Micromechanics Conference

Book of abstracts

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Organized by EU project SuperMeQ:

Gerhard Kirchmair (Universität Innsbruck), Witlef Wieczorek (Chalmers),
Michael Trupke (Universität Wien), Anja Metelmann (KIT),
Carles Navau (UAB Barcelona), Hans Huebl (Walther Meissner Institut)

YIG Photonic Crystals

John Davis (University of Alberta)

Invited Talk

Yttrium iron garnet (YIG) is a compelling material for quantum technologies due to its unique magnetic and optical properties; however, experiments involving YIG have primarily been limited to millimeter-scale spheres. The successful nanofabrication of YIG structures opens new avenues for advancing quantum technology applications. Notably, the ability to co-localize magnons, phonons, and optical photons within a nanostructured environment paves the way for novel approaches in quantum information processing, including quantum wavelength transduction and enhanced magnon-photon interactions.

Optomechanics with nonlinear quantum cavities: exciting prospects, tough challenges, and unexpected physics

Gary Steele (TU Delft)

Invited Talk

Combining optomechanical devices with (quantum) nonlinear superconducting circuits presents a potentially unprecedented opportunity to create and manipulate mechanical quantum states, with the potential to address deeply fundamental questions, such as the interaction of quantum mechanics and gravity, as well as to develop exciting quantum technologies based on the exceptional coherence possible in mechanical systems. At the same time, coupling strongly nonlinear quantum devices to high coherence center-of-mass modes of mechanical resonators is challenging due to the weak bare optomechanical coupling due to the incompatibility of devices such as superconducting qubits with the photon numbers on the order of millions or more required for coherent optomechanical coupling.

In this talk, I will outline some of the prospects are interested in pursing in this field, explain the nature of the tough challenges, and present recent work from our group embracing strongly driven nonlinear dynamics of these devices, along with the implementation of a new qubit coupling scheme which we believe will allow us to overcome the nonlinearity challenge and gain full quantum control of large mechanical quantum superpositions.

Magnetic levitation at room- and cryogenic temperatures for large mass superpositions

Bas Hensen (Leiden University)

Hot Topic Talk

I will present our ideas and progress towards building experimental platforms for large mass spatial superpositions based on magnetically levitated microparticles. I will discuss our recent levitation of magnetic particles at room temperature[1], it's miniaturized chip-based version as well as coil based levitation of superconducting particles at cryogenic temperatures. Finally, I will discuss our work towards reducing vibrations at millikelvin temperatures.

[1] M. Janse, E. van der Bent, M. Laurman, R. Smit & B. Hensen. Characterization of a levitated sub-milligram ferromagnetic cube in a planar alternating-current magnetic Paul trap. Applied Physics Letters 125, 144003 (2024). https://doi.org/10.1063/5.0233291

Exploring non linear mechanics in carbon nanotube via charge sensor

Marta Cagetti (ICFO - The Institute of Photonic Sciences)

Hot Topic Talk

Mechanical resonators are systems with high-quality factors and can easily couple to a wide range of forces rendering them excellent candidates for sensing. They are also increasingly promising candidates for quantum information technology. In particular, capacitively coupled, suspended carbon-nanotubes (CNTs) can enable new research-avenue due to their unparalleled electromechanical coupled strength . Quantum dots (QD) have been defined in nanotubes to read out and control the mechanical motion electrically. One of the main difficulties in quantum dots defined in a carbon nanotube is to measure the system's dynamics when the electrons are bounded in the quantum dot, where common techniques based on conductance measurements are not applicable. This state is however interesting for the realization of electro-mechanical qbits , ultraprecise sensors, and quantum simulators. We address this challenge by employing a CNT-based charge sensor positioned approximately 60 nm from the electromechanical system hosting a double quantum dot. We implemented a novel- in the context of charge sensing -RF technique, which not only enables the detection of these electrical states (for example, resolving the number of electrons in each dot and determining the interdot transition energy) but also allows us to measure thermomechanical motion at 20 mK with a mechanical motion resolution comparable to the zero-point motion. Our initial results are very promising, setting the stage for our next goal: conducting real-time measurements of a CNT electromechanical system hosting a double quantum dot on timescales faster than the mechanical oscillation period. Such advancements will unlock the exploration of fascinating phenomena, particularly in the realm of quantum simulation

