearity raises eigenfrequencies to real and positive values [28,29]. In stark contrast, a purely linear system will remain unstable for larger coupling rates as one normal mode effectively evolves in an inverted potential [30]: the quantum state

grows exponentially fast and becomes extremely susceptible to external disturbances [31,32]. Exploiting inverted potential dynamics due to ultrastrong coupling has been out of reach of current experiments.

In this Letter, we demonstrate a purely linear system that operates in the ultrastrong coupling regime: an optically levitated nanoparticle coupled to an optical cavity via coherently scattered trapping light. We demonstrate full tunability of the coupling strength *in situ*, paving the way for quantum sensing protocols and novel quantum control techniques in levitated optomechanics that exploit the linear nature of the interaction.

Cavity optomechanics, where the cavity field interacts with the motion of a mechanical oscillator with a frequency Ω , is a well-known paradigm of light-matter interaction [33]. The standard cavity optomechanical interaction arises from the dispersive shift of the cavity resonance induced by the object motion. The shift of the cavity frequency effectively modifies the intensity of the driven cavity field, thus yielding a nonlinear optomechanical (“Kerr”) Hamiltonian that couples the number of photons in the cavity and the oscillator. In the weak coupling limit ($g \ll \Omega$), linearizing the interaction results in the parametric coupling rate $g \propto \sqrt{n_{\text{phot}}}$ that is enhanced by the intracavity photon number n_{phot} [34–36]. Optomechanical platforms have traditionally been designed to operate in the sideband resolved regime ($\kappa/4 < \Omega$) as it allows for ground-state cooling. In this case, by increasing the photon number one first achieves strong coupling ($g > \kappa/4$), which is required for coherent two-mode interaction [37–42]. Even stronger cavity drives are then required to reach ultrastrong parametric optomechanical coupling, where the linearized approximation breaks down [29]. The ultrastrong coupling has recently been realized in several dispersively coupled systems in the sideband resolved [19,22] and unresolved regime ($\kappa/4 > \Omega$) [18,43,44].

Somewhat surprisingly, optomechanics also allows for genuinely linear interaction by using optically levitated dielectric nanoparticles or atoms in a configuration where the polarizable object “coherently scatters” the trapping laser to drive the optical cavity from within [45–47]. In contrast to dispersive coupling, here the particle motion couples to the cavity

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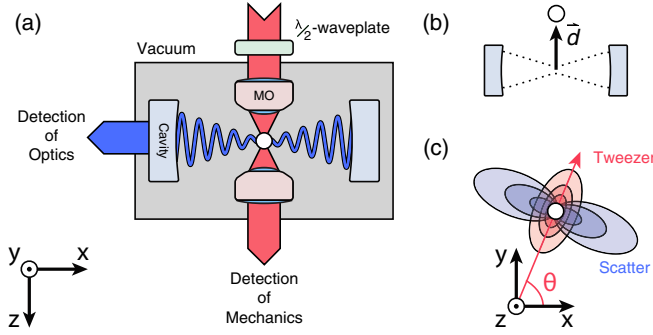


FIG. 1. Experimental setup for cavity optomechanics via coherent scattering. (a) A silica nanoparticle is trapped in an optical tweezer (propagating along the z axis, red) formed by a microscope objective (MO) inside the vacuum chamber. The particle scatters light into the empty cavity mode (oriented along the x axis, blue) to generate the optomechanical interaction. (b) The coupling rate can be changed by modifying the mean position of the nanoparticle $\vec{d}$ relative to the cavity waist with a three-axis nanopositioner on which the microscope objective is mounted. (c) The angle of the tweezer polarization relative to the cavity mode polarization θ can be used to modify the amount of the scattered light—and thus the coupling rate—by rotating the aforementioned $\lambda/2$ waveplate.

electric field, resulting in an inherently linear optomechanical Hamiltonian. This novel interaction mechanism has recently been used to cool a levitated nanoparticle to its motional quantum ground state in a room-temperature environment [48–50]. Furthermore, the possibility to simultaneously and independently tune the coupling rate and the mechanical frequency enables truly unique control techniques, which are of interest for thermodynamical studies [51–53], generation of strongly squeezed states beyond the 3-dB limit [54], or matter-wave interference [55,56]. Being of a fundamentally linear nature, the system Hamiltonian becomes unstable for $g > 0.5 \Omega$, which has recently been proposed in the context of strong mechanical squeezing [57] that enables increased force sensitivity and entanglement [31,32].

