Q 55: Optomechanics

Time: Thursday 14:30–16:30 Location: P 2

Q 55.1 Thu 14:30 P 2

Phase-adaptive cooling of fringe-trapped nanoparticles in hollow-core fiber — Soumya Chakraborty[1,2], •Gordon K. L. Wong[1], Pardeep Kumar[1], Hyunjun Nam[1,2], Claudiu Genes[3,1], and Nicolas Y. Joly[2,1] — [1]Max Planck Institute for the Science of Light, Staudtstrasse 2, D-91058 Erlangen, Germany — [2]Department of Physics, Friedrich-Alexander-University Erlangen-Nuremberg, Staudtstrasse 7, D-91058 Erlangen, Germany — [3]TU Darmstadt, Institute for Applied Physics, Hochschulstrasse 4A, D-64289 Darmstadt, Germany

Freezing thermally driven center-of-mass (CoM) motion is essential for accessing quantum effects in macroscopic systems. Here, we experimentally demonstrate a novel phase-adaptive feedback cooling of optically levitated silica nanoparticles inside a hollow-core photonic crystal fiber at room temperature. The particle is tweezed in a standing-wave potential formed by two co-linearly polarized counterpropagating fiber-guided modes. Its axial CoM motion is cooled by adjusting the relative optical phase of the modes as a response to the particle's momentum, generating a dissipative force without recoil heating. The method is applicable to neutral particles. Using this approach, the CoM temperature of a 195 nm silica particle is reduced to 58.6 K at 0.5 mbar, while for a 400 nm particle the temperature reaches 11 K at the same pressure. A stochastic analytical model accurately reproduces the experimental results. This approach enables long-range, coherent control of mesoscopic particles in fiber-based platforms for future quantum applications.

Q 55.2 Thu 14:45 P 2

Dissipation dilution in 3D direct laser written mechanical resonators — •Daniel Stachanow[1], Lukas Tenbrake[1], Florian Giefer[1], Wolfgang Alt[1], Sebastian Hofferberth[1], and Hannes Pfeifer[2] — [1]Institute of Applied Physics, University of Bonn, Germany — [2]Department of Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg, Sweden

Optomechanical platforms with high-quality mechanical and optical resonators have a wide application potential ranging from sensing to long-lived storage of quantum information. Recent developments in polymer-based 3D direct laser written structures allow for new paradigms in manufacturing micromechanical resonators due to their flexible geometries, but so far suffer from strong mechanical dissipation. Here, we present our recent progress in implementing and improving this platform. The mechanical Q-factor of the resonator in vacuum is primarily limited by intrinsic losses within the material. However, these losses can be significantly reduced by introducing strain on the membrane, leading to so-called dissipation dilution. This is done by engineering the geometry of the resonator for optimized aspect ratios and adjusting the fabrication process. To quantify the results, a scannable vacuum-integrated fiber cavity setup for probing mechanical resonators is used. We demonstrate the impact of shrinkage-induced strain on the mechanical Q-factor of polymeric bridge-like resonators. Additionally, we report the status of our current developments using post-fabrication treatment of applying oxygen-plasma to further optimize the surface properties and aspect ratios of the structures.

Q 55.3 Thu 15:00 P 2

Coherent scattering of an optically levitated nanoparticle to an ultrahigh-Q microtoroidal cavity — •Zijie Sheng[1], Seyed Khalil Alavi[1], Haneul Lee[2], Hansuek Lee[2,3], and Sungkun Hong[1] — [1]Institute Institute for Functional Matter and Quantum Technologies and Center for Integrated Quantum Science and Technology (IQST), University of Stuttgart, DE — [2]Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Republic of Korea — [3]Graduate School of Quantum Science and Technology, KAIST, Republic of Korea

