Optomechanical Cavity Cooling of an Atomic Ensemble

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We demonstrate cavity sideband cooling of a single collective motional mode of an atomic ensemble down to a mean phonon occupation number $\langle n \rangle_{min} = 2.0^{+0.9}_{-0.3}$. Both $\langle n \rangle_{min}$ and the observed cooling rate are in good agreement with an optomechanical model. The cooling rate constant is proportional to the total photon scattering rate by the ensemble, demonstrating the cooperative character of the light-emission-induced cooling process. We deduce fundamental limits to cavity cooling either the collective mode or, sympathetically, the single-atom degrees of freedom.

Cavity cooling [1–5] is unique among laser cooling techniques in that it is applicable, in principle, to arbitrary scatterers of light. The energy spectrum of the scattered field—which governs the cooling dynamics and equilibrium temperature—is shaped by the cavity resonance rather than by the internal structure of the scatterer. Cavity cooling thus offers enticing prospective applications, from preparing ultracold molecular gases [6,7] to continuous cooling of qubit registers with far-detuned light [8]. In experiments to date [9–11], cavity cooling of one atom [9] or ion [10] is well-described by a semiclassical model [2,3]. In the case of an ensemble, the coupling of many particles to a single cavity mode can yield nontrivial collective dynamics [11–14], such as enhanced cooling of the center-of-mass motion [11].

Ensemble cavity cooling (Fig. 1) differs markedly from conventional laser cooling, where emission into a plethora of free-space field modes allows for simultaneous and independent cooling of all atoms, or equivalently, all motional degrees of freedom of the ensemble. In cavity cooling, a single collective motional mode $\mathcal{C}$ can be defined that is maximally coupled to the cavity [13], while all other ensemble modes are decoupled from the cavity due to destructive interference in the light scattering from different atoms. The coupling of $\mathcal{C}$ to the cavity is cooperatively enhanced by constructive interference in proportion to atom number [6,11], allowing $\mathcal{C}$ to be cooled faster—and to lower temperatures—than a single atom.

Pioneering experiments [13,14] have recently demonstrated that the cavity-coupled collective mode $\mathcal{C}$ can be studied using the concepts of optomechanics [15]. Indeed, the cooperative cooling of $\mathcal{C}$—in the limit of weak mixing with other ensemble modes—is equivalent to the single-mode cooling [15–17] of macroscopic mechanical oscillators [18,19] by radiation pressure. Compared with solid-state mechanical oscillators, the collective atomic oscillator $\mathcal{C}$ inhabits a different parameter regime—of low mass and correspondingly large zero-point length—that may facilitate observing the quantization of

mechanical energy [20]. Furthermore, the internal degrees of freedom in an atomic ensemble constitute an extra tool for manipulating the motional quantum state. The collective motion could, e.g., be squeezed by quantum state mapping from the ensemble spin [21].

To cavity cool the single-particle degrees of freedom in the ensemble, mixing between $\mathcal{C}$ and other motional modes may be introduced by an anharmonic or inhomogeneous trapping potential or by collisions. While such cooling has been the subject of significant theoretical studies, including detailed numerical modeling [4,5], experiments confirming the predictions are few.

In this Letter, we cavity cool and directly observe the relevant collective mode $\mathcal{C}$ of a trapped atomic ensemble. The rate constant of the cooling depends linearly on both photon scattering rate per atom and atom number, demonstrating that the cooling relies on the cooperative emission of light by the ensemble. Our results are well-described by adapting an optomechanical model [16] to our system, where the mechanical oscillator $\mathcal{C}$ has a very small mass $M \sim (10^{-23} - 10^{-21})$ kg, a frequency of 500 kHz (half the 1 MHz cavity linewidth), and a comparatively low quality
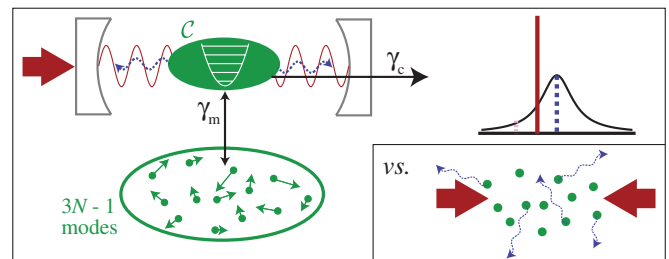