Theory. We consider a dielectric nanoparticle with a polarizability α and a radius r levitated in an optical tweezer given by the complex electric field amplitude $\vec{E}_{\text{tw}}$ and interacting with an optical cavity field $\vec{E}_{\text{cav}}$ (Fig. 1). As long as $r \ll \lambda$, where λ is the wavelength of the cavity mode of interest, one can simplify the optical interaction to the standard dipole interaction with the total electric field: $H_{\text{int}} = -\alpha |\vec{E}_{\text{tw}} + \vec{E}_{\text{cav}}|^2/2$ [45,47]. The interaction with the tweezer field $H_{\text{tw}} = -\alpha |\vec{E}_{\text{tw}}|^2/2$ is responsible for particle trapping, while the interaction with the cavity field $H_{\text{cav}} = -\alpha |\vec{E}_{\text{cav}}|^2/2$ leads to the standard dispersive coupling that is maximal at the slope of the cavity standing wave [58–60]. The interference term describes the coherent coupling of the tweezer and cavity fields: $H_{\text{coh}} = -\alpha \text{Re}(\vec{E}_{\text{cav}} \vec{E}_{\text{tw}}^*)$. We restrict our attention to the relevant motional degree of freedom along the cavity (x) axis and assume that the particle motion is well localized within a cavity standing wave period and that the particle is located at the cavity node, i.e., where the optomechanical coupling of the x motion is maximal. Under these conditions, the optomechanical Hamiltonian takes the following linear

form:

$$\hat{H}/\hbar = \Omega_x \hat{b}^\dagger \hat{b} + \Delta \hat{a}^\dagger \hat{a} + g_x (\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger). \quad (1)$$

Here, $\hbar$ is the reduced Planck constant, $\Delta = \omega_{\text{cav}} - \omega_{\text{drive}}$ is the detuning of the tweezer frequency ω_{drive} with respect to the cavity resonance ω_{cav} , Ω_x is the bare frequency of the mechanical oscillator, and $\hat{a}$ ($\hat{b}$) and $\hat{a}^\dagger$ ($\hat{b}^\dagger$) are the photon (phonon) annihilation and creation operators, respectively. The coupling rate $g_x(\vec{d}, \theta) = E_d(\theta) k x_{\text{zpf}} f(\vec{d})$ is a function of the drive $E_d(\theta) = \alpha \sqrt{\frac{\omega_{\text{cav}}}{2\hbar\epsilon_0 V_{\text{cav}}}} E_{\text{tw}} \cos(\theta)/2$, where V_{cav} is the cavity mode volume, θ is the angle set by the polarization of the tweezer field relative to the cavity field, x_{zpf} is the zero-point fluctuation, E_{tw} is the tweezer electric field and $f(\vec{d})$ is the cavity mode function at a position $\vec{d}$ relative to the central cavity node. In contrast to dispersive optomechanics, the coupling rate is independent of the intracavity photon number. Therefore, it remains constant irrespective of the detuning.

In our system, the coupling rate can be tuned in three possible ways: (i) by changing the particle position $\vec{d}$ with respect to the cavity axis [Fig. 1(b)], (ii) by turning the $\lambda/2$ waveplate outside the vacuum chamber to change the polarization angle θ and thus the amount of coherently scattered light into the cavity mode [Fig. 1(c)], and (iii) by adjusting the tweezer power, which also modifies the mechanical frequency. Furthermore, in dipole approximation, the coupling rate depends on the particle radius as $g_x \propto r^{3/2}$, while the mechanical frequency to the leading order depends only on the particle density [61]. We use only the first method in this work to avoid coupling other mechanical modes to the cavity and to minimize coupling by moving the particle far away from the cavity axis. However, the other two methods, in principle, allow for instantaneous tuning of the coupling rate and have been demonstrated elsewhere [45,46]. We consider the case where the nanoparticle is positioned at the central cavity node while allowing for displacement z_0 along the tweezer axis with $\vec{d} = (0, 0, z_0)$, in which case the dispersive interaction is negligible while the coupling due to coherent scattering is maximized. The particle position at the cavity node can be further optimized by minimizing the cavity output power [45].

