Observation of quantum-measurement backaction with an ultracold atomic gas

KATER W. MURCH[1], KEVIN L. MOORE[1], SUBHADEEP GUPTA[1] AND DAN M. STAMPER-KURN[1,2]*
[1]Department of Physics, University of California, Berkeley, California 94720, USA
[2]Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
*e-mail: dmsk@berkeley.edu

Published online: 18 May 2008; doi:10.1038/nphys965

Current research on micromechanical resonators strives for quantum-limited detection of the motion of macroscopic objects. Prerequisite to this goal is the observation of measurement backaction consistent with quantum metrology limits. However, thermal noise currently dominates measurements and precludes ground-state preparation of the resonator. Here, we establish the collective motion of an ultracold atomic gas confined tightly within a Fabry–Perot optical cavity as a system for investigating the quantum mechanics of macroscopic bodies. The cavity-mode structure selects a particular collective vibrational motion that is measured by the cavity's optical properties, actuated by the cavity optical field and subject to backaction by the quantum force fluctuations of this field. Experimentally, we quantify such fluctuations by measuring the cavity-light-induced heating of the intracavity atomic ensemble. These measurements represent the first observation of backaction on a macroscopic mechanical resonator at the standard quantum limit.

Various types of micromechanical resonator, including singly[1,2] or doubly[3–5] clamped nanofabricated beams, thin membranes[6] and toroidal structures[7], have been fabricated and used to study small-amplitude vibrations. With resonance frequencies in the kilohertz to megahertz range—an exception being the gigahertz resonator of ref. 8—these resonators remain significantly perturbed by thermal noise at cryogenic temperatures. Nevertheless, powerful schemes to cool a single mechanical mode of the resonator below its ambient temperature have been demonstrated[1–7]. These schemes use either active feedback or the passive dynamical backaction on a driven resonator, the latter being equivalent to cavity-induced laser cooling of atoms[9,10]. The use of these schemes to achieve ground-state cooling has been discussed[11–13].

Here, we demonstrate that the collective motion of a trapped macroscopic ensemble of ultracold atoms may serve as the resonator for the study of quantum micromechanics. In contrast with the mechanical systems discussed above, such atoms may be cooled directly to the ground state of motion. Non-classical states of motion have been engineered in atomic ensembles[14], and the oscillatory motion of an atomic gas has been used to measure weak forces[15], analogous to measurements using microfabricated cantilevers[16]. However, previous efforts have lacked the means to measure the motion of an atomic ensemble at the quantum limit.

COLD ATOMS AS A MICROMECHANICAL OBJECT

High-finesse optical cavities have been used to sense the motion of single atoms[17,18]. Their sensitivity results from the spatial variation of the atom–cavity coupling frequency; in a near-planar Fabry–Perot cavity, this frequency varies as $g(z) = g_0 \sin k_\mathrm{p} z$ along the cavity axis, where k_p is the wave vector of light near the cavity resonance. In the case where the detuning $\Delta_\mathrm{ca} = \omega_\mathrm{c} - \omega_\mathrm{a}$ between the bare-cavity (no atoms present) and the atomic resonance frequencies is large ($|\Delta_\mathrm{ca}| \gg \{g, \Gamma\}$), a single atom of half-linewidth Γ at position z causes the cavity resonance to be shifted by $g^2(z)/\Delta_\mathrm{ca}$. Measuring the cavity resonance thus provides information on the atom's position.

