Scalable all-optical cold damping of levitated nanoparticles

Jayadev Vijayan1, Zhao Zhang1, Johannes Piotrowski1, Dominik Windey1, Fons van der Laan1, Martin Frimmer1 & Lukas Novotny1,2

Motional control of levitated nanoparticles relies on either autonomous feedback via a cavity or measurement-based feedback via external forces. Recent demonstrations of the measurement-based ground-state cooling of a single nanoparticle employ linear velocity feedback, also called cold damping, and require the use of electrostatic forces on charged particles via external electrodes. Here we introduce an all-optical cold damping scheme based on the spatial modulation of trap position, which has the advantage of being scalable to multiple particles. The scheme relies on programmable optical tweezers to provide full independent control over the trap frequency and position of each tweezer. We show that the technique cools the centre-of-mass motion of particles along one axis down to 17 mK at a pressure of 2 × 10⁻⁶ mbar and demonstrate its scalability by simultaneously cooling the motion of two particles. Our work paves the way towards studying quantum interactions between particles; achieving three-dimensional quantum control of particle motion without cavity-based cooling, electrodes or charged particles; and probing multipartite entanglement in levitated optomechanical systems.

The success of quantum theory has led to the emergence of experimental platforms seeking to harness quantum properties to understand the fundamental aspects of nature as well as to develop next-generation technology. Levitodynamics approaches this task by using an optical tweezer to suspend a dielectric nanoparticle in ultrahigh vacuum, resulting in a highly isolated mechanical oscillator1,2. The level of control achieved in levitated optomechanical systems has led to cooling the centre-of-mass (c.m.) motion of a nanoparticle to its quantum ground state3–5 and the development of inertial6–9 and field10–12 sensors.

Scaling up to multiple particles will open up new avenues of research, including probing quantum correlations and entanglement13–16, complex phases emerging from interacting particles17–20 and sensing of weak forces21–25. Investigating these phenomena with levitated optomechanical systems requires three ingredients: (1) trapping of multiple particles, (2) cooling their motional degrees of freedom and (3) controlling the interactions between them. Here we introduce a scalable experimental platform capable of optically trapping multiple dielectric nanoparticles with tunable separation, based on techniques developed by the cold atom community26–30. The particles are trapped using a programmable array of optical tweezers generated by radiofrequency (rf) tones driving an acousto-optical deflector (AOD), allowing independent control of both trap position and trap frequency of each particle. We then introduce an all-optical linear feedback cooling scheme that cools the motional degrees of freedom of each particle along the AOD axis by modulating the spatial position of the optical traps at the trap frequency, with the optical intensity gradient providing the restoring force31,32. We demonstrate the scalability of this cold damping scheme by simultaneously cooling the c.m. motion of a pair of particles along the AOD axis.

Our scalable cooling scheme also stands out by its simplicity33,34. It does not rely on optical cavities3,35–37, near-field probes38, charged particles or external electrodes13,17. In fact, the use of electrostatic forces severely limits the potential use of levitated optomechanical systems as sensing devices or platforms to probe quantum entanglement40, making our all-optical scheme uniquely suited for such applications. The all-optical cold damping scheme, thus, serves as a complementary technique to parametric cooling41,42 and as an alternative to electrostatic linear feedback cooling for multiple particles independent of...
their charge. By utilizing the same tweezer for trapping, detection and cooling, we simplify the components required for cold damping in levitodynamics experiments.

**Experimental setup**

Our mechanical oscillators are single spherical SiO₂ nanoparticles with a nominal diameter of 117 nm, which are levitated in high vacuum using optical tweezers at wavelength \( \lambda = 1.550 \) μm and optical power \( P = 200 \) mW, focused by a high-numerical-aperture (NA = 0.75) lens. The setup makes use of an AOD to generate a tweezer array \( \omega_i \) and a telescope to angle the beams towards the high-NA lens, resulting in optical traps for multiple nanoparticles (Fig. 1a). The tweezer array is generated by sending multiple rf tones \( \omega_i \) as input to the AOD, resulting in several first-order deflected beams propagating along the \( z \) axis, shifted in frequency by \( \omega_i \) and emerging with different geometric angles along the \( y \) axis. By changing the frequencies of the rf tones, we steer the first-order beams and consequently change the positions of the optical tweezers. By construction, the tweezers are at different optical frequencies, which highly suppresses dipole–dipole interactions between the particles \( 43 \).

In our experiment, the spatial separation between the particles can be tuned up to \( d = 20 \) μm, limited by the geometry of the setup and the bandwidth of the deflector. In addition, we control the amount of optical power in the diffracted beams by tuning the amplitude of the rf tones sent to the AOD. Tuning the optical power changes the stiffness of the trap, which can be used to parametrically cool the particle motion \( 14 \).

