# Q 12: Quantum Optomechanics I

Time: Monday 17:00–19:00 Location: HS I

Q 12.1 Mon 17:00 HS I

**Coupling an optically levitated nanoparticle to an ultrahigh-Q microtoroidal cavity** — •Zijie Sheng[1,2], Seyed Khalil Alavi[1,2], Haneul Lee[3], Hansuek Lee[3,4], and Sungkun Hong[1,2] — [1]Institute for Functional Matter and Quantum Technologies, University of Stuttgart, DE — [2]Center for Integrated Quantum Science and Technology (IQST), University of Stuttgart, DE — [3]Department of Physics, Korea Advanced Institute of Science and Technology (KAIST), Republic of Korea — [4]Graduate School of Quantum Science and Technology, KAIST, Republic of Korea

Exploring the dynamics of an optically levitated dielectric nanoparticle and bringing its mechanical motion toward the quantum regime has been widely developed during the last few years. One promising way is to couple its motion to a high-finesse optical cavity. Here, we present a novel platform consisting of a conventional optical tweezer and a toroidal optical microcavity [1]. The optomechanical coupling between the particle and the cavity is established by placing the particle in the near field of the cavity. The significantly reduced mode volume allows us to achieve a 50-fold increase in the single photon optomechanical coupling compared to a conventional Fabry-Pérot cavity with macroscopic mirrors, while having ultralow loss of the cavity can allow us to potentially reach sideband resolved regime. We will present the recent progress of our experiment.

[1] S. Alavi, Z. Sheng, H. Lee, H. Lee, and S. Hong, ACS Photonics 2024 https://doi.org/10.1021/acsphotonics.4c01359

Q 12.2 Mon 17:15 HS I

**Inverse numerical design of optically levitated nanoparticles for enhanced stiffness and detection efficiency** — •Moosung Lee[1,2] and Sungkun Hong[1,2] — [1]Institute for Functional Matter and Quantum Technologies, University of Stuttgart, 70569 Stuttgart, Germany — [2]Center for Integrated Quantum Science and Technology, University of Stuttgart, 70569 Stuttgart, Germany

Levitated optomechanics offers a promising avenue for achieving quantum-limited motional control of massive objects. To enable precision sensing and quantum mechanical tests on larger mass scales, it is essential to scale particle sizes beyond the Rayleigh regime, where the particle diameter is far smaller than the wavelength of optical tweezers. However, the multiple light scattering in larger particles hamper efficient optical trapping and motional detection, limiting quantum-limited applications beyond the nanoparticle scale in levitodynamics. Here, we propose an optimization algorithm based on the adjoint state method to inversely design three-dimensional shapes of optically levitated microparticles suitable for quantum optomechanical experiments. Using this approach, we numerically optimize the structures of silica and silicon particles in a standing-wave optical trap. Preliminary results demonstrate a mass enhancement, while maintaining 3D trap frequencies and detection efficiency comparable to those of Rayleigh nanoparticles. These parameters support the feasibility of achieving 3D quantum-ground-state motional cooling of the shape-optimized microparticles.

Q 12.3 Mon 17:30 HS I

**Flexible optical levitation and motion control with 3D printed fiber lenses** — •Seyed Khalil Alavi[1,2], Manuel Monterrosas Romero[1,2], Pavel Ruchka[3], Sara Jakovljević[3], Harald Giessen[3], and Sungkun Hong[1,2] — [1]Institute for Functional Matter and Quantum Technologies, University of Stuttgart, Stuttgart, DE — [2]Center for Integrated Quantum Science and Technology (IQST), University of Stuttgart, Stuttgart, DE — [3]4. Physikalisches Institut, Research Center SCoPE and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Stuttgart, DE

Optical levitation of single nanoparticles in vacuum provides precise motion control and isolation, offering a versatile tool with applications like force sensing, and exploring macroscopic quantum mechanics. Optical levitation has been achieved using optical tweezers formed by tightly focused beams, typically requiring a high NA optical objective. This approach results in a complex and bulky apparatus with constraints in geometry and size, limiting scalability. We eliminate these constraints and ease experimental requirements by using a compact and portable trapping platform formed by a 3D-printed lens on the facet of an optical fiber, enabling simultaneous trapping and motion detection with high efficiency, a key merit for the quantum-limited control. The orientation and position of our tweezer can be adjusted by moving the fiber while trapping, allowing integration into other elements for constructing hybrid systems. Our platform paves the way for the future generation of portable quantum levitodynamics platforms.

Q 12.4 Mon 17:45 HS I

**Prospects of phase-adaptive cooling of levitated magnetic particles in a hollow-core photonic-crystal fibre** — •Pardeep Kumar[1], Fidel G. Jimenez[2], Soumya Chakraborty[3,1], Gordon K. L. Wong[1], Nicolas Y. Joly[3,1], and Claudiu Genes[1,3] — [1]Max Planck Institute for the Science of Light, Staudtstraße 2, D-91058 Erlangen, Germany — [2]Pontificia Universidad Católica del Perú, Av. Universitaria 1801, San Miguel 15088, Peru — [3]Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstraße 7, D-91058 Erlangen, Germany

We present a viable scheme to mitigate the thermal fluctuations associated with the classical motion of a micro- to nano-sized magnetic particle, optically levitated inside a hollow-core photonic crystal fiber. The proposed technique is based on a phase-adaptive feedback mechanism and requires only the detection of mechanical quadratures to accomplish cooling. Such an operation can be implemented by directly imaging the particle's position and subsequent processing of the acquired information to adjust the trapping laser's phase, which leads to a Stokes type of viscous force. We provide analytical expressions for the achievable final occupancy and cooling rates, considering both the thermal and measurement noises and benchmark our analytical expressions against full numerical stochastic simulations. Our results are consequential for using trapped micro-magnets in sensing, testing the fundamental physics and preparing the quantum states of magnetization.

