Optically detecting the quantization of collective atomic motion

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We directly measure the quantized collective motion of a gas of thousands of ultracold atoms, coupled to light in a high-finesse optical cavity. We detect strong asymmetries, as high as 3:1, in the intensity of light scattered into low- and high-energy motional sidebands. Owing to high cavity-atom cooperativity, the optical output of the cavity contains a spectroscopic record of the energy exchanged between light and motion, directly quantifying the heat deposited by a quantum position measurement’s backaction. Such backaction selectively causes the phonon occupation of the observed collective modes to increase with the measurement rate. These results, in addition to providing a method for calibrating the motion of low-occupation mechanical systems, offer new possibilities for investigating collective modes of degenerate gases and for diagnosing optomechanical measurement backaction.

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Quantized motion leads to a large asymmetry in the spectrum of light scattered by a ground-state oscillator. Such asymmetry is most commonly observed from microscopic oscillators, such as electrons bound within atoms and molecules, single neutral atoms [1], or few-ion ensembles [2–4]. In contrast, quantum aspects of the motion of massive or many-atom oscillators are typically obscured by thermal noise and high phonon occupation. These objects, therefore, usually modulate the spectrum of light in a classical, symmetric manner.

Controlling and measuring the motion of macroscopic objects at levels sensitive to quantum effects will be critical for operating gravitational-wave detectors [5], verifying the correspondence principle at macroscopic scales [6, 7], and realizing protocols that mechanically store and exchange quantum information [8, 9]. Such goals are being pursued actively using cavity optomechanical systems, wherein the motion of an object with mass ranging from attograms to kilograms is observed via its coupling to an electromagnetic cavity [10]. Implementations of cavity optomechanics using the collective motion of atomic gases [11, 12] have demonstrated sensitivity to quantum optical force fluctuations, leading to the observation of optical squeezing from ponderomotive interactions [13] and backaction from a quantum-limited position measurement [14].

In this work, we use a high-finesse optical cavity to detect the coherent, asymmetric scattering of light by collective modes of motion of a trapped atomic gas, occupied with as few as 0.5 phonons. Observations have previously been made of optical emission asymmetries from individual atoms [1] and ensembles of up to 14 ions [2–4], and of asymmetric absorption by a nanomechanical solid-state resonator [15]. Here we measure the coherent scattering of light from the collective motion of many hundreds of ultracold atoms. The scattering asymmetry acts as a self-calibrating thermometer for the atoms’ collective phonon occupation. Moreover, owing to high cavity-atom cooperativity and thermal isolation in our system, the cavity mode acts as the dominant channel for energy flux to our mechanical system. The spectrum of light emitted from the cavity therefore serves as a record of the energy exchanged between motion and the light field. We demonstrate that this energy transfer represents the necessary minimum diffusive heating of a continuous backaction-limited quantum position measurement.

Our experiment (Fig. 1) begins with an ensemble of 4,000 ultracold $^{87}$Rb atoms. The atoms are trapped in a few adjacent minima of a one-dimensional optical standing-wave potential, formed by 850-nm-wavelength light resonating within a high-finesse Fabry-Pérot optical cavity, and detuned far from atomic resonance. The curvature at each potential minimum corresponds to an oscillation frequency, along the cavity axis, of $\omega_m = 2\pi \times 110$ kHz.

We create an optomechanical coupling, which is linearly sensitive to atomic position, by trapping the atoms at locations with strong intensity gradients of 780-nm-wavelength probe light, which also resonates within the cavity [16]. The probe light is detuned from the atomic D2 transition by many gigahertz. At such large detunings, the atomic gas acts as a position-dependent retractive medium, leading to an interaction Hamiltonian $\hat{H}_{\text{int}} = \sum_{i} g_i \hat{n}_i \hat{Z}_i / \sqrt{\Omega_{\text{HO}}}$, where $\hat{n}$ is the probe’s photon number operator and $\hat{Z}_i$ is the position operator of atom $i$ [14]. Here $g_i$ represents the change in the cavity’s resonance frequency as atom $i$ is displaced by one single-atom harmonic oscillator length $z_{\text{HO}}$, equivalent to $\sqrt{\hbar / 2m\omega_m}$ for rubidium mass $m$.

