Quantum control of complex objects in the regime of large size and mass provides opportunities for sensing applications and tests of fundamental physics. The realization of such extreme quantum states of matter remains a major challenge. We demonstrate a quantum interface that combines optical trapping of solids with cavity-mediated light-matter interaction. Precise control over the frequency and position of the trap laser with respect to the optical cavity allowed us to laser-cool an optically trapped nanoparticle into its quantum ground state of motion from room temperature. The particle comprises 105 atoms, similar to current Bose-Einstein condensates, with the density of a solid object. Our cooling technique, in combination with optical trap manipulation, may enable otherwise unachievable superposition states involving large masses.

Optical levitation of dielectric particles works by using forces induced by laser light that are strong enough to overcome gravity. At its most fundamental level, an incoming laser polarizes the dielectric material, which in turn interacts with the radiation field of the laser. As a consequence, a particle in a tightly focused laser beam experiences a gradient force toward the intensity maximum of the beam, resulting in a three-dimensional confinement of the particle (1). Such “optical tweezers” have become a powerful tool to manipulate dielectric objects in isolation from other environments.

In the domain of quantum physics, optical trapping and cooling of atoms has enabled the study of individual atoms and quantum gases. It is also a fundamental technique for confining particles to optical lattice geometries for the study of many-body quantum phenomena. As such, laser cooling techniques should enable the preparation of a levitated solid-state particle in its quantum ground state of motion (2–4). The particle wave packet can then be expanded and modified by a sequence of free fall, coherent manipulations, and quantum measurement operations (5). This provides a promising platform for exploring macroscopic quantum phenomena. It entails the ability to manipulate the spatial profile of the trapping laser for implementing nonlinear potentials, and may open the possibility of creating nonclassical states of motion such as non-Gaussian states or large spatial superpositions. This is in stark contrast to experiments that prepare motional quantum states using solid-state harmonic oscillators, where coupling to external nonlinear systems or measurements provides the interaction for nonclassical state preparation (6–8). Unlike ultracold quantum gases, motional quantum states of trapped solids involve the collective motion of all atoms and hence provide a natural way toward spatial superpositions of large mass differences in so-called Schrödinger cat states, which is a fundamentally hard task for gaseous systems (9).

A key requirement for entering this new regime is to prepare the particle wave packet in a sufficiently pure quantum state—in this case, to cool its motion into the quantum ground state. One possibility is to monitor the particle motion with a sensitivity at or below the ground-state size of the wave packet and apply a feedback force to directly counteract the motion. Such feedback cooling to the quantum ground state has recently been demonstrated for harmonic modes of cryogenically cooled micromechanical membranes (10). In the context of levitated nanoparticles, feedback cooling was initially introduced to provide stable levitation in high vacuum. At present, feedback cooling is limited to approximately four motional quanta (phonons) (11). A different approach is derived from the laser cooling of atoms, where the absorption and emission of Doppler-shifted laser photons provide a velocity-dependent scattering force. The presence of an optical cavity modifies the electromagnetic boundary conditions for the scattered light. We can use this to tailor the scattering rates and therefore cool particles without an accessible internal level structure, such as molecules or dielectric solids (12, 13). These cavity-cooling schemes have been used in the past to achieve ground-state cooling of various systems ranging from individual atoms to cryogenically cooled modes of solid-state nano- and micromechanical oscillators in the context of cavity optomechanics (14). Previous attempts to apply cavity cooling to levitated solids have proven challenging, and cooling was limited to several hundred phonons (15–18), mainly as a result of co-trapping associated with high intracavity photon number and excessive laser phase noise heating at low motional frequencies (<1 MHz) (17, 18).

We apply a modified scheme—cavity cooling by coherent scattering (19–21)—that circumvents these shortcomings and enables direct ground-state cooling of a solid in a room-temperature environment.

In our experimental setup, we trap a spherical silica particle inside a vacuum chamber using an optical tweezer. A tightly focused laser beam (power in the focus $P_{\text{tw}} \approx 400 \text{ mW}$, wavelength $\lambda = 1064 \text{ nm}$, and frequency $\omega_{\text{tw}} = 2\pi c/\lambda$, where $c$ is the speed of light in vacuum) creates a three-dimensional harmonic potential for the particle motion with motional frequencies $(\Omega_x, \Omega_y, \Omega_z)/2\pi = (305, 275, 80) \text{ kHz}$. We position the particle within an optical cavity (cavity finesse $F \approx 73,000$; cavity linewidth $\kappa/2\pi = 193 \pm 4 \text{ kHz}$; cavity frequency $\omega_{\text{cav}} = \omega_{\text{tw}} + \Delta$, where $\Delta$ is the laser detuning), which collects the tweezer light scattered off the nanoparticle under approximately a right angle (Fig. 1A). The particle has subwavelength dimension and hence resembles, to a good approximation, a dipole emitter. When driven by the optical tweezer, the particle coherently scatters dipole radiation predominantly orthogonal to the tweezer polarization axis. Motorized translation stages in the tweezer optics allow us to position the particle with an accuracy of a few nanometers with respect to the cavity axis (z-direction) such that the particle can be well localized within one period of the cavity standing wave field. To achieve optimal cooling along the cavity axis, the particle needs to be located at an intensity minimum of the cavity standing wave field (19, 20). At that location the particle is “dark,” and accordingly all dipole scattering into the cavity mode is inhibited because of destructive interference imposed by the cavity. The particle motion breaks this symmetry, and therefore only inelastically scattered Stokes- and anti-Stokes photons at sideband frequencies $\omega_{\text{cav}} \pm \Omega_z$ can propagate in the cavity.