The light scattered by the particles in the forward direction, as well as light passing by the particles, is interfered on two quadrant photodetectors (QPDs), resulting in the homodyne detection of the particles’ c.m. motion \( ^{16} \). By subtracting the left (upper) and right (lower) quadrant from each other, we obtain a detection signal that is primarily sensitive to the \( y (x) \) motion of the particles (Fig. 1b). Due to the tilted alignment of the beam, we also detect the \( z \) motion on the QPDs. The two QPDs act as in-loop and out-of-loop detectors to linearly cool and independently detect the particles’ \( x \) and \( y \) motion \( ^{33,39} \) (see the ‘Detection schemes’ section). The light scattered by each particle in the backward direction is split off and interfered on detectors with backreflections from the vacuum window, primarily detecting the \( z \) motion of the particles \( ^{43} \). For the experiments that follow, we cool the particle motion along the \( z \) axis using parametric feedback to avoid nonlinearities in the trapping potential \( ^{15} \). To derive the particle c.m. temperatures, we rely on the calibration techniques outlined in another work \( ^{45} \).

**All-optical feedback cooling of a single particle**

Active, measurement-based feedback cooling schemes have been deployed to cool the c.m. motion of single nanoparticles in several recent experiments, and can be generally classified into two types: parametric and linear feedback cooling. In parametric feedback cooling, the measured signal is filtered, phase shifted and fed back at twice the frequency of particle motion. Typically, parametric feedback is applied by modulating the optical power of the tweezer \( ^{44} \), and has been used to cool the c.m. motion to several tens of phonons \( ^{45} \). In linear feedback cooling, or cold damping, the measured signal is filtered, phase shifted and applied as a direct force at the trap frequency of the particle. Cold damping schemes have been used to cool the motion of charged particles \( ^{9,46–48} \) by applying a viscous electrostatic force at the trap frequency. Such schemes have recently been used to cool the motion of a charged nanoparticle along the beam propagation direction \( 2 \) to the quantum ground state \( ^{49} \).

Our all-optical linear feedback does not require electrodes or charged particles. Rather than modulating the voltage applied to external electrodes, we modulate the spatial position of the tweezer along the AOD axis \( (y) \) at the frequency of particle motion. The gradient force acts as a restoring force, which increases with the relative distance between the tweezer and particle. In our experiment, trapping beams are generated by applying rf tones to the AOD. By appropriately choosing the amplitude and frequency of the tones, both parametric and
linear feedback cooling can be simultaneously performed. Amplitude modulation of the rf tone at twice the trap frequency parametrically cools the particle motion, whereas frequency modulation of the tone at the trap frequency linearly cools the particle by spatial displacement.

Figure 2 shows an all-optical cold damping by modulating the spatial position of the tweezer. a. Measurement of particle motion along the y axis, using the out-of-loop detector. PSDs of the motional peak are shown at the pressure of $p_{\text{gas}} = 1 \times 10^{-4}$ mbar at low (red), medium (yellow) and high (blue) feedback gains. The solid lines are Lorentzian fits to the data. b. Measured centre-of-mass temperatures ($T_{\text{c.m.}}$) at three different pressures as a function of feedback damping rate $\gamma_{\text{fb}}$. At higher gains, when the PSD of particle motion is cooled close to the noise floor, the feedback signal becomes dominated by noise and the temperatures rise again. At the lowest pressure and optimal gain, the particle motion is cooled to a temperature of 17 mK. The error of $T_{\text{c.m.}}$ is obtained by splitting the measured time trace into five subdivisions and calculating the standard deviation of the area under each PSD, and are smaller than the marker for most data points. The shaded area corresponds to the estimated temperature ranges given fluctuations in pressure during data collection, as measured from the reheating experiments.

In the first step, we perform a ring-down sequence where linear feedback cooling is turned on for 200 ms, allowing the particle to exponentially equilibrate from a high c.m. temperature $T_{\text{gas}}$ to a low c.m. temperature $T_{\text{c.m.}}$ (Fig. 3b) according to $T_{\text{c.m.}}(t) = T_{\text{gas}} + (T_{\text{gas}} - T_{\text{c.m.}})\exp(-\gamma_{\text{fb}} t)$ (ref. 5). Then, the feedback is abruptly switched off, and the particle reheats through gas collisions until it equilibrates with the background gas temperature $T_{\text{gas}}$. Following the exponential growth given by $T_{\text{c.m.}}(t) = T_{\text{gas}} + (T_{\text{gas}} - T_{\text{c.m.}})\exp(-\gamma_{\text{gas}} t) = T_{\text{c.m.}} + \gamma_{\text{gas}} T_{\text{gas}} t$ for small $t$. As the reheating dynamics are very slow ($1/\gamma_{\text{gas}}>3$ s) at pressures of $p < 10^{-3}$ mbar, we limit the reheating time and therefore fit a linear slope instead of the full exponential curve. The protocol is repeated 90 times to extract both feedback damping rate from the ring-down sequence and gas damping rate from the reheating sequence. Crucially, measuring the particle motion during the ring-down and reheating cycles allows us to continuously track the PSDs of the particle as it is cooled under the cold damping scheme and then reheated by the gas when the feedback is turned off, that is, in the absence of tweezer modulation.

We repeat the non-equilibrium protocol and extract the damping rates for different pressures and fixed gain. The feedback damping rate $\gamma_{\text{fb}}$ is found to be independent of pressure, and the gas damping rate $\gamma_{\text{gas}} T_{\text{gas}}$ decreases linearly with pressure (see the ‘Reheating and ring-down measurements’ section). According to equation (1), in a regime of low feedback gain, we expect the particle c.m. temperature to be given by the ratio of gas reheating and feedback cooling rates as $T_{\text{c.m.}} = \gamma_{\text{gas}} T_{\text{gas}}/\gamma_{\text{fb}}$. We compare the temperatures extracted from the ratio of damping rates at different pressures with the temperatures extracted from the area under the PSDs (Fig. 3c) and find them in good agreement across the entire pressure range.