Inductively coupled Optomechanics

Lukas Felix Deeg (IQOQI Innsbruck)

Talk

Among the diverse implementations of OM systems in the microwave regime, our previous theoretical and experimental works showed the benefits of using an intrinsically nonlinear microwave cavity in enhancing the backaction interaction. Our system is based on an inductive coupling scheme, magnetically coupling the motion of a cantilever to a superconducting SQUID-cavity. Such a setup yields coupling strengths orders of magnitude larger than in traditional capacitively coupled systems, while also being tunable with an external magnetic field. In the unresolved sideband regime, the intrinsic Kerr-nonlinearity of our cavity allows for an enhancement in cooling even beyond the bifurcation point of the cavity. However, our current setup remains backaction limited, not allowing us to cool below a mechanical occupation of a few tens of phonons. To overcome this limitation, we pursue two approaches. On the one hand, we try to hybridize our unresolved OM system with a high-Q post cavity. This has been theoretically proposed as a means to create hybridized modes with reduced loss rates, which are consequently in the resolved sideband regime that is critical for groundstate cooling. On the other hand, we introduce a fluxtransformer into our setup to reduce the detrimental effects of the large magnetic field generated by our cantilever on our superconducting cavity. By simultaneously adapting our fabrication techniques to make cavities with lower intrinsic loss rates, we hope to reach the mechanical ground state which would subsequently allow the transfer of quantum states into the mechanical cantilever.

Co-trapping an ion and a nanoparticle in a two-frequency Paul trap

Tracy Eleanor Northup (University of Innsbruck)

Invited Talk

Coupling a spin qubit to a mechanical system provides a route to prepare the mechanical system's motion in nonclassical states, such as a Fock state or an entangled state. While such quantum states have already been realized with superconducting qubits coupled to clamped mechanical oscillators, here we are interested in achieving an analogous coupling between a spin and a levitated oscillator, namely, between an atomic ion and a silica nanoparticle in a linear Paul trap. Levitated systems offer extreme isolation from the environment and the possibility to dynamically adjust the oscillator's confining potential, providing a path for the generation of macroscopic quantum superpositions.

I will present recent steps in this direction: First, we have adapted techniques originally developed for trapped atomic ions, including detection via self-interference and sympathetic cooling, for the domain of nanoparticles [1,2]. Second, we have confined a nanoparticle oscillator in ultra-high vacuum and obtained quality factors above 10^{10} evidence of its extreme isolation from its environment [3]. Finally, we have trapped a calcium ion and a nanoparticle together in a linear Paul trap, taking advantage of a dual-frequency trapping scheme [4].

[1] L. Dania, K. Heidegger, D. S. Bykov, G. Cerchiari, G. Arenada, T. E. Northup, Phys. Rev. Lett. 129, 013601 (2022)

[2] D. S. Bykov, L. Dania, F. Goschin, T. E. Northup, Optica 10, 438 (2023)

[3] L. Dania, D. S. Bykov, F. Goschin, M. Teller, A. Kassid, T. E. Northup, Phys. Rev. Lett. 132, 133602 (2024)

[4] D. Bykov, L. Dania, F. Goschin, T. E. Northup, arXiv:2403.02034 (2024)

Forces on micro-mechanical oscillators from NV centers

Gabriel Hétet (ENS)

Invited Talk

Controlling the motion of trapped macroscopic particles in the quantum regime has been the subject of intense research in recent decades. Especially noteworthy is the recent milestone of achieving ground state cooling for a trapped particle. However, the generation of purely non Gaussian states such as the first phonon Fock state or Schrödinger cat states, is required for further quantum control as well as for realizing quantum interference. One approach is to transfer the quantumness of a well-controlled two-level system to the mechanical degree of freedom, which can be realized by coupling trapped crystals with embedded spins using magnetic fields.

