Measurement of Intracavity Quantum Fluctuations of Light Using an Atomic Fluctuation Bolometer

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The spectral noise power of photon number fluctuations inside a driven high-finesse Fabry-Perot optical resonator is measured through the resonator-enhanced momentum diffusion of ultracold atoms trapped within. Light-induced heating of the trapped atoms is quantified by their rate of evaporation from a finite-depth intracavity optical trap. The relevance of cavity-enhanced momentum diffusion to cavity-enhanced measurements of atomic ensembles is discussed.

In quantum optics, the monochromatic electromagnetic wave of classical optics is represented as a coherent state in a suitably defined mode of the quantum electromagnetic field. Central to this representation are the measurable quantum fluctuations of light, such as temporal variations in the intensity, or, equivalently, of the photon number. For typical systems that are characterized by a continuum of electromagnetic modes, temporal fluctuations of the measured photon number result from the beating of the coherent state with vacuum modes at other frequencies. For a freely propagating coherent beam of light, commutation relations among field operators yield a white noise spectrum reflecting the flat spectrum of vacuum fluctuations in free space.

The quantum properties of light in an optical cavity differ from those in free space. According to the theory of cavity quantum electrodynamics, vacuum fluctuations, or, equivalently, the density of states of the electromagnetic field, are accentuated at frequencies near the cavity resonances and suppressed elsewhere. Thus, temporal fluctuations of the photon number of a coherent intracavity field will differ from those exhibited by light in free space, exhibiting a noise spectrum that is "colored" by the cavity-induced spectrum of vacuum fluctuations.

In this Letter, we present a measurement of the temporal intensity fluctuations of the electromagnetic field inside a coherently driven high-finesse Fabry-Perot optical resonator. To perform this measurement, we introduce into the cavity an ultracold atomic gas trapped in a one-dimensional lattice of finite-depth optical potentials. Since the frequencies ω_c and ω_p of the cavity resonance and probe fields, respectively, are both far from that of the atomic resonance (ω_a), the trapped atoms serve as spectators of the cavity field. Mechanical effects of light-atom interactions cause the atoms to be buffeted by temporal fluctuations in the intracavity field intensity. The atoms thus serve as a *fluctuation bolometer*, sensing fluctuations of the incident intensity — or, more precisely, the time-integrated noise power of photon number fluctuations at a specific temporal frequency — by an increase in thermal energy. We quantify this increase by measuring the evaporative loss of atoms from the optical trap.

In free space, spontaneous emission by atoms driven by laser light leads to momentum diffusion due to both recoil kicks and fluctuations of the optical dipole force [1, 2]. Atoms in a high finesse resonator also experience dipole force variations due to quantum fluctuations of the intracavity light field [3, 4, 5]. To assess the effect of these fluctuations, we consider the one-dimensional motion of harmonically trapped two-level atoms, with trap frequency ω_z, along the axis ($\hat{z}$) of a Fabry-Perot resonator [6]. Given that the cavity-atom detuning $\Delta_{ca} = \omega_c - \omega_a$ is large, we make two assumptions. First, we assume the force F on the atoms due to cavity photons is simply the gradient of the AC Stark potential, i.e. $F = f(z)\hat{n}$ where $f(z) = -\hbar\partial_z g^2(z)/\Delta_{ca}$ is the dipole force from a single photon, $g(z) = g_0 \sin(kz)$ is the spatially dependent vacuum Rabi frequency, and $\hat{n} = a^\dagger a$ is the cavity photon number operator. Second, we assume the effect of the atoms on the intracavity field is negligible. Fluctuations of the intracavity photon number lead to momentum diffusion with diffusion coefficient

$$D_\mathrm{c} = \frac{f^2(z)}{2}\int_0^\infty d\tau \cos(\omega_z\tau)\,\mathrm{Re}\big(\langle\hat{n}(\tau)\hat{n}(0)\rangle - \langle\hat{n}\rangle^2\big)\,, \quad (1)$$

where we assume the atoms are confined sufficiently so that the dipole force may be evaluated at a single axial position z.