Furthermore, we estimate the ratio of the amplitude of spatial motion of the tweezer and the trapped particle to be about 4% at optimal cooling (see the ‘Linear feedback circuit for spatial modulation’ section).

### Simultaneous two-particle cooling

One of the benefits of linear feedback cooling via the modulation of position is the scalability to multiple particles. Since each rf tone entering the deflector is independently generated by different channels of a function generator and the optical power and spatial position of each tweezer are solely determined by the amplitude and frequency of the tone, a separate feedback loop can be applied to each tweezer (Fig. 4b). We split the output signal of the y channel of the QPD into two paths, each going into separate electronic filters. In both paths, notch filters are used to filter out all the frequencies, except for the motional frequency of interest $\Omega/4\pi$. Appropriate delays and gains are added to each path, before the signal is fed back as the frequency modulation.
enables the simultaneous two-axis cooling of both particles. The damping rates $c$ turned on. PSD of two particles when cold damping is simultaneously applied to each particle as a function of time. The fits (orange) are used to extract the feedback motion arising from residual nonlinearities in the potential, cooling the $y$ and $z$ motion also cools the $x$ degree of freedom. However, this effect is expected to vanish as the particle is cooled further and its motional amplitudes are reduced. Small differences in particle size or motion also cool the $x$ degree of freedom. However, this effect is expected to vanish as the particle is cooled further and its motional amplitudes are reduced. Small differences in particle size or detector alignment of the tweezers can lead to a slight asymmetry in the detection efficiency of the two particles’ motion. Consequently, we choose slightly different gain settings for the linear filter of the AOD, but far enough to avoid heating due to interference.

Combining the linear feedback scheme with parametric feedback via amplitude modulation at twice the $z$ frequencies of particle motion $f_b^{(2)}$ enables the simultaneous two-axis cooling of both particles. The PSD of two particles when cold damping is simultaneously applied to both particles at a pressure of $p_{gas} = 1 \times 10^{-4}$ mbar is shown in Fig. 4c. Due to coupling between the different axes of the particle’s oscillatory motion arising from residual nonlinearities in the potential, cooling the $y$ and $z$ motion also cools the $x$ degree of freedom. However, this effect is expected to vanish as the particle is cooled further and its motional amplitudes are reduced. Small differences in particle size or detector alignment of the tweezers can lead to a slight asymmetry in the detection efficiency of the two particles’ motion. Consequently, we choose slightly different gain settings for the linear filter of the feedback loop, to obtain the same cooling rates $y_n$ for both particles.
(see the ‘Calibration of feedback gain’ section). With these adjustments, both particles can be simultaneously cooled to the same temperature (Fig. 4d).

Our cold damping scheme can be scaled up an order of magnitude by increasing the available optical power, as long as the motional peaks of the particles are spectrally separated by >5 kHz. However, to scale up by another order of magnitude or have particles with identical trap frequencies, both tweezer array generation and detection schemes would have to be modified. Generating large particle arrays with separation greater than 1 μm would require either an AOD with a larger bandwidth or two AODs to generate two-dimensional tweezer arrays. The detection and individual feedback cooling of large particle arrays can be achieved by spatially distributing the forward-scattered light or using a heterodyne detection scheme. We discuss these options in detail in the ‘Scalability of nanoparticle arrays’ section.

Conclusions

We have demonstrated an experimental platform capable of trapping and cooling multiple nanoparticles. By programming the rf tones driving the AOD, we achieve independent control of both position and trap frequency of each particle. We introduced an all-optical cold damping scheme based on the modulation of spatial displacement, which allows the usage of a single tweezer to perform trapping, cooling and detection of particle motion. Finally, we showed that the feedback cooling techniques are scalable to two particles.

The lowest temperatures we currently achieve are limited by the background pressure in the chamber as well as the detection efficiency of particle motion. Lower pressures can be achieved by baking the chamber and result in lower temperatures until we become limited by radiation-pressure shot noise. Feedback-based ground-state cooling requires adding lenses or an optical cavity along the y axis to provide a higher detection efficiency for the light scattered by the particle along the transverse direction. An optical cavity can be used to enable tunable long-range interactions between spatially separated nanoparticles, to probe hybrid modes, and to potentially generate motional quantum entanglement. Passive ground-state cooling of multiple nanoparticles can be achieved by placing them at nodes of the cavity standing wave and appropriately detuning the tweezers. Furthermore, the all-optical cold damping scheme can be readily extended to both transverse directions (x and y) by introducing a second AOD, oriented orthogonal to the first. In this way, the motion of multiple particles can be cooled along both x and y axes. Combined with parametric cooling along z, our protocol can achieve the three-dimensional cooling of multiple levitated particles entirely by optical means.

Note added in proof: We recently became aware of related work using two methods.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41565-022-01254-6.