Nitrogen Vacancy centers in diamonds are defects with a well-controlled and long-lived spin at room temperature. I will present our latest results on the forces on micro-mechanical oscillators from NV centers both from tethered and levitating mechanical oscillators.

An optically defined phononic crystal defect

Jack Sankey (Childress) (McGill University)

Invited Talk

The acoustic isolation afforded by phononic crystal defect modes has enabled continuous breakthroughs in the field of optomechanics for more than a decade. In this talk, I will present a defect mode that is entirely defined by light. Specifically, by applying an optical spring to a central unit cell of an otherwise defect-free phononic crystal membrane, we smoothly transfer a single membrane mode into the phononic band gap, thereby localizing its spatial profile from one spanning the entire crystal to one confined within a few unit cells. This localization is evidenced by an enhanced mechanical frequency shift commensurate with a 37-fold reduction in the mode's inertial mass, and a reduction in force noise below naive expectations. This fast, reversible, all-optical control represents a qualitatively new way to engineer mechanical defects, advantageously with *in situ* reconfigurability.

Interferometric gravitational wave detection – a (quantum-)metrological challenge

Michèle Heurs (Leibniz Universität Hannover)

Invited Talk

Since the first direct detection of gravitational waves in 2015, we have gained a new observation window into the universe, complementary to the electromagnetic spectrum, neutrinos, and cosmic rays. Gravitational wave detectors are now detecting astrophysical events on a near-daily basis. But for meaningful gravitational wave astronomy, ever-higher detection rates and, therefore, ever-greater detection sensitivity are required.

The sensitivity of current gravitational wave detectors is already so incredible that the quantum effects of the employed laser light and its (quantum-)optomechanical interaction with the kilogramme-scale interferometer mirrors have become limiting. Overcoming the standard quantum limit of interferometry in gravitational wave detectors in a broad frequency band calls for non-classical techniques. Non-classical ("frequency-dependently squeezed") light is already routinely employed in the current second generation of detectors (e.g., aLIGO & AdVirgo). Other noise sources, such as seismic and thermal noise, pose further challenges for third-generation detectors (e.g., the European Einstein Telescope, a planned underground gravitational wave observatory).

I will introduce the principle of interferometric gravitational wave detection and highlight some of the advanced technologies implemented, focusing on squeezed light. I will conclude my talk by showing some further possibilities related to this, as well as options for quantum noise reduction in laser interferometry and the broader field of quantum optics.

Low temparatures and low vibrations: towards superposition and milli-gravity

Tjerk Oosterkamp (Leiden University)

Invited Talk

We report experimental results on two systems:

- a high Q mechanical resonator cooled with a nuclear demagnetization cooler to thermal motion at a few milliKelvin at a frequency below one kHz. We discuss what is needed still for this system to be used to demonstrate a heavy superposition using magnetic coupling.

- a milligram Meissner levitated magnet at a frequency below 100Hz. This system is far from superposition, but suited for gravitational sensing between milligram masses.

We discuss the experimental challenges with cooling and vibration isolation and strategies that we hope to try in the coming years.

Macroscopic Quantum Superposition States of a Nanoparticle via Dynamics in Nonharmonic Potentials

Oriol Romero-Isart (ICFO)

Invited Talk

In recent years, advancements in optically levitated nanoparticles have enabled the cooling of their center-of-mass motion to the quantum ground state. As a result, a nanoparticle, which comprises billions of atoms, becomes delocalized over picometer scales. This talk aims to explore the challenges and requirements of achieving a macroscopic quantum superposition of a nanoparticle, in which the center-of-mass position is delocalized over orders of magnitude larger scales. We will discuss an experimentaly feasible approach that employs fast quantum dynamics in nonharmonic potentials to meet the stringent requirements imposed by environmentally-induced decoherence. The generation of such macroscopic quantum states would test quantum mechanics at unprecedented scales, develop highly sensitive detectors of external signals, and address fundamental questions, such as the nature of the gravitational field generated by a delocalized mass source.