The above may be rewritten [11, 12] as a collective interaction described by $\hat{H}_{\text{int}} = g_{\text{om}} \hat{n} \hat{Z} / \sqrt{\Omega_{\text{HO}}}$, where $\hat{Z} \equiv \sum_{i} g_i \hat{Z}_i / \sum_{i} g_i$ is a collective position operator, $z_{\text{HO}} = z_{\text{HO}} / \sqrt{N_a}$ is the collective oscillator length for $N_a$ atoms, and $g_{\text{om}} = \sum_{i} g_i / \sqrt{N_a}$ is the collective op-
tomechanical coupling rate. In our system, the $g_i$s are all approximately equal, and $\hat{Z}$ is nearly equivalent to the center-of-mass position $\hat{Z}_{\text{com}} = \sum_i \hat{z}_i / N_a$. In this case, $g_{\text{om}} = \sqrt{N_a} g_0^2 k_{\text{HO}} / \Delta_{\text{ca}}$, where $\Delta_{\text{ca}}$ is the probe detuning from the ground $F=2$ hyperfine manifold’s D2 resonance, and $g_0$ is the single-atom cavity-QED coupling rate ($2\pi \times 12.4$ MHz, averaged over the intracavity atomic distribution) and probe wavenumber $k$.

Unlike solid-state resonators, which are coupled to their material environments, the atoms here are isolated in vacuo, and the thermal “bath” for the measured collective oscillation consists of the remaining collective modes of atomic motion. After raising the trap potential to its final strength, the bath has an initial temperature of 2.9 µK, corresponding to a mode occupation of 0.54 phonons.

The atomic motion scatters cavity photons via collective virtual electronic excitations, causing transitions between collective motional energy levels (i.e., collective Raman scattering). In this process, the collective atomic oscillator can absorb a mechanical energy quantum, thereby downconverting the emitted photon by $\omega_m$ (Stokes scattering). If the oscillator is not in its ground state, it can alternatively upconvert the photon by $\omega_m$, thereby losing an energy quantum (anti-Stokes scattering). By Fermi’s golden rule, the rates for upconversion and downconversion, from an oscillator in its $\nu$th excited state, are proportional to $|\langle \nu | \hat{Z} | \nu - 1 \rangle|^2 \propto \nu$ and $|\langle \nu | \hat{Z} | \nu + 1 \rangle|^2 \propto \nu + 1$, respectively. A ground-state oscillator ($\nu = 0$) will thus scatter only to the Stokes sideband, with more symmetric scattering indicative of higher phonon occupation.

The Fourier spectrum $n(\omega)$ of photons emitted from the cavity, at a frequency $\omega$ relative to the probe, and normalized by the discrete Fourier window time, can be calculated by solving a set of quantum Langevin equations [15, 17]. In an experiment where the probe’s amplitude fluctuations are dominated by shot noise [18], the solution is

$$n(\omega) = \frac{C_{\text{om}}}{2} \frac{\kappa^2}{\kappa^2 + \omega^2} \times \left[ \frac{\Gamma_m^2 \tilde{\nu}}{(\omega - \omega_m)^2 + \Gamma_m^2 / 4} + \frac{\Gamma_m^2 (\tilde{\nu} + 1)}{(\omega + \omega_m)^2 + \Gamma_m^2 / 4} \right], \quad (1)$$

where $\tilde{\nu}$ is the oscillator’s mean phonon occupation. Here we have parameterized the photon scattering rate by the dimensionless optomechanical cooperativity $C_{\text{om}} \equiv 4 \pi g_{\text{om}}^2 / \Gamma_m \kappa$, which combines $g_{\text{om}}$, the mechanical damping rate $\Gamma_m$, the mean intracavity probe photon number $\bar{n}$, and the cavity half linewidth $\kappa$ ($2\pi \times 1.82$ MHz). In our atoms-based optomechanical system, $C_{\text{om}} \propto \bar{n} / \Delta_{\text{ca}}^2$, and we vary the cooperativity over orders of magnitude by tuning $\bar{n}$ between 0.1 and 2 and $\Delta_{\text{ca}}$ between −70 and −12 GHz.