Accounting also for effects of atomic spontaneous emission, the total momentum diffusion coefficient D of a harmonically trapped atom in a Fabry-Perot resonator driven with light at detuning δ from the cavity resonance is found to be [3, 4, 5]

$$D = D_\mathrm{fs}\left(1 + C\left[\phi_+ + \phi_-\right]\sin^2(2kz)\right) \quad (2)$$

where $D_\mathrm{fs} = \hbar^2 k^2 s\Gamma/2$ is the free-space momentum diffusion coefficient in a standing wave of light [1, 2]. Here Γ and κ are the half-linewidths of the atomic and cavity resonances, $s = 2g_0^2\bar{n}/\Delta_{ca}^2$ is the saturation parameter at the cavity-field antinode, $\bar{n} = \langle\hat{n}\rangle$, and $\phi_\pm = 1/(1 + (\delta \pm \omega_z)^2/\kappa^2)$ relates to the Lorentzian lineshape of the cavity. In the strong coupling regime of cavity quantum electrodynamics ($C \gg 1$), momentum diffusion may be dominated by $D_\mathrm{c} = D - D_\mathrm{fs}$ for probe frequencies near the cavity resonance ($|\delta \pm \omega_z| < \kappa$), allowing intracavity field fluctuations to be measured.

The medium we used to sense fluctuations of the intracavity field was an ultracold gas of ^{87}Rb atoms held

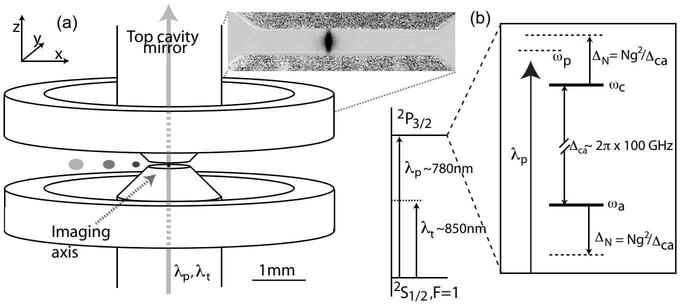

FIG. 1: (a) Ultracold atoms are produced in a magnetic trap, formed using electromagnets coaxial with the vertically oriented high-finesse cavity, and delivered to the cavity center. Trapping/locking light ($\lambda_t = 850$ nm) and probe light ($\lambda_p = 780$ nm) are sent through the cavity and monitored in transmission. An absorption image, obtained using probe light along the $\hat{y}$ axis, shows atoms trapped optically within the cavity volume. (b) Energy level scheme for the far-detuned ($\Delta_{ca} \gg \sqrt{N} g_0$) cavity.

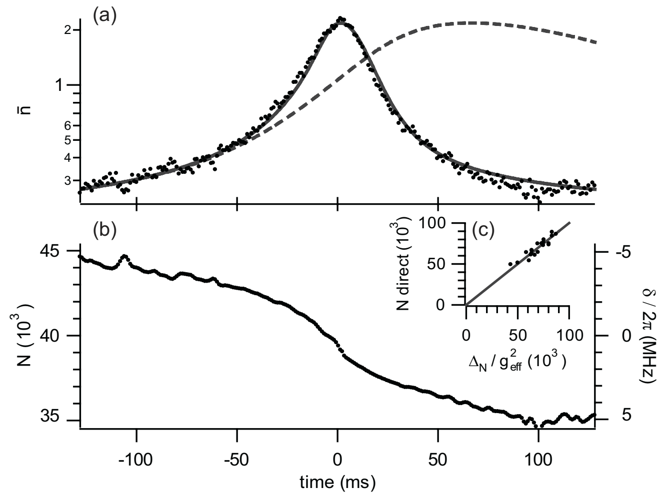

FIG. 2: Cavity-based observation of evaporative atom losses due to cavity-light-induced momentum diffusion. (a) The intracavity photon number, $\bar{n}$ (points, average of 30 measurements) is monitored as the atom number is reduced by evaporation, and the cavity resonance is brought across the fixed probe frequency. The expected $\bar{n}(t)$ for light-induced heating with (solid) and without (dashed) cavity-enhanced heating is shown. (b) The atom number $N(t)$ is inferred from the measured photon number based on the cavity lineshape. Atoms are lost at a background rate of 0.9(1) s^{-1} per atom away from the cavity resonance, and much faster (as high as 3 s^{-1}) near resonance. (c) The relation between $\Delta_N/g_{\text{eff}}^2$ and the atom number measured directly by absorption imaging matches with predictions (line).

in a one-dimensional optical lattice potential within the cavity mode volume. These atoms were prepared outside the cavity volume [7], trapped magnetically in a Time-Orbiting Potential (TOP) trap, and then translated to within the cavity mode volume (Fig. 1).

