Cavity Cooling a Single Charged Levitated Nanosphere

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Optomechanical cavity cooling of levitated objects offers the possibility for laboratory investigation of the macroscopic quantum behavior of systems that are largely decoupled from their environment. However, experimental progress has been hindered by particle loss mechanisms, which have prevented levitation and cavity cooling in a vacuum. We overcome this problem with a new type of hybrid electro-optical trap formed from a Paul trap within a single-mode optical cavity. We demonstrate a factor of 100 cavity cooling of 400 nm diameter silica spheres trapped in vacuum. This paves the way for ground-state cooling in a smaller, higher finesse cavity, as we show that a novel feature of the hybrid trap is that the optomechanical cooling becomes actively driven by the Paul trap, even for singly charged nanospheres.

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Light is an exceptionally flexible and precise tool for controlling matter, from trapping single atoms [1] to the optical tweezing of organic cells [2]. The laser cooling of atoms has led to the production of the Bose-Einstein condensate [3] and confinement in optical lattices [4], allowing the exploration of quantum physics. The control of nano- and microscale systems with light has enabled the study of mesoscopic dynamical and thermodynamical processes [5–7]. In recent years it has been possible to control the motion of nanoscale oscillators at the quantum level using light [8,9], which is of fundamental importance for the construction of quantum networks [10–13], and has enabled the generation of nonclassical states of light [14].

The creation of long-lived macroscopic quantum states of nanomechanical oscillators is challenging due to strong coupling with the environment. A mechanical oscillator, such as a nanosphere that is levitated in vacuum, minimizes the coupling to the environment [15]. The lack of clamping leads to potentially extremely high mechanical quality factors [16] ($Q \approx 10^{12}$) offering force sensing with exquisite sensitivity [17]. Active feedback cooling has achieved millikelvin center-of-mass temperatures [18,19]. In addition, the ability to change the properties of the oscillator by changing the levitating field and even to rapidly turn off the levitation offers the prospect of interferometry in the absence of any perturbations other than gravity [20].

Cavity cooling [21] has been used to cool atoms [22,23] and atomic ions [24], and it has been predicted that it will allow the cooling of larger particles to the center-of-mass quantum ground state [16,25,26]. The cooling of neutral nanoparticles transiting a cavity in vacuum [27] and trapped at 1 mbar [28] has been demonstrated.

We present a new method for cavity cooling charged nanoparticles, utilizing both the optical field of a cavity and the electric field of a Paul trap. Crucially, the Paul trap drives the cavity cooling dynamics by introducing a cyclic displacement of the equilibrium point of the mechanical oscillations in the optical field. This removes the need for a second optical cooling field [16,29]. In addition, the deep Paul trap potential avoids instabilities that have been observed in all-optical traps at low pressures [7,30] and allows us to operate in vacuum.

A schematic diagram of the hybrid electro-optical trap that combines both a Paul trap and an optical cavity dipole trap is shown in Fig. 1(a). The Paul trap is formed by two rounded electrodes separated by 1 mm that are enclosed by grounded cylindrical shields. This traps nanospheres of

