Q 21: Quantum Optomechanics II

Time: Tuesday 11:00–13:00 Location: HS I

Q 21.1 Tue 11:00 HS I

Numerical modelling of particle behaviours in optical tweezers outside paraxial approximation — •Tobias Hanke[1,2], Moosung Lee[1,2], Sara Launer[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;

Optically levitated nanoparticles have gained interest as valuable platforms for various applications in precision sensing and quantum-limited experiments. Accurately predicting the dynamics of an optically trapped nanoparticle is crucial for understanding the system. However, conventional methods of modelling the optical tweezers light rely on paraxial approximations, hindering precise characterization of dynamics. Here, we present a numerical modelling method of an optical tweezer field for predicting the dynamics of an optically trapped nanoparticle. Compared to the conventional paraxial approximation, we experimentally show that our numerical model based on the vectorial angular spectrum method demonstrates better prediction of three-dimensional trapping frequencies of optically trapped silica nanoparticles. Using our model, we also provide the predicted trap parameters relevant for future optomechanical applications, including the scattering power and the recoil heating rate.

Q 21.2 Tue 11:15 HS I

Cavity optomechanics with polymer-based multi-membrane structures — •Lukas Tenbrake[1], Sebastian Hofferberth[1], Stefan Linden[2], and Hannes Pfeifer[3] — [1]Institute of Applied Physics, University of Bonn, Germany — [2]Institute of Physics, University of Bonn, Germany — [3]Department of Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg, Sweden

Despite their application in multiple fields, ranging from quantum sensing to fundamental tests of quantum mechanics, conventional state-of-the-art cavity optomechanical experiments have been limited in their scaling towards systems with multiple mechanical resonators. 3D direct laser writing offers a new approach to fabricating multi-membrane structures that can be directly integrated into fiber Fabry-Perot cavities. Here, we experimentally demonstrate direct laser-written stacks of two or more coupled membranes – with normal-mode splittings of up to a MHz – interfaced by fiber cavities. We present finite element simulations for the optimization of the mechanical coupling and investigate the collective optomechanical coupling of multi-membrane stacks (with single-membrane vacuum optomechanical coupling strengths of $\gtrsim 30\,\mathrm{kHz}$). We present our first experimental results and give an outlook on the scalability of the system to an even larger number of coupled mechanical oscillators. Aside from tests of fundamental properties of multimode optomechanical systems, applications for sensing or routing of vibration in acoustic metamaterials and circuits are envisaged.

Q 21.3 Tue 11:30 HS I

Quantum optical binding of nanoscale particles — •Henning Rudolph[1], Uros Delic[2], Klaus Hornberger[1], and Benjamin Stickler[3] — [1]University of Duisburg-Essen, Faculty of Physics, Lotharstraße 1, 47057 Duisburg, Germany — [2]University of Vienna, Faculty of Physics, Boltzmanngasse 5, A-1090 Vienna, Austria — [3]Ulm University, Institute for Complex Quantum Systems, Albert-Einstein-Allee 11, 89069 Ulm, Germany

Recent experiments demonstrate cooling of a levitated nanoparticle to its motional ground state, and realize highly tunable non-reciprocal coupling between levitated nanoparticles invoked by light scattering [1,2]. In light of this, I will present the quantum theory of small dielectric objects interacting via the forces and torques induced by scattered tweezer photons [3,4]. The resulting Markovian quantum master equation describes non-reciprocal coupling consistently with the classical results, and is accompanied by correlated quantum noise. I will show how to tune between reciprocal coupling, non-reciprocal coupling and correlated quantum noise and discuss implications for entanglement generation and unidirectional transport through optical binding.

[1] Rieser et al., Science 377, 987 (2022)
[2] Reisenbauer et al., Nat. Phys. 20, 1629 (2024)
[3] Rudolph et al., Phys. Rev. Lett., in press (2024)
[4] Rudolph et al., Phys. Rev. A, in press, arXiv:2306.11893 (2024)

Q 21.4 Tue 11:45 HS I

Cascaded Optomechanical Sensing — •Marta Maria Marchese[1], Stefan Nimmrichter[1], Daniel Braun[2], and Dennis Rätzel[3,4] — [1]Universität Siegen, Germany — [2]University Tübingen, Germany — [3]ZARM University of Bremen, Germany — [4]Humboldt Universität zu Berlin, Germany

Coherent averaging schemes have been introduced as a method to achieve the Heisenberg limit in parameter estimation. Typically, these schemes involve multiple probes in a product state interacting with a quantum bus, with parameter estimation performed via measurements on the bus. We propose a novel coherent averaging scheme for force sensing using an array of optomechanical detectors. Our setup consists of N optomechanical cavities, unidirectionally coupled via an input laser pulse in the stroboscopic regime. The goal is to detect some weak unknown force that couples with all the mechanical elements within the cavities. Before being read out, the pulse sequentially passes through all the cavities, accumulating phase shifts, which encode information about the force. Potential applications of this approach include the sensing of gravitational fields at the Large Hadron Collider (LHC) and the detection of dark matter signatures.