Such a measurement may also be applied to monitor the motion of an ensemble of N atoms that are optically trapped (and which, for our set-up, can be treated as independent to a good approximation) within the resonator mode[19–21]. In this case, a single collective degree of freedom couples exclusively to a single mode of the cavity (see the Supplementary Information). For small displacements of the atoms from their potential minima, we define a collective position operator $Z = (N_\mathrm{eff})^{-1} \sum_i \sin(2k_\mathrm{p}\bar{z}_i)\delta z_i$, and the conjugate momentum $P = \sum_i \sin(2k_\mathrm{p}\bar{z}_i) p_i$, with $\bar{z}_i$ being the equilibrium position of the ith atom, δz_i being its position deviation from equilibrium and p_i being its momentum. The cavity then serves to monitor a specific collective motion in the atomic ensemble, with the cavity resonance being shifted by $\Delta_N - N_\mathrm{eff} f_0 Z/\hbar$, where $\Delta_N = \sum_i g^2(\bar{z}_i)/\Delta_\mathrm{ca}$ is the cavity frequency shift with all atoms localized at their potential minima and $f_i = -\hbar \partial_z g^2(\bar{z}_i)/\Delta_\mathrm{ca} = f_0 \sin(2k_p \bar{z}_i)$ is the optical dipole force from a single cavity photon. That is, the collective displacement sensed by the cavity is equivalent to the centre-of-mass motion of $N_\mathrm{eff} = \sum_i \sin^2(2k_\mathrm{p}\bar{z}_i)$ atoms trapped at locations of maximum sensitivity of the cavity properties to the atomic position.

With the identification of the collective variables Z and P, we may draw directly on results obtained for the motion of radiation-pressure-driven mechanical resonators within optical cavities. For example, we conclude that optical dipole forces in a driven cavity will displace the collective variable Z, shifting the cavity resonance frequency and leading to cavity optical nonlinearity and bistability[21,22]. We also find that force fluctuations arising from the quantum fluctuations of the intracavity optical field disturb the collective momentum P and constitute the

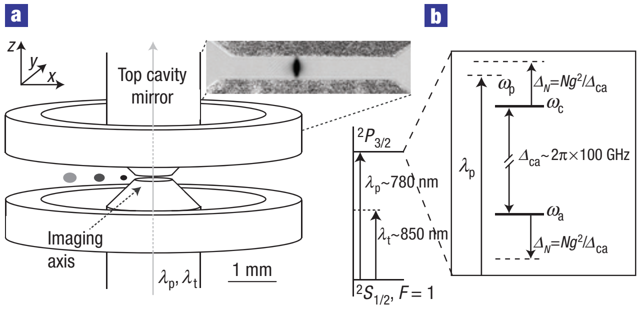

Figure 1 Experimental schematic diagram. a, Ultracold atoms are produced in a magnetic trap, formed using electromagnets coaxial with the vertically oriented high-finesse cavity and delivered to the cavity centre. Trapping/locking light (wavelength $\lambda_t = 850$ nm) and probe light ($\lambda_p = 780$ 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.

quantum backaction for cavity-based measurements of the displacement Z (ref. 23).

To assess the impact of these dipole force fluctuations, we consider the dynamics of the atoms–cavity system with the cavity continuously driven by laser light of fixed detuning Δ_{pc} from the bare-cavity resonance. The average optical force of $\bar{n}$ cavity photons displaces the collective position variable by $\Delta Z = (f_0/m\omega_z^2)\bar{n}$ and thereby shifts the cavity resonance frequency to $\omega_c' = \omega_c + \Delta_N - N_{eff} f_0 \Delta Z/\hbar$, where ω_z is the trap frequency, which is considered identical for all atoms. We define collective quantum operators a and $a^\dagger$ through the relations $Z - \Delta Z = Z_{ho}(a^\dagger + a)$ and $P = iP_{ho}(a^\dagger - a)$, with $Z_{ho} = \sqrt{\hbar/2m\omega_z N_{eff}}$ and $P_{ho} = \hbar/(2Z_{ho})$. As discussed in the Supplementary Information, we obtain equations of motion for a and for the cavity field operator b as

$$\frac{\mathrm{d}a}{\mathrm{d}t} = -i\omega_z a + i\kappa\epsilon(n - \bar{n}), \quad (1)$$

$$\frac{\mathrm{d}b}{\mathrm{d}t} = -i\omega_c' b + i\kappa\epsilon(a^\dagger + a)b - \kappa b + \sqrt{2\kappa} b_{in}, \quad (2)$$

where κ is the amplitude decay rate of the cavity field, b is the cavity photon annihilation operator and b_{in} represents the coherent-state input field that drives the cavity.