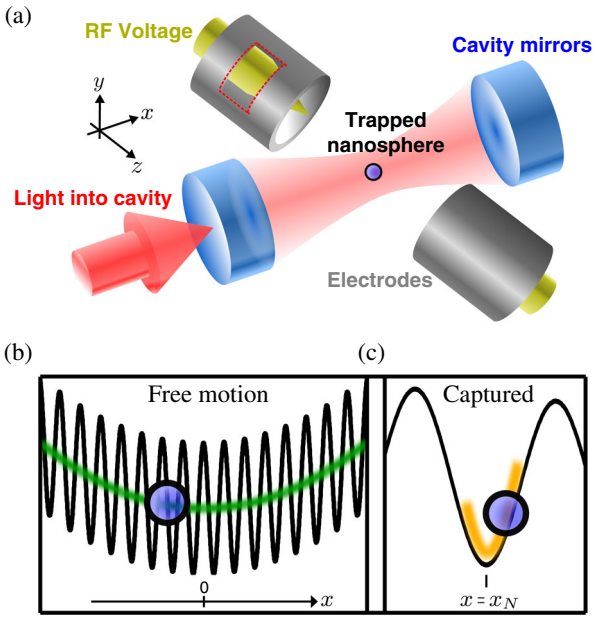

FIG. 1 (color online). (a) A schematic of the hybrid electro-optical trap, consisting of a Paul trap and standing-wave optical cavity potential, used to levitate and cool a charged silica nanosphere in vacuum. (b) The sphere is trapped by the Paul trap and driven across the standing wave formed by the light in the cavity, scattering light. (c) When cooled, the sphere is trapped by the optical field and confined to one fringe of the standing wave.

radius 209 nm, which typically have 1–3 elementary charges. An rf voltage of $V_0 \cos(\omega_d t)$ is applied to the electrodes; this has an amplitude of $V_0 = 300$–900 V and a frequency of $\omega_d = 2\pi \times 1500$ Hz. The intracavity field of a medium finesse ($\mathcal{F} \simeq 15\,000$) optical cavity passes through the middle of the Paul trap. The hybrid trap was placed within a vacuum chamber as shown in Fig. 2(a). The laser used to provide the trapping and cooling light is split into a strong and weak beam. The weak beam is used to lock the laser to the cavity via the Pound-Drever-Hall method, as illustrated in Fig. 2(b). The strong beam is used for cooling and trapping and can be arbitrarily shifted in frequency with respect to the cavity resonance.

The Paul trap potential for a nanosphere is approximated by $V(x, y, z, t) = \frac{1}{2} m\omega_T^2 (x^2 + y^2 - 2z^2) \cos(\omega_d t)$, where m is the mass of the nanosphere and $\omega_T^2 = (2qV_0)/(mr_0^2)$, with q the charge on the nanosphere, and r_0 a parameter setting the scale of the trap potential.

The optical cavity field creates a potential given by $V_{\text{opt}}(x, y, z) = U_0 \cos^2 kx e^{-2(y^2+z^2)/w^2}$ where the depth of the optical potential $U_0 = \hbar A |\alpha|^2$; here, $|\alpha|^2$ is the intracavity photon number and the coupling strength $A = (3V_s/2V_m)[(\epsilon_r - 1)/(\epsilon_r + 2)]\omega_l$ depends on the sphere volume V_s, the mode volume $V_m = \pi w^2 L$ (with $w = 140\ \mu$m the waist of the cavity field and $L = 3.7$ cm the length of the cavity), and the laser frequency ω_l. The optical potential gives rise to a mechanical frequency ω_M, which in the experiments is $\omega_M \simeq 2\pi \times 18$ kHz.