Tuning Levitation Frequencies by Shaping Magnetic Field Traps and Particle Geometry

Natanael Bort-Soldevila (UAB), Jaume Cunill-Subiranas (UAB)

Talk

The oscillatory frequencies of levitating particles can be influenced by both the shape of the magnetic field in the trap and the shape of the superconducting particle (SCP). Here, we present a method using superconductors (SC) to shape the levitating trap field as desired and explore how the geometry of the levitating SCP affects its frequencies and modes.

We present simulations demonstrating how SCs can shape the trapping potential of a magnetic trap as desired [1]. This is achieved by guiding a pre-applied magnetic field using a superconducting surface to mold the field. Using this technique, trapping fields with a broad range of potentials can be realized. Furthermore, we also show how this approach enables the levitation of an array of SC particles within the same plane, facilitating magnetic interactions between the particles.

We also present the investigations on the translational and librational modes of particles with different shapes within a harmonic potential generated using anti-Helmholtz coils[2]. Specifically, we compare levitated particles of various shapes: ellipsoids (using both analytical and numerical methods), cylinders, and rectangular cuboids (using numerical methods). Our results reveal that the stable orientations of the particles depend on their aspect ratios. Notably, the librational mode of non-shperical particles introduces an additional degree of freedom.

References

[1] A. Sanchez and N. Bort-Soldevila, “Shaping magnetic fields with zero-magnetic-permeability media,” Journal of Applied Physics, vol. 130, no. 16, 2021.

[2] N. Bort-Soldevila, J. Cunill-Subiranas, et al., “Modeling magnetically levitated superconducting ellipsoids, cylinders, and cuboids for quantum magnetomechanics,” Physical Review Research, vol. 6, no. 4, p. 043046, 2024.

Sensing force gradients with cavity optomechanics

Sofia Qvarfort (Stockholm University & Nordita)

Invited Talk

Sensing the gradient of forces, rather than their absolute value, has advantages for applications such as inertial sensing and atomic force microscopy. In this talk, I will outline a recent work where we study force-gradient sensing using a coherently driven mechanical resonator within the two-tone backaction evasion scheme. The goal is to create a phase-sensitive detection of motion, where changes in the mechanical oscillation frequency are transduced into the cavity mode. We show that the classical response of the optomechanical system exhibits an extended region which is monotonic to changes in force gradient. In addition, we use Floquet theory to model the quantum fluctuations, which rise only slightly above that of the usual backaction evading measurement in the presence of the mechanical drive.

Casimir force between superconductors

Matthijs De Jong (Aalto University)

Talk

The Casimir effect originates from quantum fluctuations of the electromagnetic field and causes an attractive force observed between closely spaced objects. The magnitude of this force can be derived from fundamental principles, yet there is a discrepancy between this value and the precise experimental tests done in the last two decades [1,2]. One hypothesis for this discrepancy points towards the low frequency contributions to the Casimir effect at finite temperature. It was proposed to measure the Casimir effect between superconductors to elucidate this contribution [3]. However, combining sufficiently accurate positioning and force readout with cryogenic temperatures to measure this contribution alone represents a significant challenge, as recent fixed-distance experiments revealed [4,5].

We measure the impact of the total Casimir force between two plates of a superconducting drum, separated by 18 nm, by making use of the strong force-distance-scaling that turns the mechanical resonator strongly nonlinear [6]. Although the drum plates are at a fixed rest distance, we observe the effect of the Casimir force on the drum motion, which utilizes the benefits of the optomechanical readout and drive. We observe mechanical softening expected from the Casimir effect. By properly characterizing the optomechanical nonlinearity and parasitic contribution from potential patches, we quantitatively extract the observed Casimir force. By this method, we could observe the change in Casimir force when one of the drum plates switches from superconducting to normal state.