References

1. Millen, J., Monteiro, T. S., Pettit, R. & Vamivakas, A. N. Optomechanics with levitated particles. Rep. Prog. Phys. 83, 026401 (2020).
2. González-Ballestero, C., Aspelmeyer, M., Novotny, L., Quidant, R. & Romero-Isart, O. Levitodynamics: levitation and control of microscopic objects in vacuum. Science 374, eabg3027 (2021).
3. Delić, U. et al. Cooling of a levitated nanoparticle to the motional quantum ground state. Science 367, 892–895 (2020).
4. Tebbenjohanns, F., Mattana, M. L., Rossi, M., Frimmer, M. & Novotny, L. Quantum control of a nanoparticle optically levitated in cryogenic free space. Nature 595, 378–382 (2021).
5. Magrini, L. et al. Real-time optimal quantum control of mechanical motion at room temperature. Nature 595, 373–377 (2021).
6. Timberlake, C., Gasbarri, G., Virante, A., Setter, A. & Ulbricht, H. Acceleration sensing with magnetically levitated oscillators above a superconductor. Appl. Phys. Lett. 115, 224101 (2019).
7. Monteiro, F. et al. Force and acceleration sensing with optically levitated nanomass arrays at microkelvin temperatures. Phys. Rev. A 101, 053835 (2020).
8. Ahn, J. et al. Ultrasonic torque detection with an optically levitated nanorotor. Nat. Nanotechnol. 15, 89–93 (2020).
9. van der Laan, F. et al. Sub-kelvin feedback cooling and heating dynamics of an optically levitated librator. Phys. Rev. Lett. 127, 123605 (2021).
10. Ranjit, G., Cunningham, M., Casey, K. & Geraci, A. C. Zeptonewton force sensing with nanospheres in an optical lattice. Phys. Rev. A 93, 053801 (2016).
11. Hempston, D. et al. Force sensing with an optically levitated charged nanoparticle. Appl. Phys. Lett. 111, 133111 (2017).
12. Hebestreit, E., Frimmer, M., Reimann, R. & Novotny, L. Sensing static forces with free-falling nanoparticles. Phys. Rev. Lett. 121, 063602 (2018).
13. Chauhan, A. K., Černotík, O. & Filip, R. Stationary Gaussian entanglement between levitated nanoparticles. New J. Phys. 22, 123021 (2020).
14. Brandão, I., Tandeitnik, D. & Guerreiro, T. Coherent scattering-mediated correlations between levitated nanospheres. Quantum Sci. Technol. 6, 045013 (2021).
15. Potel, S. et al. Direct observation of deterministic macroscopic entanglement. Science 372, 622–625 (2021).
16. de Lépinay, L. M., Ockeloen-Korppi, C. F., Woolley, M. J. & Sillanpää, M. A. Quantum mechanics–free subsystem with mechanical oscillators. Science 372, 625–629 (2021).
17. Reimann, R. et al. Cavity-modified collective Rayleigh scattering of two atoms. Phys. Rev. Lett. 114, 023601 (2015).
18. Landig, R. et al. Quantum phases from competing short- and long-range interactions in an optical lattice. Nature 532, 476–479 (2016).
19. Bernien, H. et al. Probing many-body dynamics on a 51-atom quantum simulator. Nature 551, 579–584 (2017).
20. Liu, S., Yin, Z.-q & Li, T. Prethermalization and nonreciprocal phonon transport in a levitated optomechanical array. Adv. Quantum Technol. 3, 1900099 (2020).
21. Perival, A. et al. Programmable interactions and emergent geometry in an array of atom clouds. Nature 600, 630–635 (2021).
22. Bressi, G., Carugno, G., Onofrio, R. & Ruoso, G. Measurement of the Casimir force between parallel metallic surfaces. Phys. Rev. Lett. 88, 041804 (2002).
23. Wang, M. et al. Strong geometry dependence of the Casimir force between interpenetrated rectangular gratings. Nat. Commun. 12, 600 (2021).
24. Quinn, T. J., Speake, C. C., Richman, S. J., Davis, R. S. & Picard, A. A new determination of G using two methods. Phys. Rev. Lett. 87, 111101 (2001).
25. Li, Q. et al. Measurements of the gravitational constant using two independent methods. Nature 560, 582–588 (2018).
26. Kaufman, A. M. et al. Two-particle quantum interference in tunnel-coupled optical tweezers. Science 345, 306–309 (2014).
27. Barredo, D., de Léséleuc, S., Lienhard, V., Lahaye, T. & Browaeys, A. An atom-by-atom assembler of defect-free arbitrary two-dimensional atomic arrays. Science 354, 1021–1023 (2016).
28. Endres, M. et al. Atom-by-atom assembly of defect-free one-dimensional cold atom arrays. Science **354**, 1024–1027 (2016).
29. Barredo, D., de Léséleuc, S., Lienhard, V., Lahaye, T. & Browaeys, A. An atom-by-atom assembler of defect-free arbitrary two-dimensional atomic arrays. Science **354**, 1021–1023 (2016).
30. Ebadi, S. et al. Quantum phases of matter on a 256-atom programmable quantum simulator. Nature **595**, 227–232 (2021).