For a red-detuned tweezer ($\Delta < 0$) and weak coupling ($g_x \ll \Omega_x$), it is common to simplify the interaction in Eq. (1) to keep only the terms $\hat{a}\hat{b}^\dagger$ and $\hat{a}^\dagger\hat{b}$ that preserve the total energy as the counter-rotating terms contribute weakly to the Hamiltonian. However, as g_x becomes comparable to Ω_x , the rotating-wave approximation is no longer valid as the perturbative approach fails. In the strong coupling regime ($g > \kappa/4$), the photonic and phononic modes hybridize, giving rise to so-called polariton modes with eigenfrequencies $\Omega_\pm$ and damping rates $\gamma_\pm$. In a linear system, a dynamical instability occurs when one normal mode acquires a negative spring constant (the eigenfrequency becomes imaginary), which is given by the following condition [61]:

$$\left(\frac{g_x}{\Omega_x}\right)^2 > \frac{1}{4} \left(\frac{\Delta}{\Omega_x} + \frac{\kappa^2}{4\Delta\Omega_x}\right). \quad (2)$$

In our experiment, the mechanical frequency is $\Omega_x \approx \kappa$; therefore, we operate in the sideband resolved regime. In this case,

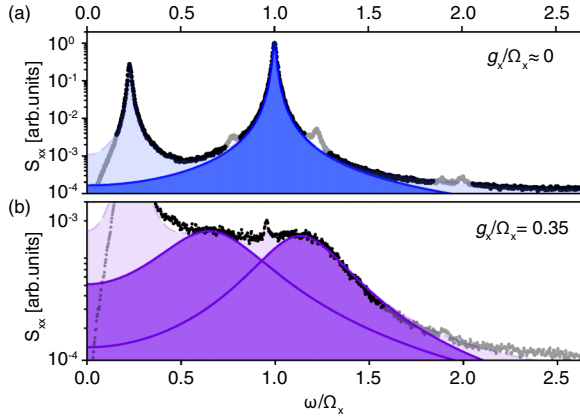


FIG. 2. Power spectral densities (PSD) $S_{xx}(\omega)$ (arb. units) of the mechanical motion obtained from the split detection. (a) The standard PSD of a thermal mechanical oscillator that is unaffected by the cavity. Two peaks corresponding to the z motion and the x motion are visible at $\Omega_z \approx 0.2 \Omega_x$ and Ω_x , respectively. We fit the full PSD (light blue shaded) to extract the relevant PSD of the x motion (dark blue shaded). (b) The mechanical mode exhibits normal mode splitting once the coupling is increased above $\kappa/4$. The full theoretical model (light purple shaded) is used to extract a coupling of $g_x/\Omega_x \approx 0.35$. The individual normal modes with frequencies $\Omega_{\pm}$ and dampings $\gamma_{\pm}$ are shown in dark purple. As the x motion is significantly cooled, a narrow peak corresponding to the y motion becomes visible at $\Omega_y \approx 0.95 \Omega_x$.

reaching the strong coupling regime automatically implies that we operate in the ultrastrong coupling regime as well as $g_x > \kappa/4 > 0.1\Omega_x$. The stability condition from Eq. (2) for the close-to-resonant detuning ($\Delta \sim \Omega_x$) is then simplified to $g_x > \sqrt{\Delta\Omega_x}/2$, which at the optimal detuning for cooling $\Delta \equiv \Omega_x$ yields $g_x/\Omega_x > 0.5$ [30].

Experiment. A schematic of our apparatus is shown in Fig. 1. A high-finesse Fabry-Pérot cavity (finesse $\mathcal{F} = 73\,000$, measured linewidth $\kappa = 2\pi \times (193 \pm 1)$ kHz, length $L = 1.07$ cm, waist $w_{\text{cav}} = 41.1$ μm) and a microscope objective (numerical aperture $\text{NA} = 0.8$) mounted on a three-axis nanopositioner (average step size ~ 8 nm) are mounted inside of a vacuum chamber [60]. The nanoparticle is trapped by an optical tweezer formed by focusing a laser beam (wavelength $\lambda = 1064$ nm, optical power $P_{\text{tw}} \approx 0.3$ W, waists $w_x = 0.79$ μm , and $w_y = 0.86$ μm) with the microscope objective, the focus of which is positioned close to the center of the cavity. A single nanoparticle with a nominal radius of $r = (105 \pm 2)$ nm (microParticles GmbH) is trapped with mechanical frequencies of $(\Omega_x, \Omega_y, \Omega_z) = 2\pi \times (190, 176, 42)$ kHz. In this work, we operate at a pressure of 4 mbar, where the mechanical dissipation $\gamma/2\pi \approx 3.4$ kHz is dominated by collisions with the background gas.