FIG. 1 (color online).   Ensemble cavity cooling. A probe laser (solid red lines) is placed at red detuning from cavity resonance to enhance anti-Stokes scattering into the cavity (dotted blue lines), which cools a single collective mode $\mathcal{C}$ (solid green oval) at a cooperatively enhanced rate γ_c. Single-particle modes can only be cooled by mixing (at rate γ_m) with $\mathcal{C}$. This differs from ordinary laser cooling (inset), where free-space emission causes the atoms to be cooled independently.

factor $Q = 19$. We verify the agreement with optomechanical theory for a wide range of collective-mode occupation numbers up to $\langle n \rangle \sim 10^3$ and we demonstrate cooling down to $\langle n \rangle_{\min} = 2.0^{+0.9}_{-0.3}$, close to the theoretical limit for our parameters.

The optomechanical interaction Hamiltonian H in our system arises from a position-dependent dispersive coupling of the atoms to the cavity mode. Formally, H describes the dipole coupling of N atoms with position operators $\hat{x}_i$ to light in a standing-wave cavity mode ("probe" mode, with wave number k and annihilation operator $\hat{a}$) at large detuning Δ from atomic resonance relative to the excited-state linewidth Γ. Adiabatic elimination of the excited state yields $H = \hbar\Omega\sum_{i=1}^{N}\sin^2(k\hat{x}_i)\hat{a}^\dagger\hat{a}$, where $\Omega = g^2/\Delta$—with vacuum Rabi frequency $2g$—represents the dispersive shift of the cavity resonance due to a single atom at an antinode, or equivalently, the ac Stark shift experienced by such an atom per intracavity photon. In our experiment, similar to Ref. [13], the atoms are trapped along the cavity axis in an optical lattice incommensurate with the probe mode. In the Lamb-Dicke regime, where the deviation $\tilde{x}_i \equiv \hat{x}_i - \xi_i$ of each atom from the local trap minimum at ξ_i satisfies $\langle(k\tilde{x}_i)^2\rangle \ll 1$, the Hamiltonian H can be written in terms of a single collective mode $\mathcal{C}$ of harmonic motion at the trap frequency ω_t [13], with position operator $\hat{X} \equiv N^{-1}\sum_{i=1}^{N}\sin(2k\xi_i)\tilde{x}_i$ [22]. In terms of $\hat{X}$,

$$H = \hbar\mathcal{G}\hat{X}\hat{a}^\dagger\hat{a}, \qquad (1)$$

where we have absorbed an overall shift $\delta\omega_N \equiv \Omega\sum_i\sin^2(k\xi_i)$ into the cavity resonance frequency. Equation (1) represents the canonical optomechanical interaction [15–17] describing an intensity-dependent force of strength $\hbar\mathcal{G} = N\hbar\Omega k$ per photon, or equivalently, a cavity frequency shift $\mathcal{G}\hat{X}$ proportional to $\hat{X}$.

For a probe laser detuned from the cavity line of width κ, small shifts $|\mathcal{G}\hat{X}| < \kappa$ yield proportional changes in intracavity and transmitted power. The $\hat{X}$-dependent transmission can be used to monitor mode $\mathcal{C}$, while the $\hat{X}$-dependent changes in intracavity intensity—delayed by the cavity response—induce either cavity cooling or its reverse process, loosely termed cavity heating: specifically, the delay converts the position dependence into a velocity dependence of the force on the atoms, which either damps or coherently amplifies the collective motion depending on the sign of the laser-cavity detuning [2,3].