31. Monteiro, F., Bykov, D. S., Knoll, M., Mestres, P. & Northup, T. E. Optical levitation of 10-ng spheres with nano-g acceleration sensitivity. Phys. Rev. A **96**, 063841 (2017).
32. Li, T. Fundamental Tests of Physics with Optically Trapped Microspheres (Springer, 2013).
33. Dania, L., Bykov, D. S., Knoll, M., Mestres, P. & Northup, T. E. Optical and electrical feedback cooling of a silica nanoparticle levitated in a Paul trap. Phys. Rev. Research **3**, 013018 (2021).
34. Bang, J. et al. Five-dimensional cooling and nonlinear dynamics of an optically levitated nanodumbbell. Phys. Rev. Research **2**, 043054 (2020).
35. Delić, U. et al. Cavity cooling of a levitated nanosphere by coherent scattering. Phys. Rev. Lett. **122**, 123602 (2019).
36. Windey, D. et al. Cavity-based 3D cooling of a levitated nanoparticle via coherent scattering. Phys. Rev. Lett. **122**, 123601 (2019).
37. Meyer, N. et al. Resolved-sideband cooling of a levitated nanoparticle in the presence of laser phase noise. Phys. Rev. Lett. **123**, 153601 (2019).
38. Wilson, D. J. et al. Measurement-based control of a mechanical oscillator at its thermal decoherence rate. Nature **524**, 325–329 (2015).
39. Tebbenjohanns, F., Frimmer, M., Militaru, A., Jain, V. & Novotny, L. Cold damping of an optically levitated nanoparticle to microkelvin temperatures. Phys. Rev. Lett. **122**, 223601 (2019).
40. Rudolph, H., Hornberger, K. & Stickler, B. A. Entangling levitated nanoparticles by coherent scattering. Phys. Rev. A **101**, 011804 (2020).
41. Gieseler, J., Deutsch, B., Quidant, R. & Novotny, L. Subkelvin parametric feedback cooling of a laser-trapped nanoparticle. Phys. Rev. Lett. **109**, 103603 (2012).
42. Jain, V. et al. Direct measurement of photon recoil from a levitated nanoparticle. Phys. Rev. Lett. **116**, 243601 (2016).
43. Rieser, J. et al. Tunable light-induced dipole-dipole interaction between optically levitated nanoparticles. Science **377**, 987–990 (2022).
44. Tebbenjohanns, F., Frimmer, M. & Novotny, L. Optimal position detection of a dipolar scatterer in a focused field. Phys. Rev. A **100**, 043821 (2019).
45. Hebestreit, E. et al. Calibration and energy measurement of optically levitated nanoparticle sensors. Rev. Sci. Instrum. **89**, 033111 (2018).
46. Steiner, V., Rabl, P. & Zoller, P. Quantum feedback cooling of a single trapped ion in front of a mirror. Phys. Rev. A **72**, 043826 (2005).
47. Bushev, P. et al. Feedback cooling of a single trapped ion. Phys. Rev. Lett. **96**, 043003 (2006).
48. Iwasaki, M. et al. Electric feedback cooling of single charged nanoparticles in an optical trap. Phys. Rev. A **99**, 051401 (2019).
49. Cohadon, P. F., Heidmann, A. & Pinard, M. Cooling of a mirror by radiation pressure. Phys. Rev. Lett. **83**, 3174–3177 (1999).
50. Poggio, M., Degen, C. L., Mamin, H. J. & Rugar, D. Feedback cooling of a cantilever’s fundamental mode below 5 mK. Phys. Rev. Lett. **99**, 017201 (2007).
51. Rossi, M., Mason, D., Chen, J., Tsatsyan, Y. & Schliesser, A. Measurement-based quantum control of mechanical motion. Nature **563**, 53–58 (2018).
52. Gieseler, J., Quidant, R., DellaC, C. & Novotny, L. Dynamic relaxation of a levitated nanoparticle from a non-equilibrium steady state. Nat. Nanotechnol. **9**, 358–364 (2014).
53. Yan, J., Yu, X., Han, Z. V., Li, T. & Zhang, J. On-demand assembly of optically-levitated nanoparticle arrays in vacuum. Preprint at https://arxiv.org/abs/2207.03641 (2022).
54. Debnath, S. et al. Demonstration of a small programmable quantum computer with atomic qubits. Nature **536**, 63–66 (2016).
55. de los Ríos Sommer, A., Meyer, N. & Quidant, R. Strong optomechanical coupling at room temperature by coherent scattering. Nat. Commun. **12**, 276 (2021).
56. Toros, M., Delić, U. C. V., Hales, F. & Monteiro, T. S. Coherent-scattering two-dimensional cooling in levitated cavity optomechanics. Phys. Rev. Research **3**, 023071 (2021).
57. Rudolph, H., Delić, U., Aspelmeier, M., Hornberger, K. & Stickler, B. A. Force-gradient sensing and entanglement via feedback cooling of interacting nanoparticles. Phys. Rev. Lett. **129**, 193602 (2022).
58. Kamba, M., Shimizu, R. & Aikawa, K. Optical cold damping of neutral nanoparticles near the ground state in an optical lattice. Opt. Exp. **30**, 26716–26727 (2022).