Here, we introduce a dimensionless 'granularity' parameter, $\epsilon = N_{eff} f_0 Z_{ho}/(\hbar\kappa)$, that quantifies the coupling between quantum fluctuations of the collective atomic and optical fields. In the non-granular regime, defined by $\epsilon \ll 1$, the generally complex atoms–cavity dynamics described by equations (1) and (2) are vastly simplified. To characterize this regime, consider the impulse $N_{eff} f_0/2\kappa$ imparted on the collective motion by the single-photon optical force over the $(2\kappa)^{-1}$ lifetime of a cavity photon. For $\epsilon \ll 1$, this impulse is smaller than the zero-point momentum fluctuations of r.m.s. magnitude P_{ho}; thus, the effects of optical force fluctuations on the atomic ensemble are adequately described by coarse graining. Likewise, the transient displacements induced by this impulse will shift the cavity resonance by an amount that is much smaller than κ; thus, the quantum fluctuations of the cavity optical field are the same as in the absence of the intracavity atomic gas, with the spectral density of photon number fluctuations being $S_{nn}(\omega) = 2\bar{n}\kappa(\kappa^2 + (\Delta + \omega)^2)^{-1}$ (ref. 11), with $\Delta = \Delta_{pc} - (\omega_c' - \omega_c)$ being the probe detuning from the atoms-shifted cavity resonance.

We then find the occupation number of the collective atomic excitation to vary as

$$\frac{\mathrm{d}}{\mathrm{d}t}\langle a^\dagger a\rangle = \kappa^2\epsilon^2\left[S_{nn}^{(-)} + \left(S_{nn}^{(-)} - S_{nn}^{(+)}\right)\langle a^\dagger a\rangle\right], \quad (3)$$

where $S_{nn}^{(\pm)} = S_{nn}(\pm\omega_z)$ and we assume $\langle a^\dagger a\rangle$ remains small. The collective atomic motion is subject to momentum diffusion, which heats the atomic gas at a per-atom rate of $R_c = \hbar\omega_z\kappa^2\epsilon^2 S_{nn}^{(-)}/N$, and also to coherent damping or amplification of the atomic motion[9–11,13,24].

So far we have neglected the force fluctuations on the atoms associated with incoherent scattering. As 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[25,26]. Allowing the trapped atoms to be distributed evenly along the cavity axis, the total light-induced per-atom heating rate becomes $R = R_{fs} + R_c$, where $R_{fs} = (f_0^2/2m)(\bar{n}/\kappa)(1/C)$ is the free-space diffusive heating rate in a standing wave of light[25,26]. For this atomic distribution, $N_{eff} = N/2$ and we obtain $R_c = R_{fs} \times C(1 + (\Delta - \omega_z)^2/\kappa^2)^{-1}$. Thus, in the strong coupling regime of cavity quantum electrodynamics, with single-atom cooperativity $C = g_0^2/2\kappa\Gamma \gg 1$, diffusive heating may be dominated by backaction heating (R_c) for probe frequencies near the cavity resonance ($|\Delta - \omega_z| < \kappa$).

QUANTIFICATION OF MEASUREMENT BACKACTION

In our experiment, this backaction heating was measured bolometrically. Because the mechanical Q of the collective vibrational motion is low (∼40 as determined in ref. 21), backaction-induced excitation of this motion soon leads to a rise in the total thermal energy of the atomic sample. We quantify this energy increase by measuring the evaporative loss of trapped atoms from a finite-depth optical trap. By using an ultracold atomic gas, with temperature $T \ll \hbar\kappa/k_B$, we may neglect the coherent amplification or damping of atomic motion (the last two terms of equation (3)). The atom heating rate is then related directly to the spectral density of photon fluctuations in the cavity.