Q 21.5 Tue 12:00 HS I

Probing spin-rotation coupling with gyroscopically stabilized nanoparticles — •Vanessa Wachter and Benjamin A. Stickler — Institute for Complex Quantum Systems, Ulm University, Germany

Nanoscale objects hosting internal magnetic degrees of freedom can exhibit strong signatures of spin-rotation coupling, rendering them attractive for sensing applications and for future quantum tests. We present a theoretical toolbox to describe the quantum dynamics of a gyroscopically stabilized nanodiamond, electrically suspended in a Paul trap, and show how its rotation can be controlled by microwave driving of a single embedded nitrogen vacancy spin. We study potential applications of the spin-rotational interplay for sensing and gyroscopy.

Q 21.6 Tue 12:15 HS I

Optically Hyperpolarized Materials for Levitated Optomechanics — •Marit O. E. Steiner, Julen S. Pedernales, and Martin B. Plenio — Institute of Theoretical Physics, Ulm University, Germany

Levitated optomechanics is an emerging field that offers unprecedented opportunities. One of the most exciting applications are matter-wave interference experiments with particles of increasing mass.

In my presentation, I will explore the potential of levitating solids embedded with non-permanent, optically controllable electron spins, which can be used to hyperpolarize their nuclear spin ensemble. Pentacene doped naphthalene will serve a leading example. Leveraging photo-excited triplet states in pentacene, this system enables exceptional nuclear spin hyperpolarization in naphthalene, achieving up to 80% polarization rates and ultra-long relaxation times of T1=800 hours. These remarkable properties enable stronger spin-dependent forces.

In that spirit, we explore the applications of naphthalene for tests of fundamental physics such as a multi-spin Stern-Gerlach-type interferometry protocol which, thanks to the homogeneous spin distribution and the absence of a preferential nuclear-spin quantization axis in such materials, avoids many of the limitations associated with materials hosting electronic spin defects, such as diamonds containing NV centers.

[1] M. Steiner, J. S. Pedernales, and M. B. Plenio, Pentacene-Doped Naphthalene for Levitated Optomechanics, arXiv:2405.13869

Q 21.7 Tue 12:30 HS I

Training of neuromorphic systems based on coupled phase oscillators via equilibrium propagation: effects of network architecture — •Qingshan Wang[1], Clara Wanjura[1], and Florian Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, Staudtstrasse 2, Erlangen, Germany — [2]Department of Physics, University of Erlangen-Nuremberg, 91058 Erlangen, Germany

The increasing scale and resource demands of machine learning applications have driven research into developing more efficient learning machines that align more closely with the fundamental laws of physics. A key question in this field is whether both inference and training can exploit physical dynamics to achieve greater parallelism and acceleration. Equilibrium propagation, a learning mechanism for energy-based models, has shown promising results in physical systems with energy functions more complex than Hopfield-like models.

In this study, we focus on equilibrium propagation training of coupled phase oscillator systems.We investigate the influence of different experimentally feasible network architectures on the training performance. We analyze lattice structures, convolutional networks, and autoencoders, examining the effects of network size and other hyperparameters. Our findings lay the ground work for future experimental implementations of energy-based neuromorphic systems for machine learning, encompassing systems such as coupled laser arrays, CMOS oscillators, Josephson junction arrays, coupled mechanical oscillators, and magnetic systems.

Q 21.8 Tue 12:45 HS I

Towards hybrid cavity optomechanics including an excitonic degree of freedom — •Lukas Schleicher[1,2], Leonard Geilen[1,3], Anne Rodriguez[1,2], Irene Sánchez Arribas[1,2], Benedict Brouwer[1,3], Alexander Musta[1,3], Petricia Peter[1,2], Alexander Holleitner[1,3], and Eva Weig[1,2] — [1]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [2]Chair of Nano and Quantum Sensors, TU Munich, Germany — [3]Walter Schottky Institute, TU Munich, Germany

Freely suspended van-der-Waals materials like hBN or transition metal dichalcogenides (TMDC) like MoS2 are interesting hybrid physical systems which allow for the mutual coupling of mechanical, electronic, as well as optical degrees of freedom. The electromechanical coupling is mediated by strain, and leads to a modification of the electronic band structure upon mechanical deflection, which allows for the coupling exitons.

Here, we present first result on mechanical resonators made of suspended monolayer MoS2 membranes. The mechanical mode shape of these resonators is mapped. Moreover, we map spatially the excitonic shift of the material which is related to mechanical strain. These findings pave the way to a hybrid quantum system, also incorporating additional quantum emitters and a ultra high-finesse fiber optical cavity.