The Fabry-Perot cavity was formed using two mirrors, each with 5 cm radius of curvature. Measured losses and transmissions per reflection of 3.8 and 1.5 ppm, respectively, for light of wavelength $\lambda_p = 780$ nm yielded a cavity finesse of $\mathcal{F}_{780} = 5.8 \times 10^5$. This cavity supported a TEM$_{00}$ mode at a frequency ω_c which we tuned within the range $|\Delta_{ca}| = 2\pi \times (10 - 100)$ GHz from the ^{87}Rb D2 atomic resonance. The mirror separation of $194\,\mu$m was maintained by passive *in vaccuo* vibration isolation and by active stabilization of a different TEM$_{00}$ cavity mode to a frequency-stabilized laser at the wavelength $\lambda_t = 850\,$nm. At this wavelength, the cavity finesse was reduced to $\mathcal{F}_{850} = 3.8 \times 10^4$.

The light used for cavity stabilization also produced a one-dimensional optical lattice potential within the cavity. Atoms were loaded into this lattice by increasing the intensity of the trapping light to produce trap depths of $U/k_B = 6.6(7)\,\mu$K before the TOP trap was suddenly switched off. After transfer, the remaining atoms, all in the $|F=1, m_F=-1\rangle$ hyperfine ground state, occupied ~ 300 adjacent sites in the optical lattice. Evaporative cooling from the optical trap rapidly reduced and then stabilized the temperature of the trapped atomic gas at $T = 0.8\,\mu$K. This trapped gas resided mostly in the lowest band of the trapping potential since $k_B T < \hbar\omega_z$, with $\omega_z = 2\pi \times 42(2)$ kHz being the axial trap frequency in each potential well.

Our measurement relies on counting the number of trapped atoms N to determine the evaporation rate of atoms from the trap. This number was measured using the atom-induced cavity resonance frequency shift,

$$\Delta_N = \sum_i N_i \frac{\langle g^2 \rangle_i}{\Delta_{ca}} = N \frac{g_{\text{eff}}^2}{\Delta_{ca}}, \qquad (3)$$

given for large $|\Delta_{ca}|$, where N_i is the number of atoms and $\langle g^2 \rangle_i$ is the position-averaged squared Rabi frequency in lattice site i. Since the atoms are tightly confined, and evenly distributed over the occupied lattice sites, we may approximate $g_{\text{eff}}^2 \simeq g_0^2/2$. The Rabi frequency $g_0 = 2\pi \times 14.4$ MHz is determined from measured cavity parameters and by summing over all excitations from the ground state by σ^+ probe light on the D2 resonance line. The relationship between Δ_N and N was also verified experimentally by comparing measurements of Δ_N with collocated absorption measurements of the number of trapped atoms (Fig. 2 (c)).

We now turn to our measurement of intracavity intensity fluctuations near the cavity resonance. Nearly $N = 10^5$ atoms were loaded into the cavity, causing the cavity resonance to be shifted by $\Delta_N = 2\pi \times 100$ MHz at the atom-cavity detuning of $\Delta_{ca} = 2\pi \times 100$ GHz. The cavity was then driven with probe light at frequency $\omega_p - \omega_c = 2\pi \times 40$ MHz from the bare cavity resonance. Transmission through the cavity was monitored using single-photon counting devices. The cavity photon number $\bar{n}$ was obtained from the transmission signal using the measured quantum efficiency of 0.040(8) for detecting intracavity photons.