For this heating measurement, we prepared an ultracold gas of ^{87}Rb atoms within a high-finesse Fabry–Perot optical resonator[21] (Fig. 1). One lowest-order transverse mode of the cavity was excited resonantly with light at wave vector $k_t = 2\pi/(850\,\mathrm{nm})$. This light, far detuned from atomic resonances, formed a one-dimensional optical lattice of depth $U/k_B = 6.6(7)\,\mu$K in which the atoms were trapped and evaporatively cooled to a temperature of $T = 0.8\,\mu$K, as determined by time-of-flight measurements after the atoms were released from the trap. The atoms occupied approximately 300 adjacent sites in the optical lattice. Given $k_B T < \hbar\omega_z$, where $\omega_z = 2\pi \times 42$ kHz is the axial trap frequency in each lattice site, all axial vibration modes, including the motion pertinent to cavity-based position measurements, were cooled to their ground state. The atomic sample was probed using light with wave vector $k_p = 2\pi/(780\,\mathrm{nm})$ that was nearly resonant with another lowest-order transverse mode of the cavity. For this light, the cavity mirrors, separated by 194 μm and each with 5 cm radius of curvature, exhibited measured losses and transmissions per reflection of 3.8 and 1.5 p.p.m., respectively, yielding $\kappa = 2\pi \times 0.66$ MHz. The bare-cavity resonance frequency for this mode ω_c was maintained at a detuning of $|\Delta_{ca}| = 2\pi \times (30\text{–}100)$ GHz from the ^{87}Rb D2 atomic resonance. The cavity was stabilized by passive *in vacuo* vibration isolation and by active feedback based on transmission measurements of the trapping light at wave vector k_t.

The atom–cavity coupling frequency $g_0 = 2\pi \times 14.4$ MHz was determined from measured cavity parameters and by summing

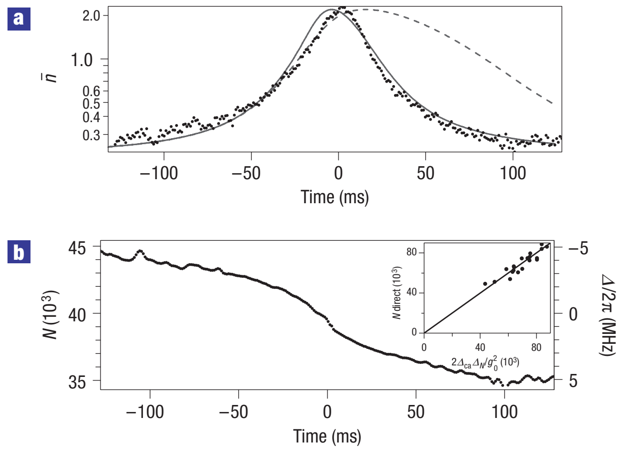

Figure 2 Cavity-based observation of evaporative atomic losses due to cavity-light-induced diffusive heating. a, The intracavity photon number, $\bar{n}$ (points, average of 30 measurements), is monitored as the atom number is reduced by evaporation, and the cavity resonance is brought across the fixed probe frequency. The expected $\bar{n}(t)$ excluding (dashed line) or including (solid line) cavity-enhanced diffusive heating are shown. **b**, The atom number $N(t)$ is inferred from the measured photon number based on the cavity line shape. Atoms are lost at a background rate of 0.9(1) s^{-1} per atom away from the cavity resonance, and three times faster near resonance. Inset: The relation between $2\Delta_{ca}\Delta_N/g_0^2$ and the atom number measured directly by absorption imaging matches with predictions (line).

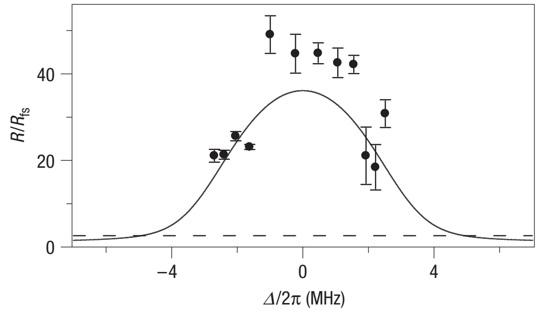

Figure 3 Cavity heating of the collective atomic motion in a strongly coupled Fabry–Perot cavity over spontaneous emission dominated free-space heating. The measured ratio R/R_{fs} is shown with 1σ statistical error bars. For each measurement, a 12-ms-long range of the probe transmission measurement data was used to determine dN/dt and $\bar{n}$. Systematic errors, at a level of 23% at the cavity resonance, arise from uncertainty in the background loss rate, the background light level and overall photodetection efficiency. The grey line shows the theoretical prediction (with no adjustable parameters) as described in the text. The dashed line shows an upper bound on the off-resonance heating rate based on measurements at $\Delta_{ca} = 2\pi \times 29.6$ GHz and $\Delta = 2\pi \times 40$ MHz.

over all excitations from the $|F=1, m_F=-1\rangle$ hyperfine ground state by σ^+ probe light on the D2 resonance line. With the atomic resonance half-linewidth being $\Gamma = 2\pi \times 3.0$ MHz, the single-atom cooperativity of $C = g_0^2/2\kappa\Gamma = 52$ satisfies the criterion for strong coupling.