Normal modes. We perform spectroscopy on the cavity and tweezer optical modes to reconstruct the normal modes. Light from the cavity output is mixed with a local oscillator to perform a heterodyne measurement, which allows us to extract information about the hybridized optical mode. Furthermore, we recollimate the tweezer light after it has weakly interacted with the nanoparticle. This light can then be used in subsequent split detection to monitor all three mechanical

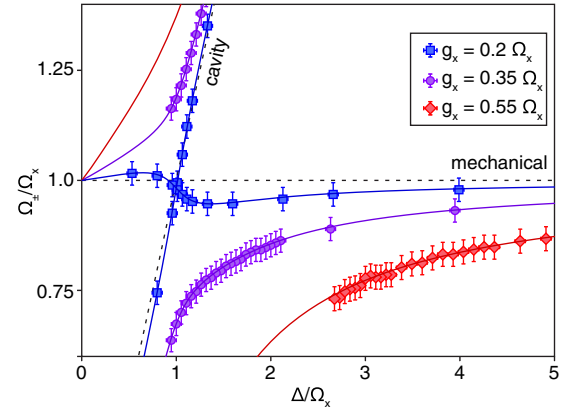


FIG. 3. Measured normal mode frequencies (markers) and fits (solid lines) as a function of detuning. The decoupled cavity and mechanical mode frequencies are shown as black dashed lines. We fit all markers from the same measurement set (markers with the same shape) with theory modeled with a single coupling rate [61], which yields lines in strong agreement with our measurement. For a weakly coupled system ($g < \kappa/4$), the modes repel one another but still cross. This phenomenon still occurs at $g_x/\Omega_x \approx 0.2$ (blue). As the coupling increases to $g_x/\Omega_x \approx 0.35$, the system enters the strong coupling regime for $g \geq \kappa/4$, at which point the mechanical and optical modes hybridize, giving rise to new normal modes of the coupled system (purple). As the coupling is increased to $g_x/\Omega_x \approx 0.55$, the splitting grows, and the lower eigenfrequency decreases significantly already for large detunings (red).

modes [61]. We simultaneously record time traces of the photocurrents from all detections, which we use to calculate the power spectral density (PSD) of the hybridized modes.

Figure 2 shows the appearance of normal mode splitting in the mechanical mode as we increase the coupling rate to $g_x > \kappa/4$. We first position the particle far away from the cavity mode where we do not observe coherently scattered light in the cavity output. For such weak coupling $g_x \ll \Omega_x, \kappa$, the cavity backaction is negligible; therefore, the spectral feature of the particle motion in the PSD takes the form of a simple thermal harmonic oscillator [Fig. 2(a)]. We then place the particle at a distance of $z_0 \approx 0.6w_{\text{cav}}$ away from the cavity axis and set $\Delta = \Omega_x$, at which point we observe normal mode splitting [Fig. 2(b)]. On its own, normal mode splitting clearly indicates that the system operates in a strong coupling regime. In the strong coupling approximation, the normal mode eigenfrequencies are symmetric around the intrinsic mechanical frequency Ω_x . However, we observe that the normal modes are shifted toward lower frequencies, as predicted from the full solution to the system dynamics [19,61]. We fit the spectra of the hybridized optical and mechanical modes to recover the normal mode frequencies [61]. We obtain the coupling of $g_x/\Omega_x = 0.35$, demonstrating that the system operates in the ultrastrong coupling regime.

Avoided crossing. We perform spectroscopy of the mechanical and optical modes as the detuning Δ is scanned towards the cavity resonance (Fig. 3). We jointly fit all PSDs in a detuning scan with a theory model with a single set of parameters to recover the coupling rate g_x [61]. For weak coupling ($g_x = 0.2\Omega_x$), the modes repel each other (“optical