Cavity cooling of the particle motion occurs because Stokes scattering processes along the cavity, which increase the kinetic energy of the particle by $\hbar \Omega_z$ per photon, are suppressed, while anti-Stokes scattering processes, which reduce the energy accordingly, are enhanced (14). This process is maximized at the optimal detuning $\Delta = \Omega_z$, where the anti-Stokes sideband becomes fully resonant with the cavity. A particle in its quantum ground state of motion cannot further reduce its energy, hence anti-Stokes scattering close to the ground state is fundamentally inhibited (Fig. 1, B and C).
resulting sideband asymmetry in the scattering rates is a direct measure of the temperature of the harmonic particle motion, which does not require calibration to a reference bath (22). We observe these sidebands, which are modulated by the cavity envelope (23), using frequency-selective heterodyne detection of the cavity output, specifically by mixing it with a strong local oscillator field \( P_{LO} = 400 \mu W \) detuned from the tweezer laser by \( 8 \omega_{loc}/2 \pi = 10.2 \text{ MHz} \).

Independent measurements of the cavity linewidth \( \kappa \) and the laser detuning \( \Delta \) allow us to correct the detected sideband ratios for the cavity envelope (24), and hence to extract the motional temperature of the particle via the fundamental sideband asymmetry (Fig. 2A). For this method to work reliably, it is important to exclude all relevant influences of noise contributions to the sideband asymmetry (25). We ensure this by confirming that the detection process is shot noise–limited and that both amplitude- and phase-noise contributions of the drive laser are negligible (24). Figure 2B shows the measured phonon number \( \hat{n}_x \) along the cavity axis for different laser detunings \( \Delta \). For near-optimal detuning of \( \Delta/2\pi = 315 \text{ kHz} \), we observe a final occupation as low as \( \hat{n}_x = 0.43 \pm 0.03 \), corresponding to a temperature of \( 12.2 \pm 0.5 \text{ µK} \) and a ground-state probability of \( 70 \pm 2 \% \). That in contrast to previous quantum experiments involving cryogenically cooled solid-state oscillators, ground-state cooling here is achieved in a room-temperature environment.

The final occupation \( \hat{n}_{\text{fin}} \) along any direction is reached when the total heating rate \( \Gamma_{\text{tot}} \) is balanced by the cooling rate \( \hat{n}_{\text{fin}} \times \gamma \), where \( \gamma \) is the linewidth of the motional sidebands (26). For the resolved sideband regime \( (\kappa < \Omega_c) \) as studied here, and in the absence of any other heating mechanisms, Stokes scattering due to the finite cavity linewidth limits cooling with optimal parameters to a minimum phonon occupation of \( \hat{n}_{\text{fin}} = (\kappa/4\Omega_c)^2 = 0.025 \). Note that in this case, detailed balance implies that the fundamental ground-state asymmetry exactly compensates the effect of the cavity envelope and therefore both sidebands have equal power. Additional sources of heating are balanced by larger anti-Stokes scattering, which results in the overall observed sideband imbalance. By independently measuring \( \hat{n}_x \) and \( \gamma \), we extract a total heating rate as low as \( \Gamma_{\text{tot}}/2\pi = 20.6 \pm 2.3 \text{ kHz} \) at a pressure of \( \sim 10^{-6} \text{ mbar} \). This is consistent with the separately measured heating rate due to background gas collisions (18), \( \Gamma_{\text{gas}}/2\pi = 16.1 \pm 1.2 \text{ kHz} \), and the expected heating contributions from photon recoil, \( \Gamma_{\text{rec}}/2\pi = 6 \text{ kHz} \), and from laser phase noise, \( \Gamma_{\text{phase}}/2\pi < 200 \text{ Hz} \).
In future experiments, reduction of decoherence can be achieved mainly by lower background pressures, but potentially also by operating at lower temperatures and using smaller cavity mode volumes. At present, using the measured heating rates, we estimate a maximum coherence time of $7.6 \pm 1$ $\mu$s in the optical trap, corresponding to approximately 15 coherent oscillations before populating the ground state with one phonon ($2, 27$). In a free-fall experiment, where the particle would be released from the optical trap, the dominant source for decoherence is the collision with background gas molecules. At the achieved pressure of $10^{-9}$ mbar, this limits the free-fall coherence time to $1.4$ $\mu$s, which would allow for an expansion of the wave packet by approximately a factor of 3, from the ground state size of 3.1 pm to 10.2 pm ($24, 28$). Larger wave packet sizes can be achieved by further decreasing this decoherence rate—for example, by operating at much lower pressures. Blackbody radiation will then become the dominant source of decoherence and will, for our room-temperature parameters, allow for wave packet expansions up to several nanometers. A wave packet size on the order of the particle radius could be achieved by combining ultrahigh vacuum (approximately $10^{-11}$ mbar) with cryogenic temperatures (below 130 K).

The combination of cavity optomechanical quantum control of levitated systems and free-fall experiments can open up a new regime of macro–quantum physics, with additional potential applications in quantum sensing ($29$) and other fields of fundamental physics ($30$). Most important, we believe that the quantum control of levitated systems is a viable route toward experiments in which quantum systems can act as gravitational source masses, as was originally suggested by Feynman ($31$) and recently revisited in the context of levitation ($32, 33$).

REFERENCES AND NOTES

24. See supplementary materials.

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SUPPLEMENTARY MATERIALS

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Supplementary Text

Figs. S1 to S7
References (34–57)

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