References

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[2] V. M. Mostepanenko, *Universe* **7** (2021), 84

[3] G. Bimonte, *Phys. Rev. A* **78** (2008), 062101

[4] R.A. Norte et al., *Phys. Rev. Lett.* **121** (2018), 030405

[5] G. Bimonte, Phys. Rev. A **99** (2019), 052507

[6] H.B. Chan et al., *Phys. Rev. Lett.* **87** (2001), 211801

High intrinsic quality factors with SiC nanomechanical resonators

Eva Weig (Technical University of Munich)

Invited Talk

Silicon carbide (SiC) has extraordinary material properties, combining some of the faborable properties of diamond and silicon. It it thus ideally suited for the realization of advanced hybrid nanomechanical devices incorporating atomic-scale defects. In addition, SiC crystalizes in a variety of polytypes which entails different routes towards realizing high Q mechanical resonators. Hexagonal 4H-SiC is a well-established material in nanophotonics and known for its highly coherent color centers. Monolithic processing of free-standing devices yields high intrinsic quality factors. On the other hand, the effects of dissipation dilution are best studied in cubic 3C-SiC which allows for thin-film epitaxial growth on silicon. Strong tensile pre-stress is incorporated along the (111) direction, allowing to boost the quality factor beyond its intrinsic value. Here I will compare nanomechanical resonators made of both 4H-SiC and 3C-SiC, and discuss the prospects of both materials for spin-mechanics and spin-cavity optomechanics.

Translations, Librations, Rotations and Vibrations of Levitated Nanoparticles

Lukas Novotny (ETH Zurich)

Invited Talk

We use levitated nanoparticles to explore the quantum-classical boundary and to investigate the limits of measurement precision. To this end, we utilize the many degrees of freedom of these nanoparticles, including translations, librations, rotations and vibrations. I will report on our recent progress in controlling these modes and discuss potential applications in sensing and metrology.

Spin-coupled diamond mechanical systems

Ania Bleszynski-Jayich (UCSB)

Invited Talk

Diamond mechanical systems in the quantum regime provide many excite opportunities in quantum sensing, networking, and computing. Diamond combines superb mechanical and thermal properties with highly coherent embedded defect-based qubits, such as the nitrogen vacancy (NV) center and silicon vacancy (SiV) center. Here I present work on a novel hybrid quantum system based on a diamond nanomechanical resonator strain-coupled to embedded spin qubits. I discuss the properties of diamond optomechanical crystals operating near their quantum ground state, and I discuss ongoing efforts to realize metrologically useful many-body entangled states of embedded spin, where interactions are mediated by the phononic modes.

High-precision motional readout of levitated superconductors

Jannek Hansen (IQOQI Vienna), Remi Claessen (IQOQI Vienna)

Talk

The preparation of non-classical states of massive objects is an important milestone towards the exploration of gravitational interactions between quantum mechanical systems. Magnetic levitation of superconducting masses on the microgram scale offers a promising experimental platform towards this goal. A high degree of decoupling of the particles from the environment has already been demonstrated, with mechanical Q-factors reaching $2.6 \cdot 10^7$ at millikelvin temperatures.

To feedback-cool a harmonic oscillator to its lowest energy state and move towards quantum control of its motion, it is necessary to reach a spatial resolution on the scale of the ground state extent, with a measurement rate that exceeds the decoherence rate. To this end, we have recently implemented interferometric readout of the mechanical motion of levitated, superconducting microspheres, in both the optical and microwave regimes. These measurements allow us to define a quantitative path towards ground-state cooling of the centre-of-mass motion, and thereby towards quantum control of levitated particles with Planck-scale masses. We will discuss the prospects and challenges of the envisioned approach, along with the current status of our experimental systems.

Quantum transduction between the microwave and optical domains

Konrad Lehnert (Yale)

Invited Talk

Can superconducting qubit be entangled by optical signals? The ability to do so would enable the creation of large-scale quantum networks of superconducting qubits. But the very different energy scales and basic incompatibility of superconducting qubits with optical light have turned out to be very difficult to overcome. I will describe our progress in this challenging ambition. In our most mature concept, we use vibrating membranes of Si3N4 to modulate information between the microwave and optical domains. In this system, we can achieve high photon number efficiency, continuous operation with 20 kHz of transduction bandwidth, and integration with advanced superconducting qubit cavity modules. Nevertheless, we can also identify lingering amounts of technical noise in the transduction process that thwart quantum operation. I will discuss prospects for taming these.