While the transmitted probe intensity was initially negligible owing to the large detuning between the probe and cavity resonance frequencies, the ongoing loss of atoms from the optical trap eventually brought the cavity resonance frequency to near the probe frequency, leading to discernible transmission (Fig. 2(a)). We used this transmission signal to determine the atom number N and its rate of change dN/dt as functions of time. We related Δ_N to the instantaneous transmitted probe power by assuming a Voigt lineshape for the cavity transmission, with a Gaussian rms frequency width of $\sigma = 2\pi\times 1.1$ MHz that accounts for the broadening of the transmission spectrum due to technical fluctuations in $\omega_p - \omega_c$. This lineshape matched well to that observed for the bare cavity. We also modified the lineshape to account for optical nonlinearities associated with the probe-induced displacements of atoms in the intracavity optical trap [8], which cause a $\simeq 2\%$ decrease of g_{eff}^2 at the maximum cavity photon number ($\bar{n} = 1.9$) used here. As shown in Fig. 2(b), the loss of atoms from the trap is strongly enhanced near resonance due to increased light-induced heating.

The observed atomic loss rate was used to measure the per-atom heating rate of the trapped atomic sample as $dE/dt = -U d(\ln N)/dt$, and then the momentum diffusion coefficient as $D = m\, dE/dt$ with m being the atomic mass. For each measurement shown in Fig. 3, a 12 ms-long range of the probe transmission measurement data (Fig. 2) was used to determine dN/dt and $\bar{n}$. Atoms experiencing intracavity intensity fluctuations of cavity-resonant light underwent momentum diffusion that is $D/D_{\mathrm{fs}} \simeq 40$ times larger than that of atoms exposed to a standing wave of light of *equal intensity* in free space. The cavity-induced heating was abated for light detuned from the cavity resonance. While this enhancement in momentum diffusion has been observed indirectly in the lifetime [9] and spectrum [10] of single atoms strongly coupled to Fabry-Perot optical cavities, our measurements provide its direct quantification.

The accuracy of our measurement depends on a number of assumptions made in interpreting the observed transmission lineshapes, several of which we verified experimentally. For example, we examined the dynamics of evaporative cooling in the atomic medium. For this, we interrupted the cavity transmission measurement, released the atoms from the intracavity optical trap and imaged 4 ms later to measure their temperature. Within our measurement resolution of 0.1 μK, this temperature remained constant. Thus, our quantification of heating through the rate of atom loss is valid. Furthermore, by extinguishing the cavity probe light momentarily during cavity probing, and comparing the cavity transmission when the probe was turned off and then turned on again, we determined a timescale of 3 ms for the atom number to equilibrate by evaporative cooling following an increase of thermal energy. Since this timescale is short compared to the $\simeq 100$ ms span of the resonant transmission signal,

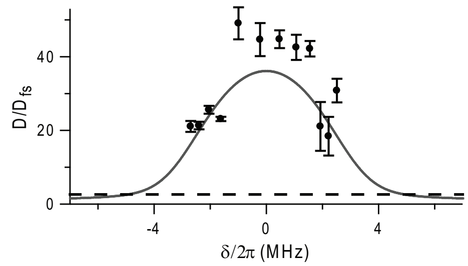

FIG. 3: Cavity-enhancement of momentum diffusion in a strongly coupled Fabry-Perot cavity over that in free space. The measured ratio D/D_{fs} is shown with 1σ statistical error bars. Systematic errors, at a level of 23% at the cavity resonance, arise from uncertainty in the background loss rate and the background light level in and overall efficiency of our photodetectors. Grey line shows theoretical prediction (with no adjustable parameters) as described in the text. Dashed line shows an upper bound on the off-resonance momentum diffusion based on measurements at $\Delta_{ca} = 2\pi\times 29.6$ GHz and $\delta = 2\pi\times 40$ MHz.

we are justified in using simultaneous measurements of dN/dt and $\bar{n}$ to determine the instantaneous momentum diffusion rate.

To interpret our measurements as relating to the quantum nature of the intracavity field, it was necessary to establish that quantum fluctuations dominate over classical, technical intensity fluctuations which would also lead to heating [11]. For this, we measured the light-induced heating for varying probe intensities, with $\bar{n}$ at the cavity resonance ranging from $\bar{n} = 0.2$ to 20. Noting that the contribution of quantum fluctuations to the atom heating rate scales as $\bar{n}$ while that of classical fluctuations scales as $\bar{n}^2$, we find that classical fluctuations account for less than 10% of the momentum diffusion at the light level used for Figs. 2 and 3.