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2022
Methods

Detection schemes
A complete sketch of the optical setup is shown in Extended Data Fig. 1. As described in the main text, we have two QPDs in the forward-scattering direction. One of the two QPDs, labelled QPD1, serves as an in-loop detector for our optical linear feedback cooling. The a.c. component of the voltage signal corresponding to the channel of QPD1 is amplified and sent to a field-programmable gate array (Red Pitaya STEMlab 125-14) that carries out three functions: (1) uses notch frequency filters to suppress the frequency components not relevant to feedback cooling; (2) introduces a tunable time delay, which shifts the phase of the feedback signal; and (3) amplifies the signal with a variable gain. The signal is then sent as a frequency modulation input to the appropriate channel of the function generator (MOGLabs Agile RF Synthesizer) driving the AOD (AA Opto-Electronic DSTX).

The second QPD in the forward direction, labelled QPD2, serves as an out-of-loop detector of particle motion. It is a home-built QPD that is designed to withstand higher optical power (50 mW) than the in-loop QPD (Thorlabs PDQ30C, 1 mW).

In the back-scattered direction, we use separate single-chip photodiodes, labelled PD, to measure the signal from either trapped particle. These detectors are primarily sensitive to the z motion of the particle. The output signal is used to generate a new oscillator (Zürich Instruments MFLI), which is then doubled in frequency, phase shifted and amplified. The output from the lock-in amplifier is fed back to the amplitude modulation input of the function generator and used to parametrically cool the z motion of the particles.

Finally, we have a heterodyne detection scheme in the back-scattered direction capable of spectrally resolving the signal from any number of particles. Typically, for two-particle experiments, we add rf tones centred at \( \omega_1 = 47 \text{ MHz} \) and \( \omega_2 = 53 \text{ MHz} \) and send the output to the AOD to generate the two tweezers. Consequently, the back-scattered light from the particle motion appears as sidebands around the carriers at frequencies of \( \omega_1 = 47 \text{ MHz} \) and \( \omega_2 = 53 \text{ MHz} \). By appropriately tuning a quarter-wave plate before the chamber, the back-scattered light can be sent back towards the AOD rather that be split off to the photodiodes PD. On passing through the AOD from the backwards direction, the tweezers are double-shifted in frequency (that is, they now appear as sidebands around a carrier shifted by \( 2 \times \Delta \omega = 94 \text{ MHz} \) and \( 2 \times \Delta \omega = 106 \text{ MHz} \)). The beams are spatially overlapped by construction, picked off using a combination of a Faraday rotator and polarizing beamsplitter, and coupled into an optical fibre. The same beamsplitter is used to split off a small fraction of the input light from the laser source and frequency shifted by \( \Delta \omega = 80 \text{ MHz} \) to be used as a local oscillator, and coupled into a fibre. The local oscillator at \( \omega_0 = 50 \text{ MHz} \) and the signal from the particles at \( 2 \times \omega_0 = 94 \text{ MHz} \) and \( 2 \times \omega_0 = 106 \text{ MHz} \) are then interfered and balanced to extract the motional sidebands around carriers at 14 and 26 MHz, respectively.

Scalability of nanoparticle arrays
The biggest advantages of trapping nanoparticles in optical tweezers arrays are their scalability and local control. Experiments with arrays of cold atoms have already demonstrated the trapping of hundreds of atoms in one and two dimensions. In the case of our all-optical cold damping, scalability does not simply refer to trapping multiple nanoparticles but also to feedback cooling of their motion.

Our cold damping scheme can be scaled up in an order of magnitude by increasing the laser power. Each of our nanoparticles requires about 150 mW of optical power at 1.550 nm to be stably trapped. Using a standard laser source with an output of 2−3 W, and taking into account losses in the optical path, tens of particles can be trapped in tweezers arrays generated by arbitrary waveform generators. Beyond this, it becomes necessary to consider the spatial extent of the tweezers array (currently 20 μm), which is determined by the bandwidth of the AOD (currently 20 MHz) and the telescope used between the AOD and trapping lenses (Fig. 1). Given a fixed bandwidth of the AOD and assuming a separation of at least 1 μm between the traps to prevent interference, scaling beyond ten particles will require changing the telescope—in particular, increasing the focal length of the second lens of the telescope.

Currently, our cooling scheme relies on the particles having different trap frequencies to perform independent feedback cooling. When scaling up to multiple particles, the spectral separation between the two motional peaks in the PSD needs to be at least 5 kHz for the notch filters to filter out the contribution from other particles. A straightforward alternative solution to detect the motion of the approximately ten particles would be to use spatial filters to distribute the forward-scattered light from each particle to a separate QPD for feedback.

To scale up by another order of magnitude (hundreds of particles), we would need to overcome the spatial-extent limit of the one-dimensional array mentioned above and to separately detect the motion of each particle for feedback. The former can be achieved by adding a second AOD orthogonal to the first, to generate a two-dimensional array of optical tweezers. The latter can be achieved in a few different ways. A brute-force way would be to use spatial masks to redistribute the forward-scattered light of each particle to separate detectors or to use photodetector arrays. A more elegant solution would be to use the heterodyne detection scheme discussed earlier. Since it relies on the spectral separation of the signal of each particle rather than spatial separation, it can be scaled up to any number of particles, as long as the double-shifted carriers are spectrally separated by at least 100 kHz, corresponding to the highest trap frequency of a single particle of around \( (2n \times 85 \text{ kHz}) \).

The bandwidth of the AOD of 20 MHz, this corresponds to 200 particles. In our experiment, the balanced heterodyne scheme is currently fibre based, leading to the motional information—except for that by frequency—being lost. Replacing the fibres with a free-space setup, where the signal beams are interfered with an appropriate local oscillator directly on a QPD, will allow us to feedback multiple cool particles with degenerate trap frequencies.