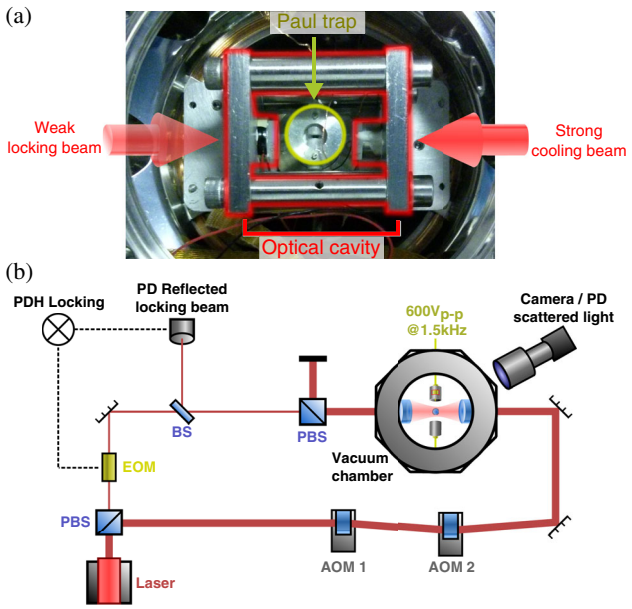

FIG. 2 (color online). (a) The experimental setup for trapping and cooling nanospheres. A Paul trap sits in the middle of an optical cavity. (b) Optical layout for cooling. A weak beam resonant with the optical cavity is used to stabilize the cavity through Pound-Drever-Hall locking. A much stronger beam which can be detuned from the cavity resonance is used for trapping and cooling. The light which the nanosphere scatters as it moves through the optical cavity field is collected and is used to characterize its motion.

We define two regimes of motion within the hybrid trap. Free motion refers to when the particle is driven across the optical standing-wave potential by the Paul trap [Fig. 1(b)], while captured motion corresponds to where the nanosphere is confined and oscillates within a single well of the standing wave [Fig. 1(c)], where most of the cooling takes place.

Near turning points of the Paul trap motion a small amount of damping can lead to the nanosphere losing enough energy to be captured by the optical potential within a well at $x = x_N$ [Fig. 1(c)]. Optomechanical damping occurs when the light is red detuned with respect to the cavity resonance. The damping occurs as the nanosphere oscillates across the periodic optical potential. This motion modulates the effective cavity length and periodically brings the cavity closer to resonance, increasing the intracavity power and thus the optical potential. Because of the decay time of light in the cavity the intracavity buildup is delayed with respect to the motion, which causes damping [25]. In the absence of the Paul trap field, the nanosphere is cooled towards an optical antinode. In this region, cooling is ineffective as the nanosphere's motion does not significantly modulate the cavity length. However, in our hybrid system, the additional force on the charged nanosphere by the Paul trap acts to periodically pull the particle away from the antinode, leading to enhanced cooling. The oscillation within the optical potential is therefore asymmetric around the bottom of the potential well as illustrated in Fig. 1(c).

To observe the cooling of a single particle, we measure the scattered light S as the nanosphere passes through the standing-wave field. This provides a measurement of particle position as a function of time. Free motion of the particle produces a rapid modulation as the particle moves through many antinodes of the standing-wave cavity field, as shown in Fig. 3(a). During free motion, the trajectory of the nanoparticle is well parametrized by the Paul trap secular $\omega_S \simeq \omega_T^2/\sqrt{2}\omega_d$ and micromotion frequency ω_d [see Fig. 3(b)], despite the addition of the optical field.

However, when a particle is captured and cooled, it oscillates around a single antinode and the time-averaged scattered light increases. A time series recorded for both free and captured motion is shown in Fig. 4, for two detunings from the cavity resonance. The red trace is taken for light that is red detuned and shows regions of increased intensity as the particle is captured in the standing-wave potential and is cooled. A similar trace for blue detuned light shows no capture, as this detuning leads to heating of the particle motion (see the Supplemental Material [31] for further details).