To measure the backaction heating near the cavity resonance, $N = 10^5$ 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 detuned by $\Delta_{pc} = 2\pi \times 40$ MHz from the bare-cavity resonance. Light transmitted through the cavity was directed to 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.

Whereas 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 atoms–cavity resonance near the probe frequency, leading to discernible transmission (Fig. 2a). 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 line shape for the cavity transmission with a gaussian kernel of r.m.s. frequency width $\sigma = 2\pi \times 1.1$ MHz chosen to account for broadening due to technical fluctuations in Δ_{pc}. We also modified the line shape to account for the probe-induced displacements of the collective position Z that were as high as 3.5 nm for the maximum cavity photon number ($\bar{n} = 1.9$) used here[21]. As shown in Fig. 2b, the atom loss rate was strongly enhanced near resonance owing to increased light-induced heating.

From the observed loss rate, we determined the per-atom heating rate of the trapped atomic sample as $R = -U d(\ln N)/dt$ (Figs 2,3). Atoms experiencing intracavity intensity fluctuations of cavity-resonant light were heated at a per-atom rate that is $R/R_{fs} \simeq 40$ 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. Whereas this cavity-enhanced diffusion has been inferred from the lifetime[27] and spectrum[28] of single atoms in optical cavities, our measurements are carried out under experimental conditions that enable its direct quantification.

To compare the observed heating rate with that expected based on quantum-measurement backaction (Fig. 3), we account for technical fluctuations in the probe detuning Δ by a convolution of the predicted frequency dependence with the aforementioned gaussian kernel. For $\Delta = 0$, this convolution reduces the measured heating rate per photon by a factor of 0.7 below what is expected in the absence of technical fluctuations. The measured atom heating rates agree well with their predicted value, confirming that the backaction heating of the atomic ensemble is at the level required for quantum-limited measurements. Using the relation between R_c and S_{nn}, the measured heating rate may be interpreted as a measurement of the spectral density of intracavity photon number fluctuations where the atomic ensemble is used as a mechanical sensing medium for these fluctuations. From the measured maximum heating rate of $R/R_{fs} = 43(10)$, the error being predominantly systematic, and incorporating the convolved cavity line shape, we obtain the spectral noise power of photon fluctuations in a resonantly driven cavity as $S_{nn}/\bar{n} = 4.0(9) \times 10^{-7}$ s, in agreement with the predicted $S_{nn}/\bar{n} = 2/\kappa = 4.8 \times 10^{-7}$ s.

We have shown that heating due to cavity-induced fluctuations of the optical dipole force dominates the heating of a trapped atomic gas near resonance. To highlight this finding further, we measured the atom heating rate due to intracavity light that is far from the cavity resonance, for which we should observe the spontaneous-emission-dominated heating of atoms in free space. For a atom–cavity detuning of $\Delta_{ca} = 2\pi \times 29.6$ GHz and $N \simeq 9{,}000$ atoms, we excited the cavity for a variable time with probe light at detuning $\Delta = 2\pi \times 40$ MHz with an intracavity photon number of $\bar{n} = 2$. From the decay rate of N, we observed a probe-light-induced per-atom loss rate that, if ascribed completely to diffusive heating of the atomic sample, yields a heating rate of $R/R_{fs} = 2.9(7)$, far smaller than that observed at the cavity resonance. Yet, these losses exceeded those expected based on diffusion from Rayleigh scattering. This discrepancy may be explained by further 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 extra effects seem sufficient to account for our observations at the large probe detuning, yet are shown by our measurements to contribute only slightly to the atom losses observed from probe light at the cavity resonance.