Chip-based levitation of superconducting microparticles at mK temperatures

Fabian Resare (Chalmers University of Technology),

Achintya Paradkar (Chalmers University of Technology)

Talk

Magnetic levitation of superconducting microparticles has been proposed as a platform to greatly decouple the center-of-mass (COM) motion of a levitated mechanical resonator from its environment. This platform would enable novel, ultra-sensitive force and acceleration sensors, as well as quantum experiments with macroscopic objects of 10^{13} atomic mass units. In our work, we have demonstrated chip-based magnetic levitation of superconducting microparticles in a dilution refrigerator environment. We have demonstrated levitation of the particle for days with continuous SQUID-based detection of its position. We show first steps for coupling the levitated particle to a flux-tunable superconducting microwave resonator, a prerequisite for increased readout sensitivity and future quantum control.

Detecting Gravity at the Milligram Scale Using Optomechanics

Matthew Herbst (Aalto University)

Hot Topic Talk

Strong nonlinear interactions between quantized excitations are an important resource for quantum technologies based on bosonic oscillator modes. However, most electromagnetic and mechanical nonlinearities are far too weak to allow for nonlinear effects to be observed on the single-quantum level. This limitation has been overcome in electromagnetic resonators by coupling them to other strongly nonlinear quantum systems such as atoms and superconducting qubits. I will present the realization of the single-phonon nonlinear regime in a solid-state mechanical system. The single-phonon anharmonicity in our system exceeds the decoherence rate by a factor of 6.8, allowing us to use it as a mechanical qubit and demonstrate initialization, readout, and single qubit gates. Our approach provides a powerful quantum acoustics platform for quantum simulations, sensing, and information processing.

Motional entanglement of remote optically levitated nanoparticles

Andrei Militaru (Institute of Science and Technology Austria (ISTA))

Hot Topic Talk

Optical levitation of dielectric nanospheres represents a rich experimental platform that is particularly suited for the study of macroscopic quantum mechanics. One of the most intriguing prospects of the field is to entangle the motional states of two different particles.

Such entangled states would enable testing of quantum mechanics in novel regimes, and sensing of extremely small force gradients. Currently, the levitation community has demonstrated the preparation of a pure quantum

mechanical states through ground-state cooling, and the coupling between different nanoparticles. While both achievements represent crucial ingredients for the generation of motional entanglement, an outstanding obstacle is represented by the photon recoil introduced by the trapping laser.

In this work [1], we propose a novel coupling scheme between two levitated particles that allows to overcome this photon recoil roadblock and entangle their motion. The coupling scheme consists of collecting the portion of light scattered by each nanoparticle that encodes optimally the position information. This light is then propagated through optical fibers, and shone on the other particle in such a way that its interference with the trapping laser drives the motion optimally. In our analysis, we show that the loop created by the circulating light allows to couple the two particles while simultaneously suppressing the photon recoil. Under these conditions, we show that motional entanglement is possible under feasible experimental conditions.

The scheme proposed is highly attractive for three reasons. First, the coupling introduced is mediated by light that circulates through transmission lines. There is thus no distance scaling involved, and the particles can be arbitrarily far from each other as long as delay effects are negligible. Second, because the scheme allows to create motional entanglement between the particles without making use of any high-finesse cavity nor squeezed light, which simplifies considerably the experimental overhead. Third, because we show that we can use part of the scattered light to readily reconstruct the joint state of the particles. Thus, the experiment proposed is able to both entangle the motion of the particles, and certify the final result.