Optically levitated dielectric nanoparticle offers a versatile platform for studying quantum physics beyond microscopic domain. Coupling its mechanical motion to the optical cavity enables the investigation of diverse optomechanical phenomena, which rely strongly on the strength of optomechanical coupling. An effective approach to enhancing the coupling is cavity-enhanced coherent scattering, where the cavity mode is driven by photon coherently scattered from the nanoparticle. Using this scheme, quantum ground state cooling has been achieved with the conventional Fabry-Pérot mirror cavity in weak coupling regime. Here we present the coherent scattering of the nanoparticle trapped by optical tweezer to a silica toroidal optical microcavity, where the significantly reduced mode volume enhances the optomechanical coupling, placing our platform in the ultrastrong coupling regime ($g \gg \omega$). We will report the key findings in this regime, together with the significant anomalous cooling to be explained.

Q 55.4 Thu 15:15 P 2

Amplification of optical forces via interference in levitated optomechanics — •Youssef Ezzo, Seyed Khalil Alavi, Ashik Pulikkathara, and Sungkun Hong — Institute for Functional Matter and Quantum Technologies and Center for Integrated Quantum Science and Technology (IQST), University of Stuttgart, 70569 Stuttgart, Germany

Precise tailoring of optical forces is fundamental to the control of levitated mesoscopic particles. While direct radiation pressure is typically the dominant mechanism, interference effects offer a powerful route to engineer light-matter interactions. In this work, we demonstrate the significant amplification of optical forces exerted by weak light fields through their interference with a strong trapping beam. By co-propagating a weak signal field with the optical tweezer, we exploit the interference term to generate an enhanced force that scales linearly with the signal field amplitude, rather than its intensity. We experimentally characterize this force enhancement using a silica nanoparticle, resolving the mechanical motion driven by weak fields with a sensitivity of 37.2 pW/Hz. We further discuss how this interference-based force scaling can be extended to counter-propagating geometries to maximize interaction strengths, enabling zeptowatt-level force control and efficient 3D all-optical cooling.

Q 55.5 Thu 15:30 P 2

Release and recapture of millikelvin cooled levitated nanoparticles in microgravity conditions — •Govindarajan Prakash[1], Sven Herrmann[1], Ralf B. Bergmann[2], and Christian Vogt[2] — [1]Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation (ZARM), Universität Bremen, Bremen, Germany — [2]BIAS - Bremer Institut für Angewandte Strahltechnik GmbH, Klagenfurter Str. 5, 28359 Bremen, Germany

Optomechanical levitation of nanoparticles provides a promising platform to perform tests with macroscopic particles on the interface between quantum and classical regimes. Many proposed schemes involve free evolution of such a particle after preparation in a known quantum state. Increasing mass requires increased free evolution times for which even space-based experiments have been proposed. As a first step in this direction, we have performed experiments with a millikelvin cooled levitated silica nanoparticle at the Gravitower Bremen Pro. We use the microgravity conditions of the facility to try and extend the free-fall duration of the nanoparticle to greater than what is possible on ground[1]. So far, we have achieved up to 300 microseconds of free-fall duration with a single beam trap. In this talk, we will present the analysis of the first results, limitations, and possible improvements to our current setup.

[1]. Prakash, G., Herrmann, S., Bergmann, R. B. & Vogt, C. Release and recapture of silica nanoparticles from an optical trap in weightlessness. arXiv:2509.08666 [physics.optics] (2025)

Q 55.6 Thu 15:45 P 2

Probing Quantum Mechanics with Nanorotors — Stephan Troyer[1], •Florian Fechtel[1], Henning Rudolph[2], Benjamin Stickler[3], Uroš Delić[4], and Markus Arndt[1] — [1]University of Vienna, VDS, VCQ, Faculty of Physics, Boltzmanngasse 5, A-1090 Vienna, Austria — [2]University of Duisburg-Essen, Faculty of Physics, Lotharstraße 1, 47057 Duisburg, Germany — [3]Ulm University, Albert-Einstein-Allee 11, 89069 Ulm, Germany — [4]TU Wien, Stadionallee 2, 1020 Vienna, Austria