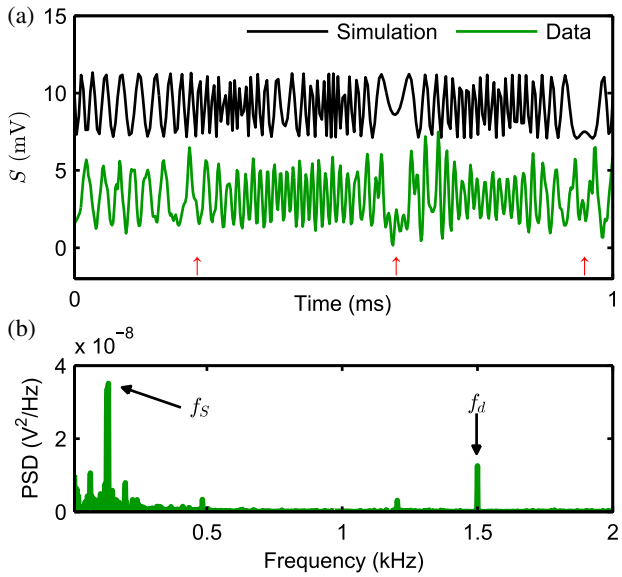

FIG. 3 (color online). Free motion in the Paul trap. (a) The scattered signal S (green trace), and a simulation (black trace, offset for clarity), as a nanosphere undergoes free motion. The nanosphere is driven across the optical standing wave, and the turning points of the motion are marked with arrows. (b) The power spectral density (PSD) of the nanosphere's motion during free motion shows the Paul trap secular frequency $\omega_S = 2\pi \times f_S$ and micromotion $\omega_d = 2\pi \times f_d$. The measurement of f_S allows readout of the charge, in this case just a single charge $q/e = 1$.

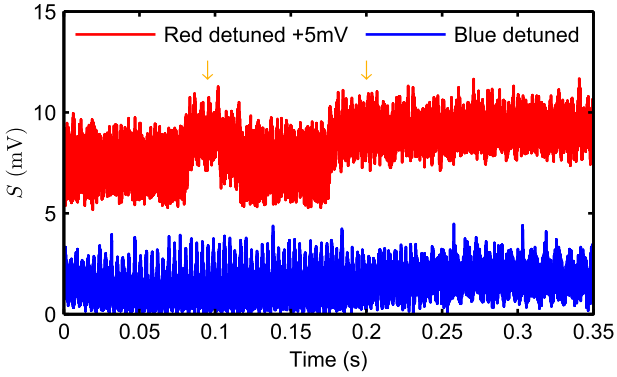

FIG. 4 (color online). The effect of detuning Δ from the cavity resonance on the nanospheres motion. Scattered light signal S from the nanosphere at a pressure of 7.4×10^{-3} mbar with $\Delta \simeq \pm\kappa$, where κ is the cavity linewidth. When the light is red detuned from the cavity resonance (upper red trace, signal offset for clarity), there are periods of free motion in the Paul trap and regions where the nanosphere is captured in the optical potential (marked with arrows), with a cooling rate depending upon the location within the optical standing wave. The nanosphere is not captured by the optical potential when the light is blue detuned from the cavity resonance (lower blue trace).

Figure 5(a) shows the capture and initial cooling process. In this trace, the initial rapid modulation is followed by a dip in intensity as the particle is trapped. The particle then starts to undergo a well defined motion in the optical well, showing period doubling as the Paul trap causes asymmetric oscillations about the optical antinode [as illustrated in Fig. 1(c)]. The period doubling is clear evidence that the Paul trap is modifying the dynamics within the optical potential, which is essential for efficient cooling.

To quantify the cavity cooling, we consider the motion of the nanosphere within one well of the optical potential $x'(t) = x(t) - x_N$. The mechanical frequency ω_M can be defined, which depends upon U_0 and x_N (see the Supplemental Material [31]). Since $\omega_M \gg \omega_S, \omega_d$, the motions due to the optical and Paul trap potentials are adiabatically separable; as $t \to \infty$, we approximate the motion along the optical axis by $x'(t) \sim X_d \cos(\omega_d t) + X_M^{\infty} \cos(\omega_M t)$.