This work demonstrates the bright prospects for studying quantum aspects of the motion of macroscopic ($N_{\mathrm{eff}} \simeq 10^5$ atoms) mechanical systems. The optical confinement of ultracold atoms within a high-finesse optical resonator enabled the construction of a nearly ground-state mechanical resonator. The quantitative measurement of quantum backaction on a macroscopic object is a powerful demonstration of the ultracold-atom approach to quantum micromechanics.

Working in the non-granular regime and with an atomic medium at sufficiently low temperatures so that coherent amplification and damping could be neglected, we may interpret the measured backaction heating as a direct measurement of the spectrum of photon fluctuations in a driven cavity, a quantity of fundamental interest in quantum optics. We note that these fluctuations are not visible in the coherent light transmitted through the cavity, for which the shot-noise spectrum remains white (see the Supplementary Information). 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 collective 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 collective motion, as demonstrated in ref. 21, our set-up may also serve to probe quadrature-squeezed light before the intracavity squeezing is degraded by attenuation outside the cavity[29].

We have demonstrated that atoms in a strong-coupling cavity are heated optically at a rate that exceeds that calculated for free-space illumination. This fact presents a challenge to cavity-aided non-destructive measurements of atom number or spin with uncertainty below the standard quantum limit[30–35]. 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. Our work suggests that cavities with single-atom cooperativity beyond $C = 1$ will yield benefits to these measurements only if the measurement is made insensitive to the atomic position, for example, by placing atoms at antinodes of the cavity field or in traps for which $\omega_z \gg \kappa$.

Received 2 January 2008; accepted 23 April 2008; published 18 May 2008.