[1] N. Carlon Zambon, M. Rossi, M. Frimmer, L. Novotny, C. Gonzalez-Ballestero, O. Romero-Isart, A. Militaru, *Motional entanglement of remote optically levitated nanoparticles*, arXiv:2408.14439v1 (2024)

Quantum Circuit Optomechanics with Millimeter Wave Photons

John Teufel (NIST Boulder)

Invited Talk

In all cavity optomechanical systems, the coupling between the electromagnetic and mechanical modes is a crucial parameter for achieving arbitrary quantum states of mechanical resonators. Circuit optomechanics, the electromechanical analogue of optomechanics, uses the forces from the electric fields of microwave photons to provide this radiation-pressure coupling. In this talk, I will review the milestones in quantum optomechanics which have been achieved with such circuits, as well as experimental progress toward new regimes. Specifically, by increasing the cavity frequency from the microwave to the millimeter-wave band, we demonstrate dramatic improvement in both the vacuum and parametric coupling that is experimentally achievable. Ideally, this increased coupling will unlock full quantum control of a mechanical mode using only a few photons in the cavity.

New results on magnetically levitated drops of superfluid helium

Jack Harris (Yale University)

Invited Talk

We have measured mm-scale drops of superfluid helium that are levitated in UHV. The drop cools itself via evaporation to 280 mK (even in the presence of 50 mW laser beams, indicating optical absorption less than a few parts per trillion). For roughly half of the drops we have measured, the frequencies of the first ~300 surface modes all agree (to 10 ppm) with the analytic prediction for an elastic sphere, presumably due the drop's purity and nearly-spherical shape. However in other drops, the spectrum of surface modes suggests the presence of one or more vortex lines in the drop. We have found that the drops' evaporation rate is sufficiently low (less than 1 picometer/s) that a laser can be locked to its optical whispering gallery modes. This has allowed us to measure the surface modes' thermal motion, and to observe radiation pressure effects in the drop.

Understanding and improving coherence in Lithium Niobate Mechanical Oscillators

Amir Safavi-Naeini (Stanford University)

Invited Talk

Two-level system (TLS) defects fundamentally limit the coherence of nanomechanical resonators, particularly in emerging quantum acoustic platforms based on Lithium Niobate (LN). This talk will present recent advances in understanding and controlling TLS-induced decoherence in LN mechanical oscillators across different architectures. We'll examine how TLS manifest differently in surface and bulk-limited regimes, featuring results from both phononic crystal nanobeams and bulk acoustic wave resonators with quality factors up to $6 \cdot 10^7$. Special attention will be given to the observation and characterization of individual TLS through random telegraph signals, including their temperature and power dependence. Understanding these fundamental noise mechanisms provides clear pathways for improving device performance in quantum information and sensing applications.

Backaction effects in nonlinear electromechanics

Shivangi Dhiman (KIT), Nicolas Diaz Naufal (KIT)

Talk

Dynamical backaction in optomechanical systems is a powerful tool to control and manipulate mechanical resonators close to the quantum regime. On the one hand, optomechanical backaction cooling has successfully brought mechanical systems to their motional ground state. While on the other hand, optomechanical backaction heating has allowed for the generation of entanglement and squeezing. However, while massive mechanical systems are desirable for many applications, increasing their size severely limits the effectiveness of dynamical backaction effects. In this work, we investigate a novel optomechanical setup in which a nonlinear cavity is inductively coupled to a mechanical oscillator. We demonstrate that the cavity's intrinsic nonlinearity enhances cooling performance in the unresolved sideband regime. Furthermore, we theoretically model the system's response in the mechanically unstable regime, where it exhibits self-sustained oscillations. We show, that in contrast to well-studied linear systems, these rich nonlinear dynamics are accessible at driving powers lower by several orders of magnitude. Our theoretical findings are augmented with experimental results from two distinct electromechanical platforms.

Ultra coherent circuit optomechanics: From watching decoherence of a squeezed mechanical oscillator to collective ground state cooling

Tobias Kippenberg (EPFL)