Q 12.5 Mon 18:00 HS I

**Rotational dynamics of Meissner-levitated micromagnets** — •Zhiyuan Wei and Benjamin A. Stickler — Institute for Complex Quantum Systems, Ulm University

Levitating microscale magnetic particles above type-II superconductors through the Meissner effect [1,2] reduces heating and photon scattering associated with optical levitation and holds the promise to yield large mechanical quality factors. Here we present the equations of motion for a permanent magnet with arbitrary internal magnetization field interacting with its dynamic image and the flux-pinned fields formed in the superconductor. We show how the magnetic quadrupole moments of the particle can give rise to three-dimensional alignment via normal-modes analysis and numerical Hamiltonian simulations. We discuss implications for future experiments [3] probing the quantum dynamics of Meissner-levitated micromagnets.

[1] J. Gieseler, A. Kabcenell et al., Phys. Rev. Lett. 124, 163604 (2020).

[2] T. Wang, S. Lourette et al., Phys. Rev. Applied 11, 044041 (2019).

[3] P. Fadeev, T. Wang et al., Phys. Rev. D 103, 044056 (2021).

Q 12.6 Mon 18:15 HS I

**Towards Matter-Wave Interference Experiments with Levitated Nanoparticles** — •Florian Fechtel, Stephan Troyer, Lorenz Hummer, Uroš Delić, and Markus Arndt — University of Vienna, VDS, VCQ, Faculty of Physics, Boltzmanngasse 5, A-1090 Vienna, Austria

When investigating microscopic systems, we usually successfully use quantum mechanics. However, understanding its transition to classical phenomena has remained a significant challenge. Levitated nanoparticles offer a promising platform for observing quantum behavior at mass scales beyond current limits. In our experiment, we trap 150 nm diameter silica nanoparticles, loaded into an infrared tweezer by laser-induced acoustic desorption. We employ coherent scattering cooling in ultra-high vacuum, with a high-finesse (F $>$ 300,000) optical cavity driven by light scattered from the particle. By blue-detuning the cavity mode relative to the optical tweezer, we enhance Anti-Stokes scattering, effectively removing motional energy and cooling the three translational modes to temperatures below 10 mK. Using a fiber laser at 1550 nm, the ultimate cooling limit is constrained by laser phase

noise, which acts as a stochastic heating force, as it converts to amplitude noise in the high-finesse cavity. To mitigate this effect, we implement a feedback loop that significantly reduces laser phase noise at frequencies relevant to particle motion. This allows for further cooling and enables precise temperature measurements using sideband thermometry. Looking ahead, we aim to conduct quantum experiments around translational and/or rotational interferometry.

Q 12.7 Mon 18:30 HS I

**Loading technique for quantum experiments with levitated dielectric and biological nanoparticles** — •Stefan Schrems, Lorentz Hummer, Stephan Troyer, and Markus Arndt — Fakultät für Physik, Universität Wien, Wien, Österreich

Levitated optomechanics has seen a rapid development. A typical experiment requires loading, cooling, detection and ideally also coherent state manipulation. However, in many cases the time scale and success of the experiment is still determined by the time to load a suitable particle. Different techniques have been developed throughout the years: Aerosol based nebulization and electrospray ionization, mechanical piezo loading or laser based methods such as optical desorption, matrix-assisted laser desorption or laser-induced acoustic desorption (LIAD). Our goal is to build a reproducible, on-demand source for loading future quantum experiments with dielectric or biological nanoparticles.To desorb dielectric nanoparticles, we are investigating a new source based on the disintegration of (Poly-)Phtalaldehyde (PPA). It relies on the unique properties of this special polymer to absorb light, depolymerize at a temperature TC = 150°C and sublimate immediately after depolymerisation. We coat a thin PPA layer on a glass slide and nebulize size-selected nanoparticles on top of the polymer layer. A highly focused 266 nm pulsed laser (3 $\mu$m waist) of low energy sets individual particles free by disintegrating the PPA layer, avoiding van der Waals forces to the substrate. A visible, off-resonant laser then guides the desorbed nanoparticles into the interaction zone, using the dipole force.

Q 12.8 Mon 18:45 HS I

**Dynamics of ellipsoidal superconductors levitated in magnetic quadrupole traps** — •Fynn Köller[1], Klaus Hornberger[2], and Benjamin Stickler[1] — [1]Ulm University, Institute for Complex Quantum Systems, Ulm, Germany — [2]University of Duisburg-Essen, Faculty of Physics, Duisburg, Germany

Superconducting bodies can be diamagnetically levitated in magnetic quadrupole traps, where their dynamics is governed by the internal magnetization field induced by the trapping field. We derive an analytical expression for the internal magnetization in ellipsoidal bodies. The induced dipole and quadrupole moments give rise to diamagnetic forces and torques as well as to spin-rotation coupling due to the Einstein-de Haas and Barnett effects, enabling full three-dimensional alignment in the trap center. We investigate how spin-angular momentum of superconductors can be observed through their motion and how the resulting dynamics can be measured, controlled and eventually cooled in upcoming experiments with levitated micron-sized superconductors.