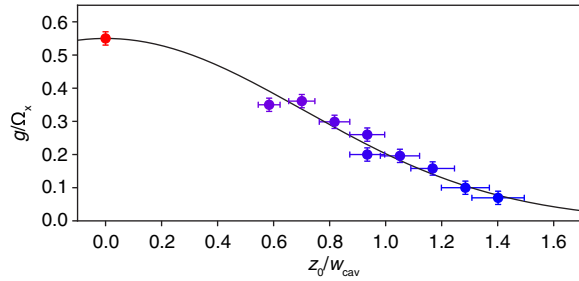


FIG. 4. Spatial dependence of coupling via coherent scattering. As the nanoparticle is displaced away from the cavity axis, the overlap between the dipole scatter and the cavity mode should decrease following the cavity waist. Measured coupling rates (circles) decrease as the particle is displaced away from the cavity axis. The solid line is theory normalized to the highest observed coupling (red circle).

spring”), but still cross as $g_x < \kappa/4$ (blue). As the detuning is tuned away from $\Delta/\Omega_x = 1$, the normal mode frequencies converge to the bare frequencies of the optics and mechanics (black dashed lines), in agreement with the theory. At a larger coupling rate ($g_x = 0.35 \Omega_x$), the system reaches the strong coupling regime as $g_x > \kappa/4$. The modes strongly hybridize, confirmed by the avoided crossing of the normal mode frequencies (purple). At an even larger coupling rate of $g_x \approx 0.55 \Omega_x$, the avoided crossing is more prominent (red). Loss of the particle occurs at a detuning of $\Delta/\Omega_x \approx 2.6$, far away from the expected unstable region. This has occurred for four particles at approximately equal detuning. We attribute this to small deviations of the particle position away from the cavity node, which has been observed due to the displacement of the tweezer relative to the cavity node [48], in addition to the still significant thermal motional amplitude. This leads to a partial population of the cavity mode and pulls the particle further toward the cavity antinode. Experimental stability at lower detunings can be realized with more careful placement of the particle at the cavity node. Although we were unable to probe the emergence of instability due to ultrastrong coupling in detail, we note that it is only required to instantaneously jump to the unstable detuning and back to far detuning to use unstable dynamics for squeezing [57].

Spatial dependence of coupling. We measure a maximum coupling of $g_x/\Omega_x = 0.55 \pm 0.02$ for the particle placed directly on the cavity axis. Displacing the particle by z_0 away

from the cavity axis maintains the form of the Hamiltonian to leading order and simply reduces the coupling as $g_x(z_0) \propto \exp(-z_0^2/w_{\text{cav}}^2)$ [61]. We characterize the spatial dependence of the coupling by performing detuning scans as a function of z_0 (Fig. 4). The actual particle position z_0 has been previously calibrated through a measurement of the dispersive coupling [60]. We normalize the theoretical value of $g_x(z_0 = 0)$ to the maximum measured coupling, which yields a good agreement with the measured coupling over the entire spatial profile of the cavity mode.

Conclusion and outlook. We have demonstrated linear ultrastrong coupling between the motion of a solid-state object and an optical cavity field in the resolved sideband regime. We have characterized the high degree of *in situ* tuning of the system parameters, which we use to explore our system in all relevant regimes of coupling: from weak over strong to ultrastrong coupling regime. We are able to recover the full system dynamics of the optical and mechanical modes by combining several detection schemes. This allows us to obtain a maximum coupling of $g_x/\Omega_x = 0.55 \pm 0.02$ for a particle with a radius of 105 nm. At this coupling rate, the system would exhibit a dynamical instability when $\Delta \approx \Omega_x$, a necessary requirement for quantum sensing protocols [27]. Using cavities with smaller mode volumes will increase the coupling by several orders of magnitude to $g_x/\Omega_x = 10^2$, which would result in strong mechanical squeezing by 30 dB due to unstable dynamics [57]. For coupling slightly below $g_x/\Omega_x = 0.5$ we expect ground-state cooling and optomechanical entanglement to exist simultaneously [6,7]. This will in the future allow for detailed studies of global master equations and thermodynamics in the presence of ultrastrong coupling [62,63].

Acknowledgments. We thank John Teufel, Peter Rabl, Louis Garbe, Fatemeh Bibak, and Anton Zasedatelev for valuable discussions. This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (Grant Agreement No. 649008 QLev4G and No. 951234 Q-Xtreme) and from the European Union’s Horizon 2020 research and Innovation Programme under Grant Agreement No. 101017733 (QuantERA II). We acknowledge support by the Austrian Science Fund (FWF) through doctoral school CoQuS (Project No. W1210), and by the ESQ Discovery Grant “Ultrastrong cavity optomechanics” of the Austrian Academy of Sciences.

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