The drive amplitude $X_d \approx (\omega_T^2/\omega_M^2)x_N$ is largely undamped. X_M^{∞} is the steady-state amplitude of the mechanical motion; initially, $X_M(t)$ decays as $\sim e^{-\Gamma_{\rm opt} t}$ but tends to a steady-state value determined by noise heating processes. By analyzing the Fourier spectrum of S due to $x'(t)$, one finds frequencies at $\omega_M \pm \omega_d$ with amplitude A_1 and a single peak at $2\omega_M$ with an amplitude A_2 (Supplemental Material [31]). Since the form of the signal is $S \propto \cos^2(kx)$, one can see that a large amplitude oscillation ($X_M^{\infty} \sim \lambda/2$) generates two maxima per period and, hence, an appreciable component at $2\omega_M$. In contrast, a small oscillation ($X_M^{\infty} \ll \lambda/2$) will generate only a single maximum per oscillation, thus, $A_1 \gg A_2$. The amplitudes of the Fourier peaks $A_{1,2}$ are related to the amplitude of the motion through $A_2/A_1 \to X_M^{\infty}/X_d$ for small amplitude oscillations. Hence, by analyzing the Fourier spectrum, the cooling rate of the nanoparticle's motion can be measured.

In Fig. 5(b), the Fourier spectrum of captured nanosphere motion is shown. At a pressure of 7.4×10^{-3} mbar (gray line) background gas damping $\Gamma_M \sim \Gamma_{\rm opt}$; hence, no cooling is evident and $A_2 > A_1$. At an order of magnitude lower pressure where $\Gamma_{\rm opt} \gg \Gamma_M$ (orange line), both the capture and subsequent cooling are dominated by optomechanical damping with a significant reduction in A_2.

For small oscillations, the cooling can be studied using the Hamiltonian [33] $\hat{H}_{\rm Lin}/\hbar = -\Delta \hat{a}^{\dagger}\hat{a} + (\omega_M/2)(\hat{x}^2 + \hat{p}^2) + g(\hat{a} + \hat{a}^{\dagger})\hat{x}$, where $\hat{x}$ is a small fluctuation (in units of $X_{\rm ZPF} = \sqrt{\hbar/2m\omega_M}$) about an equilibrium point x_0 and $\hat{a}$ is a fluctuation of optical field about the mean value α. The corresponding damping $\Gamma_{\rm opt}$ is then given by $\Gamma_{\rm opt} = g^2\kappa[\mathcal{S}(\omega_M) - \mathcal{S}(-\omega_M)]$ where $\mathcal{S}(\omega) = [(\Delta - \omega)^2 + (\kappa^2/4)]^{-1}$. Simulations with the full 3D nonlinear dynamics of the hybrid trap show that the above expressions are accurate provided one allows for the slow excursion in the equilibrium point, since $x_0 \equiv x_0(t) \simeq X_d \cos\omega_d t$ and the equilibrium point can be far from the antinode ($0 \le kX_d \lesssim \pi/2$). This consideration leads to an effective optomechanical