It is worth noting that a modified version of our cooling scheme can also be used to feedback multiple cool particles that have the same trap frequency. In the modified detection techniques mentioned above such as using spatial masks to distribute light from each particle to a separate detector and/or the heterodyne detection scheme, it does not matter what the trap frequency of each particle is because the signal from the two particles is indistinguishable. Therefore, by using the local feedback control afforded by the all-optical spatial-modulation-based feedback scheme (as opposed to electrostatic feedback via electrodes, which are global), we can also linearly cool the motion of multiple degenerate nanoparticles.

Linear feedback circuit for spatial modulation
The linear feedback loop used in the all-optical cold damping scheme is shown in detail in Extended Data Fig. 2A. The y motion of the particle is detected by the in-loop QPD, whose output is d.c. blocked, amplified and denoted as the in-looped signal \( V_y \). It is then sent to a field-programmable gate array (Red Pitaya), which first applies notch filters suppressing all the frequencies that are not relevant. The signal is then phase shifted and amplified. In our experiment, the gain factor at the Red Pitaya is set to 1. The filtered signal is sent as a frequency modulation input to the function generator driving the AOD.

The resulting frequency modulation around the central frequency of the tone \( \Delta \omega = G_{\text{loop}} V_y \), where \( G_{\text{loop}} \) is the controllable gain factor of the frequency modulation at the function generator and ranges from 1 to 30 kHz V\(^{-1}\) in the experiment. The frequency modulation of the rf driving the AOD leads to a modulating tilt angle of the diffracted first-order beam that eventually generates the trap: \( \Delta \theta = G_{\text{loop}} \Delta \omega \). Here \( G_{\text{loop}} \) (in rad Hz\(^{-1}\)), the gain factor of the AOD, is the ratio between its scan angle and input bandwidth. For the AOD that we use, the factor...
is $G_{\text{opt}} = 49$ mrad/20 MHz $= 2.5$ mrad MHz$^{-1}$. The tilt in the diffracted beam results in the spatial displacement of the tweezer position: \( \Delta y = \Delta \theta \times f_{\text{opt}} / M \), where $M = 0.6$ is the linear magnification of the telescope and $d_{\text{foc}} = 0.5$ mm is the effective focal length of the trapping lens inside the chamber. Finally, we obtain the total gain from the measured in-loop signal $V_0$ to the spatial modulation $\Delta y$ of the tweezer as $\Delta y = G V_0$, where $G = G_{\text{opt}} \approx 0.1$ nm kHz$^{-1}$. Since we are only interested in the c.m. motion of the particle along the y direction, we apply a band-pass filter $F_y$ in the range $G^0 = \pm 5$ kHz. Thus, the amplitude of tweezer modulation during feedback cooling has the form $\Delta y_0 = F_y G V_0 \approx 0.1$ nm kHz$^{-1}$. The modulation amplitude as a function of feedback gain is shown in Extended Data Fig. 2B.

We can do a simple scaling analysis of the various quantities in the feedback loop as a function of the gain factor at rf function generator, $G_{\text{rf}}$. The PSD contribution from the particle motion, which is proportional to the energy of the mode, is $A_{\text{particle}} = E = E_{\text{vac}} / T_\text{vac} = 1 / G_{\text{rf}}$, where $E$ is the energy of the mode of a cooled (uncooled) particle. The in-loop voltage is proportional to the square root of the PSD: $V_0 \propto A_{\text{particle}} \propto 1 / \sqrt{G_{\text{rf}}}$. The final tweezer modulation amplitude, which is the product of the in-loop voltage and total gain, is thus $\Delta y = G V_0 \propto \sqrt{G_{\text{rf}}}$ This matches the square root of static tweezer frequency (Extended Data Fig. 2B). For the largest feedback gains that we apply for the optimal cooling of the particle, the amplitude of tweezer motion is $\sim 15$ pm.

We can calculate the c.m. displacement of an optimally cooled particle at 17 mK using the following formula.

$$\frac{1}{2} m \omega^2 (x^2) = \frac{1}{2} k_0 T$$

(2)

$$\Rightarrow \sqrt{(x^2)} = \frac{k_0 T}{ma^2}$$

(3)

Substituting the values of our particle $(m = 7.69 \times 10^{-18}$ kg, $\omega = 2\pi \times 75$ kHz, $T = 17$ mK), we get a displacement of 0.37 nm. Hence, we can conclude that the ratio of the amplitude of spatial motion of the trapping laser over the trapped nanoparticle is about 4%.

Reheating and ring-down measurements

With the non-equilibrium measurement protocol given in the main text, we extract the feedback damping rate $\gamma_0$ and gas damping rate $T_{\text{gas}} \gamma_{\text{gas}}$ from ring-down and reheating cycles at fixed low function generator gain $G_{\text{rf}} = 5$ kHz V$^{-1}$ over a pressure range from $2 \times 10^{-3}$ to $5 \times 10^{-3}$ mbar. We show that across this pressure range, the c.m. temperatures measured from a calibrated PSD match the temperatures extracted from the damping rates, as predicted by equation (1) at low gain. Tracking the non-equilibrium dynamics during the ring-down and reheating cycles also allows us to directly measure $\gamma_n$ and $T_{\text{vac}} \gamma_{\text{gas}}$ as a function of pressure. We observe that the feedback damping rate at a fixed gain is independent of pressure (Extended Data Fig. 3), confirming that the damping rate under feedback is dominated by the cold damping feedback. The gas damping rate, on the other hand, increases with gas pressure, as expected from previous experiments.