References

1. Kleckner, D. & Bouwmeester, D. Sub-kelvin optical cooling of a micromechanical resonator. *Nature* **444**, 75–78 (2006).
2. Poggio, M. *et al.* Feedback cooling of a cantilever's fundamental mode below 5 mK. *Phys. Rev. Lett.* **99**, 017201 (2007).
3. Arcizet, O. *et al.* Radiation-pressure cooling and optomechanical instability of a micromirror. *Nature* **444**, 71–74 (2006).
4. Gigan, S. *et al.* Self-cooling of a micromirror by radiation pressure. *Nature* **444**, 67–70 (2006).
5. Naik, A. *et al.* Cooling a nanomechanical resonator with quantum back-action. *Nature* **443**, 193–196 (2006).
6. Thompson, J. D. *et al.* Strong dispersive coupling of a high-finesse cavity to a micromechanical membrane. *Nature* **452**, 72–75 (2008).
7. Schliesser, A. *et al.* Radiation pressure cooling of a micromechanical oscillator using dynamical backaction. *Phys. Rev. Lett.* **97**, 243905 (2006).
8. Huang, X. M. H. *et al.* Nanodevice motion at microwave frequencies. *Nature* **421**, 496 (2003).
9. Horak, P. *et al.* Cavity-induced atom cooling in the strong coupling regime. *Phys. Rev. Lett.* **79**, 4974–4977 (1997).
10. Vuletić, V. & Chu, S. Laser cooling of atoms, ions or molecules by coherent scattering. *Phys. Rev. Lett.* **84**, 3787–3790 (2000).
11. Marquardt, F. *et al.* Quantum theory of cavity-assisted sideband cooling of mechanical motion. *Phys. Rev. Lett.* **99**, 093902 (2007).
12. Vitali, D. *et al.* Macroscopic mechanical oscillators at the quantum limit through optomechanical cooling. *J. Opt. Soc. Am. B* **20**, 1054–1065 (2003).
13. Wilson-Rae, I. *et al.* Theory of ground state cooling of a mechanical oscillator using dynamical backaction. *Phys. Rev. Lett.* **99**, 093901 (2007).
14. Bouchoule, I. *et al.* Neutral atoms prepared in Fock states of a one-dimensional harmonic potential. *Phys. Rev. A* **59**, R8–R11 (1999).
15. Harber, D. *et al.* Measurement of the Casimir-Polder force through center-of-mass oscillations of a Bose–Einstein condensate. *Phys. Rev. A* **72**, 033610 (2005).
16. Mohideen, U. & Roy, A. Precision measurement of the Casimir force from 0.1 to 0.9 μm. *Phys. Rev. Lett.* **81**, 4549–4552 (1998).
17. Hood, C. *et al.* The atom-cavity microscope: single atoms bound in orbit by single photons. *Science* **287**, 1447–1453 (2000).
18. Mabuchi, H. *et al.* Real-time detection of individual atoms falling through a high-finesse optical cavity. *Opt. Lett.* **21**, 1393–1395 (1996).
19. Brennecke, F. *et al.* Cavity QED with a Bose–Einstein condensate. *Nature* **450**, 268–271 (2007).
20. Colombe, Y. *et al.* Strong atom-field coupling for Bose–Einstein condensates in an optical cavity on a chip. *Nature* **450**, 272–276 (2007).
21. Gupta, S. *et al.* Cavity nonlinear optics at low photon numbers from collective atomic motion. *Phys. Rev. Lett.* **99**, 213601 (2007).
22. Dorsel, A. *et al.* Optical bistability and mirror confinement induced by radiation pressure. *Phys. Rev. Lett.* **51**, 1550–1553 (1983).
23. Caves, C. M. Quantum-mechanical noise in an interferometer. *Phys. Rev. D* **23**, 1693–1708 (1981).
24. Marquardt, F., Harris, J. G. E. & Girvin, S. M. Dynamical multistability induced by radiation pressure in high-finesse micromechanical optical cavities. *Phys. Rev. Lett.* **96**, 103901 (2006).
25. Dalibard, J. & Cohen-Tannoudji, C. Dressed-atom approach to atomic motion in laser light: The dipole force revisited. *J. Opt. Sci. Am. B* **2**, 1707–1720 (1985).
26. Gordon, J. P. & Ashkin, A. Motion of atoms in a radiation trap. *Phys. Rev. A* **21**, 1606–1617 (1980).
27. Maunz, P. *et al.* Normal-mode spectroscopy of a single-bound-atom–cavity system. *Phys. Rev. Lett.* **94**, 033002 (2005).
28. Münstermann, P. *et al.* Dynamics of single-atom motion observed in a high-finesse cavity. *Phys. Rev. Lett.* **82**, 3791–3794 (1999).
29. Loudon, R. & Knight, P. Squeezed light. *J. Mod. Opt.* **34**, 709–795 (1987).
30. Kuzmich, A., Bigelow, N. P. & Mandel, L. Atomic quantum non-demolition measurements and squeezing. *Europhys. Lett.* **42**, 481–486 (1998).
31. Takahashi, Y. *et al.* Quantum nondemolition measurement of spin via the paramagnetic Faraday rotation. *Phys. Rev. A* **60**, 4974–4979 (1999).
32. Bouchoule, I. & Mølmer, K. Preparation of spin-squeezed atomic states by optical-phase-shift measurement. *Phys. Rev. A* **66**, 043811 (2002).
33. Auzinsh, M. *et al.* Can a quantum nondemolition measurement improve the sensitivity of an atomic magnetometer? *Phys. Rev. Lett.* **93**, 173002 (2004).
34. Hald, J. *et al.* Spin squeezed atoms: a macroscopic entangled ensemble created by light. *Phys. Rev. Lett.* **83**, 1319–1322 (2000).
35. Geremia, J. & Mabuchi, J. K. S. Real-time quantum feedback control of atomic spin-squeezing. *Science* **304**, 270–273 (2004).

Supplementary Information accompanies this paper on www.nature.com/naturephysics.

Acknowledgements

We thank T. Purdy and S. Schmid for early contributions to the experimental apparatus, and S. M. Girvin, J. Harris, H. J. Kimble, H. Mabuchi and M. Raymer for helpful discussions. This work was supported by AFOSR, DARPA and the David and Lucile Packard Foundation.

Author contributions

K.W.M., K.L.M. and S.G. contributed experimental work, data analysis and theoretical work to the article and supplemental information. D.M.S.-K. contributed project guidance, data analysis and theoretical work.

Author information

Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to D.M.S.-K.