Viewed in the frequency domain, the dissipative process arises from unequal scattering rates on the Stokes and anti-Stokes sidebands due to the cavity resonance [3]. The full optomechanical Hamiltonian [16], with the interaction term given by Eq. (1), predicts a cooling power

$$P_c = N\Gamma_{\mathrm{sc}}\eta E_r\zeta[\langle n\rangle|\mathcal{L}_+|^2 - (\langle n\rangle + 1)|\mathcal{L}_-|^2], \qquad (2)$$

for a mean occupation number $\langle n\rangle$ of mode $\mathcal{C}$; here, $\Gamma_{\mathrm{sc}} = \langle a^\dagger a\rangle\Gamma g^2/\Delta^2$ is the photon scattering rate of a single atom

at a probe antinode into free space, $\eta = 4g^2/(\kappa\Gamma)$ the cavity-to-free-space scattering ratio (single-atom cooperativity) [3], $E_r = \hbar^2 k^2/(2m)$ the recoil energy for atomic mass m, $\zeta = N^{-1}\sum_i\sin^2(2k\xi_i)$, and $\mathcal{L}_\pm^{-1} = 1 \mp 2i(\delta \pm \omega_t)/\kappa$, where δ is the probe-cavity detuning. In our experiments, where the atomic cloud is long (≈ 1 mm) compared to the 5-μm beat length between trap and probe light, $\zeta = 1/2$. For $\omega_t \gtrsim \kappa/2$, the cooling rate is maximized by placing the anti-Stokes sideband on resonance, $\delta = -\omega_t$. Equation (2) indicates a collective rate constant $\gamma_c = dP_c/d(\langle n\rangle\hbar\omega_t)$ that is proportional to N due to cooperative scattering: the larger the ensemble, the faster $\mathcal{C}$ is cooled.

We study the cooling in a symmetric near-confocal optical cavity with linewidth $\kappa = 2\pi \times 1.01(3)$ MHz at the wavelength $2\pi/k = 780$ nm of the ^{87}Rb D_2 line, mode waist $w = 56.9(4)$ μm, and cooperativity $\eta = 0.203(7)$. We trap 10^2–10^4 atoms of ^{87}Rb in the state $|5^2S_{1/2}, F = 2, m_F = 2\rangle$ in the cavity mode in a standing wave of 851-nm light, with trap frequency $\omega_t/(2\pi) = 480(40)$ kHz and typical trap depth $U_0/h = 18(3)$ MHz. A σ^+-polarized 780-nm probe laser drives the cavity on a TEM$_{00}$ mode at a detuning $\Delta/(2\pi) \gtrsim 70$ MHz from the $|5^2S_{1/2}, F = 2\rangle \rightarrow |5^2P_{3/2}, F' = 3\rangle$ transition with linewidth $\Gamma = 2\pi \times 6.1$ MHz. The atom number N is measured via the average cavity shift $\delta\omega_N$ [22]. To perform cavity cooling or heating, we detune the laser by $\delta = \mp\kappa/2 \approx \mp\omega_t$ from cavity resonance, simultaneously probing the position $\hat{X}$ via the transmitted light. Note that we work with blue light-atom detuning $\Delta > 0$, where free-space scattering results in Doppler heating.

We first verify cavity heating of mode $\mathcal{C}$ by choosing the probe-cavity detuning $\delta = +\kappa/2$. Suddenly turning on the probe light triggers a collective oscillation that is rapidly amplified by parametric instability (inset to Fig. 2). After typically 10 μs of this heating, we switch to cavity cooling
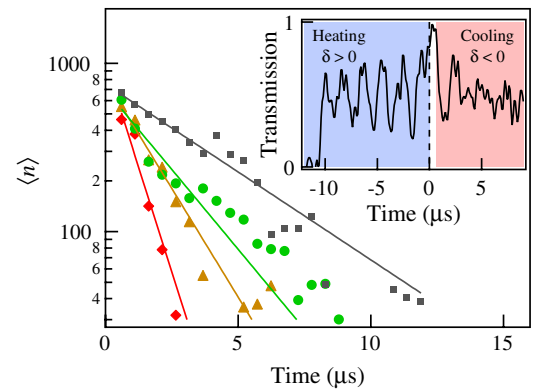