Levitated nanoparticles are promising candidates for observing quantum effects and even matter-wave interference at unprecedented mass scales. In this regime, the rotational dynamics are particularly intriguing, as the nonlinear motion on a compact, closed configuration space provides a rich platform for phenomena such as interference or quantum tunnelling. To access these effects, quantum control over the rotational motion is essential. For instance, rotational revival necessitates a tightly aligned nanorotor, motivating cooling of at least two librational modes. Coherent scattering cooling provides a versatile method capable of coupling simultaneously to multiple motional degrees of freedom. In our implementation, a cavity supporting two orthogonal optical modes couples each mode to one librational mode. When the frequency splitting between the librational modes is comparable to the cavity linewidth, efficient two-mode cooling becomes experimentally feasible. Aligning a nanorotor with a well-characterized geometry that supports millisecond-scale revival times will open the door to future experiments on rotational interference.

Q 55.7 Thu 16:00 P 2

Tunable light induced dipole-dipole interactions — •Livia Egyed[1], Manual Reisenbauer[1], Henning Rudolph[3], Murad Abuzarli[2], Klaus Hornberger[3], Anton Zasedatelev[5], Benjamin Stickler[4], and Uros Delic[1] — [1]Atominstitut, Technische Universität Wien, A-1020 Vienna, Austria — [2]Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics, University of Vienna, A-1090 Vienna, Austria — [3]Faculty of Physics, University of Duisburg-Essen, 47048 Duisburg, Germany — [4]Institute for Complex Quantum Systems, Ulm University, D-89069 Ulm, Germany — [5]Department of Applied Physics, Aalto University School of Science, FI-00076 Espoo, Finland

Tweezer arrays can be used to trap, arrange, and control atoms or dielectric nanoparticles, while ensuring strong environmental isolation. Our platform of programmable arrays of levitated nanoparticles with highly tunable optical interactions provide access to a wide range of system parameters, enabling us to adjust the coupling between the particles from fully reciprocal to uni-directional and up until fully anti-reciprocal by modifying their trapping fields. In case of anti-reciprocal coupling, we observe PT-symmetry breaking, and for strong coupling rates the system transitions into a mechanical lasing phase. Furthermore, dynamically modulating the trapping potential of particles with non-degenerate mechanical frequencies allows us to engineer an arbitrary combination of beamsplitter and two-mode squeezing type interactions between them.

Q 55.8 Thu 16:15 P 2

Entanglement of nanoparticles via Coulomb force under optimal control — •Nancy Gupta[1,2], Ayub Khodaee[1,2], Klemens Winkler[1], Kaspar Schmerling[3], Andreas Deutschmann-Olek[3], Nikolai Kiesel[1], Anton Zasedatelev[5], Uroš Delić[4], and Markus Aspelmeyer[1,2] — [1]University of Vienna, Faculty of Physics, Vienna Center for Quantum Science and Technology (VCQ), Boltzmanngasse 5, A-1090 Vienna, Austria — [2]Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, A-1090 Vienna, Austria. — [3]Automation and Control Institute (ACIN), TU Wien, 1040 Vienna, Austria — [4]Atominstitut, TU Wien — [5]Department of Applied Physics, Aalto University

Optomechanics with levitated particles offers a powerful route to explore quantum behavior at macroscopic scales, including ground-state cooling. A central goal is to entangle the motion of two levitated nanoparticles to study decoherence, but weak interactions have limited the experimental progress. We address this challenge using electrostatic Coulomb forces between two optically trapped silica particles. By employing active and passive charging, we achieve strong coupling with an interaction strength of 17 percent of the mechanical frequency and realise cooling and readout of the coupled modes. Because steady-state entanglement demands stronger coupling, we introduce an optimal-control protocol that exploits time-dependent interactions in a continuously measured system. This approach relaxes coupling requirements and enables unconditional entanglement while addressing stabilization, feedback, and noise near the ground state.