We measure the Stokes asymmetry by integrating the optical power $P_{\pm}$ scattered to frequencies near $\pm \omega_m$, detected using a balanced heterodyne receiver. The
FIG. 2: (Color online) Asymmetric optical scattering from quantum collective motion. (A) Photon spectra of light exiting the cavity, scattered by collective atomic motion. Shown are the Stokes sidebands (left panels, red) and anti-Stokes sidebands (right panels, blue) at various cooperativities (from top to bottom, $C_{\text{om}} = 9.6, 3.2, 1.6$). Traces are vertically offset for clarity (by $12, 2, 0 \times 10^{-27} \text{ W/Hz}$). (B) Measured phonon occupation vs. cooperativity. The collective mode occupation (green circles) increases by $C_{\text{om}}/2$, according to the zero-free-parameter measurement backaction theory (red line, shaded region indicates 68% systematic confidence interval). In contrast, the r.m.s. single-atom axial occupation, measured using time-of-flight thermometry of the gas (yellow diamonds, measured at 1 ms of probing), remains near its initial value during the measurement (gray line indicates theoretical prediction).

detector measures a power spectral density $S_{\text{det}}(\omega) = S_{\text{SN}} [1 + \varepsilon (n_0(\omega) + n(\omega)) / 2]$, where $S_{\text{SN}}$ is the mean shot-noise spectrum as measured by the detector and $n_0(\omega)$ is the spectrum of technical noise, which contributes less than 1% to the observed spectrum at $\pm \omega_m$. The quantum efficiency for measuring intracavity photons is $\varepsilon = 16\% \pm 2\%$. For each run of the experiment we measure the spectral density $S_A$ with atoms and $S_0$ without atoms (which measures $n_0$), and then measure $S_{\text{SN}}$ by extinguishing the probe beam. The unitless photon spectrum is then $n(\omega) = 2(S_A - S_0) / \varepsilon_S S_{\text{SN}}$. In order to avoid excessive accumulated heating of the atomic gas, we acquire data for only 5 ms each run of the experiment, after which we observe the mechanical resonance to broaden significantly.

Measured spectra are shown in Fig. 2. At the lowest optomechanical cooperativities ($\approx 0.1$, a weak probe detuned far from atomic resonance), the probe contributes only minimally to the phonon occupation. Rather, the collective mode occupation should approach the average thermal occupation ($0.54 \pm 0.02$ phonons, measured via time-of-flight thermometry). We measure a large Stokes asymmetry: $P_- / P_+ = 3.0 \pm 0.8$, corresponding to a phonon occupation $\bar{\nu} = P_+ / (P_- + P_+) = 0.49 \pm 0.10$. We note that such a “Stokes thermometer” is self-calibrating, in that no experimental parameters are involved in extracting the phonon occupation number.

The mechanical resonance widths of the observed spectra are generally larger than the native mechanical damping rate. We measure the native damping rate by probing...
to the blue of cavity resonance and finding the phonon lasing threshold \[18, 20\], at which point the mechanical damping rate is equal to the optomechanical amplification rate. In our system, we find a damping rate of \(2\pi \times 0.46\) kHz. Comparing to the observed inhomogenous linewidth of \(2\pi \times 3\) to 4 kHz indicates that \(\tilde{Z}\) dephases into approximately 7 to 9 collective normal modes, each containing 400 to 500 atoms. We suspect that this dephasing is due mostly to slight differences in trap curvature in adjacent potential minima arising from the probe beam \[16, 18\], and partly to the anharmonicity of the standing-wave optical trap, as well as the variation of axial oscillation frequency with radial displacement. Note that this calculation represents an upper bound on the number of detected collective modes, as sources of broadening beyond dephasing could contribute to the observed widths (i.a., shot-to-shot fluctuations in the mechanical resonance frequency).