FIG. 2 (color online).   Mean occupation number $\langle n \rangle$ of mode $\mathcal{C}$ vs time during cavity cooling at $\Gamma_{\mathrm{sc}} = 1.1 \times 10^5$ s^{-1} (gray squares), 2.3×10^5 s^{-1} (green circles), 3.4×10^5 s^{-1} (gold triangles), and 6.4×10^5 s^{-1} (red diamonds). Each data set is obtained by averaging variances from 10 traces. Inset: single trace of cavity transmission during cavity heating ($t < 0$, blue background) followed by cooling ($t > 0$, red background).

at $\delta = -\kappa/2$. The mean occupation number $\langle n \rangle$ of $\mathcal{C}$ is obtained from the observed time trace of the transmitted photon rate R via the fractional variance $\sigma^2 \equiv \overline{R^2}/\bar{R}^2 - 1$ in a sliding 2-μs window. The linear approximation $X \propto R - \bar{R}$ gives the relation $\sigma^2 - \sigma_{bg}^2 = 8(\mathcal{G}X_0/\kappa)^2|\mathcal{L}_+ - \mathcal{L}_-|^2\langle n \rangle$, where $X_0 = \sqrt{\hbar\zeta/(2Nm\omega_t)}$ and σ_{bg}^2 is a constant technical-noise offset [22]. Figure 2 shows $\langle n \rangle$ vs time at four different probe powers, with fixed atom number $N = 2800(400)$ and detuning $\Delta/(2\pi) = 140$ MHz from atomic resonance. The cooling is well-described by an exponential decay with rate constant γ_{exp} that depends on the probe power. Consistent values of γ_{exp} are obtained by fitting exponentially decaying sinusoids to averaged transmission traces.

To compare γ_{exp} to the predicted cooling rate constant γ_c, we measure the dependence of γ_{exp} on the photon scattering rate $\Gamma_{sc} = \bar{R}\eta\Gamma^2/(2\Delta^2)$ per atom into free space for various probe-atom detunings Δ and atom numbers N. As Fig. 3(a) shows, the data are consistent with a linear model $\gamma_{exp} = f(N)\eta\Gamma_{sc} + \gamma_m$. The offset $\gamma_m = 1.6(6) \times 10^5/$s indicates a quality factor $Q = \omega_t/\gamma_m \approx 19$ for mode $\mathcal{C}$, largely attributable to mixing with other motional modes in the anharmonic trapping potential. Note that our system allows cavity cooling at very low Q compared to solid mechanical oscillators [18,19] because the "thermal bath" comprising the other $3N - 1$ ensemble modes has a sub-mK temperature.

To verify the cooperative nature of the cavity cooling of mode $\mathcal{C}$, we plot in Fig. 3(b) the fitted slopes $f(N)$ as displayed in 3(a) vs atom number N. Accounting for the slight ($< 20\%$) reduction of the cooperativity η due to atomic absorption, the measured dependence $d\gamma_{exp}/d(\eta\Gamma_{sc}) = 3.4(5) \times 10^{-3}N$ agrees well with the prediction from cavity cooling $\gamma_c/(\eta\Gamma_{sc}) = 3.0(2) \times 10^{-3}N$. This confirms that the collective-mode cooling speed

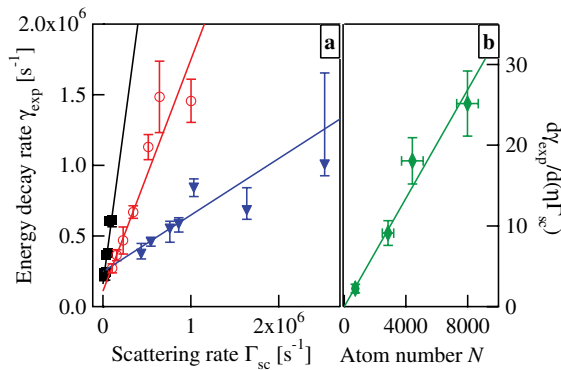increases linearly with ensemble size and is proportional to the total power scattered by the ensemble into the cavity.