The non-equilibrium experiments offer a way to reliably extract the damping rates and consequently the temperature, independent of the effect of tweezer motion. In the reheating process, the feedback is turned off and the gas damping rate $T_{\text{gas}} \gamma_{\text{gas}}$ is measured free from tweezer motion. Although the feedback is turned on during the ring-down experiment, the extraction of feedback damping rate $\gamma_0$ is not affected by the tweezer modulation for the following reason. We assume that the energy of particle motion during ring down has the form $E(t) = E_0 \exp(-\gamma_0 t)$. Since the feedback circuit is linear, the total measured energy is $\hat{E}(t) = E_0 (1 + \eta) \exp(-\gamma_0 t)$, where $\eta$ is the additional contribution from the tweezer motion that—through feedback—is proportional to the contribution from particle motion. When we then perform an exponential fitting of the measured data $\hat{E}(t)$, we get $\gamma_0$ exactly the same as the damping rate of particle motion, regardless of the value of $\eta$.

Calibration of feedback gain

As we alluded to in the main text, the detection efficiency of light scattered by each particle can be different, depending on the experimental parameters and alignment. The simultaneous cooling of different particles to the same temperature, therefore, requires adjusting the gain set in each feedback loop to result in the same feedback damping rate $\gamma_n$. We use the rf amplitude modulation control of the MOGLABs function generator to set the gain $G_{\text{rf}}$ in units of kHz V$^{-1}$. To calibrate the feedback gain set at the function generator, we perform ring-down measurements for a wide range of gains and obtain the feedback cooling rate $\gamma_n$ (Hz) as a function of applied gain $G_{\text{rf}}$ (kHz V$^{-1}$). For the two particles used in Fig. 4, the calibration is shown in Extended Data Fig. 4. For the same feedback gain $G_{\text{rf}}$, we observe the same feedback damping rates $\gamma_n$. In the experiment, for simultaneous cooling, we adjust the feedback gain settings to obtain the same feedback damping rates for both particles.

Data availability

Source data for Figs. 1b, 2–4 and Extended Data Figs. 1–4 are available via the ETH Zürich Research Collection at https://doi.org/10.3929/ethz-b-000569410.

References

59. Hebestreit, E. Thermal Properties of Levitated Nanoparticles. PhD thesis, ETH Zürich (2017).

Acknowledgements

This research was supported by the Swiss National Science Foundation (SNSF) through the NCCR-QSIT programme (grant no. 51NF40-160591; L.N.), European Union’s Horizon 2020 research and innovation programme under grant nos. 863132 (iQlev; L.N.) and 951234 (Q-Xtreme; L.N.), and ETH Grant ETH-47 20-2 (M.F.). The funders had no role in the study design, data collection and analysis, decision to publish or preparation of the manuscript. We thank our colleagues at the Photonics Laboratory at ETH Zürich, U. Delic and A. Omran, for valuable input and discussions.

Author contributions

J.V., Z.Z., J.P. and D.W. performed the measurements and analysed the data. J.V. and L.N. conceptualized the experiments with input from F.v.d.L. and M.F. All the authors discussed the results and contributed to writing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41565-022-01254-6.

Correspondence and requests for materials should be addressed to Jayadev Vijayan.

Peer review information Nature Nanotechnology thanks Klaus Hornberger, Tongcang Li and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.
Extended Data Fig. 1 | Detection schemes used in the experiment. Light scattered by the particle in the forward direction is detected on the QPD which performs measurement-based cold damping of the particle motion. The back-scattered light is detected on photodiodes that perform parametric cooling of the particle motion. Additionally, the back-scattered light is also used in a heterodyne detection scheme that can overcomes the scalability limitations of the forward detection. At the moment, it is used as a tool to detect multiple particles as they are loaded into the chamber. A green laser is used to illuminate the particles for taking high resolution images, such as in Fig. 4a of the main text.
Extended Data Fig. 2 | Linear feedback circuit. A) A schematic of the cold damping feedback loop from the detected signal \( V_i \) to the spatial displacement of the tweezer \( \Delta y \). B) Estimated tweezer displacement \( \Delta y \) (green circles) for different gains applied at the function generator \( G_{\text{FG}} \). The dashed line is a square root fit to the data.
Extended Data Fig. 3 | Damping rates from ring-down and reheating measurements. The feedback damping rate (green circles) is independent of pressure whereas the gas damping rate (red circles) increases with pressure. As in the main text, the gain is fixed to a low value of $\gamma_f = 2\pi \times 42 \text{ Hz}$, corresponding to $G_{\text{FG}} = 5 \text{ kHz/V}$. 
Extended Data Fig. 4 | Calibration of feedback gain. Due to differences in the detection efficiency of the motional signal from particle 1 (red circles) and 2 (blue circles), the gain applied at the function generator $G_{FG}$ is adjusted to get the same $\gamma_{fb}$. Dashed lines are a linear fit to the data.