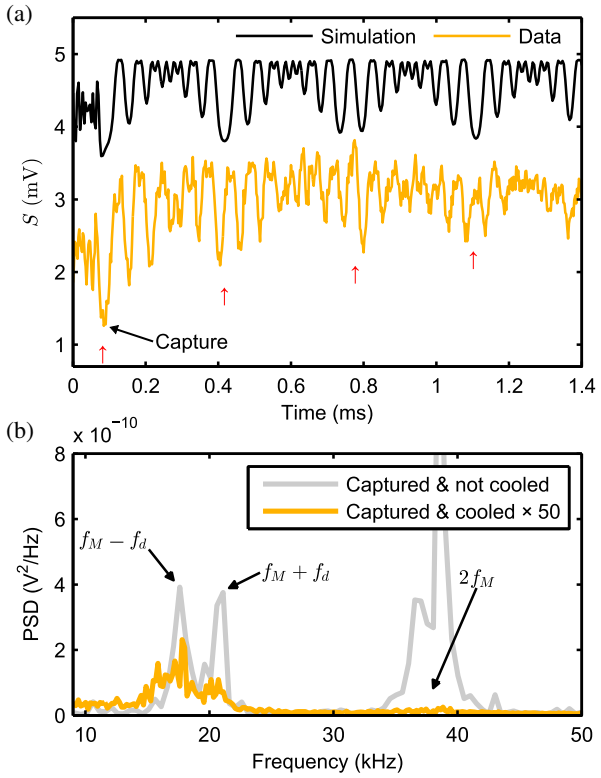

FIG. 5 (color online). Capture and optomechanical cooling of a nanosphere. (a) The scattered signal S from the captured nanosphere, at a pressure of 4.6×10^{-4} mbar, and a simulation of the process (offset for clarity). The mechanical motion is cooled, and the motion due to the Paul trap is still present (marked by arrows). (b) The PSD of the nanosphere's motion while captured by the optical field. At a low pressure of 4.6×10^{-4} mbar (orange line) the split mechanical frequency $f_M \pm f_d$ is visible, but the doubled frequency $2f_M$ is heavily suppressed, indicating cooling. At a higher pressure of 7.4×10^{-3} mbar (gray line), mechanical damping from the background gas dominates and the nanoparticle is not cooled, as shown by the unsuppressed peak at $2f_M$.

coupling $g^2 = [(\hbar k^2 A^2 |\alpha|^2)/(2m\omega_M)][1 - J_0(4kX_d)]$ (see the Supplemental Material [31]).

Using the experimental parameters for the data in Fig. 5(a) ($\mathcal{F} \simeq 15\,000$, $\Delta = 2\pi \times 288$ kHz, intracavity power $P = 14$ W, $\omega_S = 2\pi \times 100$ Hz), we find $\Gamma_{\rm opt} \approx$ 20–30 Hz, where the capture is at well position $N = kx_N/\pi \simeq$ 600–700. The expected equilibrium temperature $T_{\rm eq} \simeq (\Gamma_M/\Gamma_{\rm opt})T_B$, where here $T_B = 300$ K, and $\Gamma_M \simeq$ 1 Hz at 4.6×10^{-4} mbar pressure. This means that the motion of the nanosphere is cooled to ~10 K, which represents a factor of ~100 reduction in energy from the well depth U_0. This reduction in energy is consistent with the Fourier analysis of the peaks in Fig. 5(b), which shows a typical example of cooling that is observed in multiple trapping events.

The nanospheres are confined within an optical well for ~200 ms, far longer than the time needed to attain a steady-state temperature (of order 10 ms). They escape the optical potential since both the optomechanical coupling g and the optical potential U_0 are weak, and noise on the light field is sufficient to kick the nanospheres out of the well, a situation we have confirmed with simulations. Once the spheres are lost from the optical well they are recaptured by the Paul trap and returned to the cooling cycle. To solve the problem of loss from the optical potential, a higher finesse optical cavity can be used, with a smaller mode volume V_m, since $g^2 \propto V_m^{-2}$ and we can operate at the sideband-resolved regime $-\Delta \simeq \omega_M \gtrsim \kappa/2$, which yields maximum cooling, and the size of the optical potential $U_0 \propto V_m^{-1}$ is enhanced. For example, for a cavity with $\mathcal{F} = 100\,000$ and $w = 60$ μm, cooling rates of ~10 kHz are possible.

We have reached low temperatures with very low cooling rates of 30 Hz, and the introduction of a higher finesse optical cavity would greatly lower our final temperature. So far we have only discussed cooling in the x direction, along the optical axis. Our simulations show that cooling in the y and z directions can be achieved with the addition of a small angle between the coordinate systems of the optical and Paul trap fields.

In conclusion, we present a hybrid optical and quadrupole electric trap for both confining and optomechanically cooling charged levitated dielectric objects in high vacuum. Since the levitation is not by an optical field alone, light intensities that have been shown to melt silica nanospheres [7] do not have to be used. The system we present in this Letter is very suitable for cooling nanoscale objects to the quantum level; in principle, the only required modification is a higher finesse optical cavity. This work opens the way for the exploration of fundamental questions in quantum physics [34–36], and the development of macroscopic quantum technologies. Since Paul traps are used widely for the characterization of nanoparticles, our work introduces a powerful new tool for their manipulation and the damping of their motion.

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