To determine the equilibrium temperature of $\mathcal{C}$ under cooling, we require—given our detection noise—a longer observation time than shown in Fig. 2. We therefore observe the cooling or (for comparison) heating in spectra obtained from 150 time traces of the cavity transmission, each 440-μs long, with $\bar{R} = 1.2(2) \times 10^9$ s^{-1}. Figure 4 shows normalized one-sided spectral densities $S_I/\bar{I}^2$ of photocurrent $I \propto R$ with (a) $N = 230(50)$ and (b) $N = 450(90)$ atoms at a detuning $\Delta/(2\pi) = 70$ MHz from atomic resonance. Each spectrum displays a peak at ω_t with an area approximately proportional to both atom number N and mean occupation number $\langle n \rangle$. The disparity in area between cooling and heating increases with N due to the cooperative nature of the processes.

We fit the spectra in Fig. 4 with a quantum mechanical model (black curves) adapted [22] from Ref. [16]. The model $S_I/\bar{I}^2 = S_{mech} + S_{bg}$ contains the signal $S_{mech} \approx (2\mathcal{G}/\kappa)^2|\mathcal{L}_+ - \mathcal{L}_-|^2 S_X$ arising from atomic motion with spectral density S_X, and a background S_{bg} (gray curves) that is dominated by electronic photodetector noise but also accounts for photon shot noise, slightly smaller fluctuations from laser phase noise, and frequency-dependent correlations between light noise and atomic motion. These last are responsible for the dips in S_{bg} below the white noise [19]. With the photon rate $\bar{R}$ and optomechanical coupling $\mathcal{G}$ constrained to their independently measured and calculated values, the cooling spectra are well fit by taking the collective mode to be coupled to a white Markovian bath with $\langle n_{bath} \rangle = 3.1(4)$ motional quanta per mode; the corresponding coupling rate $\gamma'_m = 2.6(1.1) \times 10^5$ s^{-1} is consistent with the mixing rate γ_m from Fig. 3. Fits to the heating spectra, complicated by sympathetic heating of other modes, indicate a higher mixing rate of $4.8(5) \times 10^5/$s.

FIG. 3 (color online). Collective cooling rates. (a) Energy decay rate γ_{exp} vs scattering rate Γ_{sc} for: $N = 8000(700)$, $\Delta/(2\pi) = 270$ MHz (solid black squares); $N = 2800(400)$, $\Delta/(2\pi) = 140$ MHz (open red circles); $N = 700(200)$, $\Delta/(2\pi) = 70$ MHz (solid blue triangles). Lines are fits to data. (b) N dependence of cooling rate normalized to single-atom scattering rate into cavity.
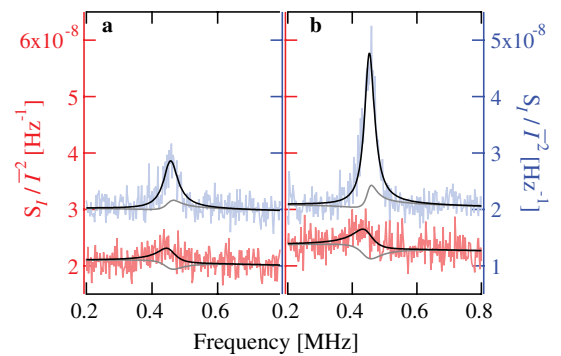