We next apply the sideband thermometer to probe the effects of measurement backaction. A quantum measurement of position must be accompanied by a corresponding motional disturbance \[21\]. In this experiment, where the motion is driven by the light’s radiation-pressure shot noise \[13\], and where \(\omega_m \ll \kappa\), we expect an increase in the phonon occupation by an amount \(C_{om}/2\). As we increase the cooperativity, the sideband asymmetry decreases as theoretically predicted. Finally, we can compare the collective mode’s mean phonon occupation \(\tilde{v} = \left\langle \left(\sum_i g_i z_i / g_{om}\right)^2 \right\rangle / 2 \tilde{z}^2_{HO} - \frac{1}{2}\) to an upper bound on the mean single-atom phonon occupation \(\tilde{v}_a = \left\langle \left(\sum_i z_i^2 \right) / 2 N_{a} \tilde{z}^2_{HO} - \frac{1}{2}\right\rangle\), extracted by measuring the gas temperature using time-of-flight thermometry. The upper bound is derived by assigning the gas’s entire temperature increase after 1 ns of probing (equivalent to many motional equilibrium times) to the mean single-atom motion along the cavity axis. The large discrepancy observed between the optically detected and single-atom occupations (Fig. 2b) highlights the fact that our detector senses the collective motion of the gas, rather than the motion of individual atoms.

The optical spectrum moreover serves as a record of the energy exchanged between light and motion. A photon recorded at frequency \(\omega\) indicates the emission of an energy \(\hbar\omega\) from the atoms into the cavity field. The spectral density of energy passing from the light field into motion is therefore \(-\hbar\omega n(\omega)\) (units of W/Hz), and the total power passing from the light to motion is \[14, 17\]

\[
P_{om} = -\frac{1}{2\pi} \int \hbar \omega n(\omega) d\omega \approx \frac{\Gamma_m \hbar \omega_m C_{om}}{2} \frac{\kappa^2}{\kappa^2 + \omega_m^2}.
\]

Heat-exchange spectra for several values of the cooperativity, as well as heating rates taken from integrating over the sidebands, are shown in Fig. 3. The heating rates agree well with the prediction of measurement back-action. We additionally correlate the total energy exchanged with the atoms to the increase in the (finite) bath’s temperature. The bath temperature should increase by an amount given by equating the backaction heat with the temperature integral of the gas’s heat capacity \(C_N\). We calculate \(C_N\) using Bose-Einstein statistics for axial motion and the ideal gas law for radial motion, yielding \(C_N = \alpha(T) N_{a} k_B\) where \(\alpha(T)\) is between 2.8 and 3.0 over the experimental temperature range. We find quantitative agreement to this theory as we vary both the cooperativity and the probe duration.

In this work, we have demonstrated the quantization of the collective motion of thousands of atoms, observing Stokes asymmetry and zero-point motion. The Stokes asymmetry provides a self-calibrating thermometer for low-occupation collective modes. We have in addition observed the spectrum of energy exchanged between light and collective atomic motion, spectroscopically identifying backaction heating from a quantum position measurement. While our system measures center-of-mass motion, other modes \[12, 15, 16\] of physical interest could be addressed by tailoring the light-motion interaction. For example, quadrupole \[22–24\] or scissors \[25\] modes could be sensed using quadratic optomechanical coupling \[16\], allowing for precise measurements of the effects of interactions, superfluidity, and viscosity in degenerate Bose and Fermi gases. Sideband spectroscopy of phonon modes in spatially extended gases \[12\] provides the means to study thermodynamics in static and driven systems \[26\].

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[18] See supplemental material.