A theoretical prediction for the ratio D/D_{fs} was determined by adapting the results of Eq. (2) to the experimental situation. Assuming the trapped atoms are uniformly distributed in the standing-wave potential, we average over the z-dependence of Eq. (2). We account for technical fluctuations in the probe detuning δ by a convolution of the predicted frequency dependence with the same Gaussian kernel used for the Voigt cavity transmission lineshape. Importantly, we take $\delta = \omega_p - (\omega_c + \Delta_N)$ to represent the detuning of the cavity probe light from the atom-shifted cavity resonance frequency. The measured atom heating rates agree well with this prediction.

We have shown that cavity-induced fluctuations of the optical dipole force can exacerbate the heating of atoms in a standing-wave optical field. To highlight this finding further, we measured the atom heating rate from intracavity light that is far from the cavity resonance. Since intensity fluctuations at relevant temporal frequencies should be suppressed in this case, the momentum diffusion should return to the spontaneous-emission-dominated level observed in free space.

For this, we first prepared the cavity with a precise number of trapped atoms. This was done by monitoring the cavity transmission as N decreased and initiating our measurements upon observing the transmission surpass a threshold level. With $\Delta_{ca} = 2\pi \times 29.6$ GHz and $\omega_p - \omega_c = 2\pi \times 32$ MHz, this starting atom number was $N \simeq 9000$. We then rapidly switched the probe frequency to set $\delta = 2\pi \times 40$ MHz, and increased the probe intensity significantly, allowing an average population of $\bar{n} = 2$ off-resonant photons into the cavity. After a variable heating time, the probe frequency was swept across the cavity resonance, and the resulting transmission spectrum used to determine Δ_N. We observed a probe-light-induced per-atom loss rate that, if ascribed completely to momentum diffusion of the atomic sample, yields a diffusion coefficient of $D/D_{\mathrm{fs}} = 2.9(7)$, far smaller than that observed at the cavity resonance. Yet, these losses exceeded those expected based on momentum diffusion from Rayleigh scattering. This discrepancy may be explained by additional effects of Raman scattering. Atoms scattered by the σ^+ probe light into different hyperfine ground states couple to the cavity probe light with different strength, thereby changing the relationship between Δ_N and the atom number N. These additional effects appear sufficient to account for our observations, yet are constrained by our measurements to contribute only slightly to the atom losses observed from probe light at the cavity resonance.

In this work, the placement of ultracold atoms within a high-finesse optical resonator has enabled a measurement of the intensity fluctuations of an intracavity optical field. Specifically, in a cavity driven by coherent laser light, the atoms serve as an *in-situ* heterodyne detector of cavity-enhanced fluctuations of the electromagnetic field, with the two quadratures of the harmonic atomic motion serving as two heterodyne receivers at the beat frequency ω_z. At present, by quantifying only the total heating rate of the trapped atomic gas, we cannot access information on the individual noise quadratures. However, augmented by time-resolved measurements of the atomic motion, as demonstrated in Ref. [8], our fluctuation bolometer may also serve to probe quadrature-squeezed light before the intracavity squeezing is degraded by attenuation outside the cavity [12].

Conversely, cavity-enhanced light-atom interactions may serve to probe quantum properties of the matter-wave field. Of particular interest is the passive [13, 14, 15] or active [16] non-destructive measurement of atom number or spin with uncertainty below the standard quantum limit. In such measurements, the sensitivity gained by increasing the probe light fluence is eventually offset by the increased disturbance of the atoms due to incoherent light scattering. In our work, Δ_N measures a weighted sum of the atom numbers in many lattice sites. The disturbance from such a measurement is the modification of the atomic motional state due to probe-induced heating. Considering just motion along the cavity axis, we may assign a heating-induced uncertainty $\sigma_N^2 = N\Delta E/\hbar\omega_z$ to the atomic number. This corresponds to the variance in the number of atoms excited out of the motional ground state, where ΔE is the per-atom energy increase. Previous works [14, 16] identified the strong coupling regime ($C \gg 1$) as required for non-destructive Heisenberg-limited measurements. However, we find that cavity-enhanced heating can eliminate the benefits of cavity-enhanced quantum measurements for large cooperativity. Nevertheless, as shown in Eq. (2), this heating may be obviated by performing cavity-based measurements that are insensitive to the atomic position, e.g. by placing atoms at antinodes of the cavity field or by confining atoms sufficiently so that $\omega_z \gg \kappa$.

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