FIG. 4 (color online). Spectra of fractional transmission fluctuations $S_I/\bar{I}^2$ taken with (a) $N = 230(50)$ atoms and (b) $N = 450(90)$ atoms during cavity cooling at $\delta = -\kappa/2$ [lower (red) traces, left axis] or heating at $\delta = +\kappa/2$ [upper (blue) traces, right axis]. Black curves are fits; subtraction of the background level S_{bg} (gray curves) yields collective-mode occupation $\langle n \rangle^{\pm}$ at $\delta = \pm\kappa/2$: (a) $\langle n \rangle^+ = 4.4 \pm 0.7$, $\langle n \rangle^- = 2.3^{+0.7}_{-0.3}$; (b) $\langle n \rangle^+ = 7 \pm 1$, $\langle n \rangle^- = 2.0^{+0.9}_{-0.3}$.

The bath occupation is consistent with a measured upper bound on the axial temperature of 150(50) μK, corresponding to $\langle n_{\text{bath}} \rangle = 6(2)$ [22]. The white spectrum of n_{bath} is a simplistic ansatz but helps to establish the background S_{bg} and thus the motional spectrum S_X. By subtracting S_{bg} from the measured spectrum, we obtain a minimum mean occupation number of $\mathcal{C}$ of $\langle n \rangle_{\text{min}} = 2.0^{+0.9}_{-0.3}$ with $N = 450(90)$ atoms. Note that failing to account for the dip in S_{bg} would underestimate $\langle n \rangle_{\text{min}}$.

We now consider limits to cooling the collective mode. For $\gamma_c \gg \gamma_m$, the cooling power $P_c \propto N\eta$ competes only with the N-independent recoil heating $P_{\text{rec}} \approx E_r\Gamma_{\text{sc}}$ of $\mathcal{C}$, yielding a fundamental limit $\langle n \rangle \gtrsim n_0 + D(1 + n_0)/(N\eta)$, where $n_0 \equiv (\kappa/4\omega_t)^2$ and D is a prefactor of order unity [3]. Thus, for large collective cooperativity $N\eta \gg 1$ (easy to achieve), the resolved-sideband regime $n_0 < 1$ allows, in principle, ground-state cooling [3,16,17] of $\mathcal{C}$. The thermal heat load from other modes mixing at rate γ_m with $\mathcal{C}$ then sets the limit $\langle n \rangle \gtrsim \langle n_{\text{bath}} \rangle \gamma_m/(\gamma_m + \gamma_c)$. While this limit improves with increasing cooling rate γ_c, for the values $(\omega_t, \kappa, Q = \omega_t/\gamma'_m)$ in Fig. 4 amplification of low-frequency noise on approaching the regime of static bistability $\gamma_c \gtrsim \omega_t^2/\kappa$ [16] sets a bound $\langle n \rangle \gtrsim 1.5$, even though $n_0 = 0.3$.

A low occupation $\langle n \rangle$ of $\mathcal{C}$ is disadvantageous for cooling the individual atoms, since the absolute cooling power is proportional to $\langle n \rangle$ [see Eq. (2)]. Cooling of all degrees of freedom is thus facilitated by strong mixing $\gamma_m \gg \gamma_c$ that keeps $\mathcal{C}$ in thermal equilibrium with the other $3N - 1$ modes. The cooling power per atom P_c/N then approaches that of an isolated atom. Thus, even in an ensemble, recoil heating sets a limit for the temperature of individual atoms $\langle n_i \rangle \gtrsim n_0 + 1/\eta$ that depends on the *single-atom* cooperativity η: ground-state cooling requires $\eta > 1$ [3]. Whether the same result holds in other cooling geometries, e.g., with transverse pumping [5,6,23], is under investigation [23].

Even for $\eta < 1$, ground-state cooling of $\mathcal{C}$ alone—in future experiments deeper in the resolved-sideband regime—may enable the preparation of nonclassical motional states [18,21]. Further, the sensitive detection demonstrated here for $\hat{X}$ can alternatively be applied to measure $\hat{X}^2$ and thereby observe phonon shot noise [24] or perhaps even quantum jumps in n [20].

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