Invited Talk

Optomechanical systems provide powerful tools for controlling and measuring mechanical oscillators in the quantum regime. Achieving scalability in such systems is paramount for studying complex many-body interactions or even for distributing quantum mechanical motions among many. However, the scalability of such systems is limited by technical challenges, such as low reproducibility and nonnegligible parameter disorders, refraining from further applications of optomechanics. By introducing a superconducting circuit optomechanics platform that has 8 milliseconds of thermal decoherence time and achieved 93% fidelity ground-state cooling, we can observe the time evolution of the squeezing of the mechanical oscillator [1]. Moreover, by using this system as unit-cell, we build large optomechanical lattices. We present superconducting optomechanical lattices, implementing the Su–Schrieffer–Heeger model or even extending to two-dimensional strained graphene-like structures [2]. By further increasing the control over the mechanical and microwave frequencies, we show collective phenomena by coupling six nearly- egenerate mechanical oscillators to a common microwave bath and cooling their collective mode to the quantum ground state [3]. These achievements promise a step towards more nontrivial quantum regimes in larger mechanical arrays and pave the way for their integration with superconducting qubits.

[1] Youssefi et al. Nature Physics (2023)

[2] Youssefi et al. Nature (2022)

[3] Chegnizadeh et al. Science (2024)

Prospects of inductively coupled cavity-optomechanics

Korbinian Rubenbauer (WMI, TUM), Hans Huebl (WMI, TUM, MSQST)

Talk

Optomechanical systems are an ideal platform for exploring quantum sensing techniques at the ultimate sensitivity level. Their implementation with superconducting quantum circuits allows the combination of several advantages such as inherently low environmental temperatures, low and ultra-low intrinsic losses of the electromagnetic systems, and the ability to engineer these hybrid systems, including the seamless integration with other quantum systems, like qubits, on a single chip.

Here, we discuss a mechanical nanostring oscillator inductively coupled to a flux tunable superconducting microwave resonator in the context of quantum storage, quantum state preparation and quantum sensing applications. In particular, we will present the key parameters of the device such as the coupling rate, the quantum cooperativity and discuss those in the perspective of quantum measurement protocols. Moreover, we will show data suggesting the potential use of this device class for sensing solid-state phenomena and outline avenues how to improve the device performance.

Leveraging magneto-mechanics for clamped and levitated mechanics

Mathieu Juan (University of Sherbrooke)

Invited Talk

Optomechanical interactions in the microwave regime has been a very active field of research, leveraging advanced micro-fabrication techniques with the large non-linearities enabled by circuits to reach regimes difficult to access in the optical regime. In this context, the interaction between the mechanical system and the circuit is realized through a change in the capacitance or the inductance. While more recent, very large interactions have been demonstrated with the inductive approach, providing a promising avenue towards the strong coupling regime. This approach typically relies on a flux sensitive microwave resonator coupled to a mechanical mode via a magnetic field.

In this presentation, I will discuss our group's progress in developing magneto-mechanical systems with both clamped and levitated resonators. Our methodology, developed in Innsbruck, relies on distinct chips for the mechanical resonator and the circuit, enabling independent optimization of each component. In this context, we have been working on the micro-fabrication of strong magnet to further increase the magneto-mechanical coupling of silicon-nitride membranes. In parallel, we are also developing a levitation setup based on Paul trap levitation allowing us to directly couple the mechanical resonator to the superconducting circuit. This novel integration of levitation and circuit quantum electrodynamics (cQED) opens new avenues for controlling the quantum state of massive mechanical systems. While still in its early stages, our approach shows promise for applications in precision sensing and fundamental quantum science.

A mechanical qubit

Yiwen Chu (ETH Zürich)

Invited Talk

Strong nonlinear interactions between quantized excitations are an important resource for quantum technologies based on bosonic oscillator modes. However, most electromagnetic and mechanical nonlinearities are far too weak to allow for nonlinear effects to be observed on the single-quantum level. This limitation has been overcome in electromagnetic resonators by coupling them to other strongly nonlinear quantum systems such as atoms and superconducting qubits. I will present the realization of the single-phonon nonlinear regime in a solid-state mechanical system. The single-phonon anharmonicity in our system exceeds the decoherence rate by a factor of 6.8, allowing us to use it as a mechanical qubit and demonstrate initialization, readout, and single qubit gates. Our approach provides a powerful quantum acoustics platform for quantum simulations, sensing, and information processing.

Ultrafast spinning of a levitated micromagnet

Andrea Vinante (CNR - Istituto di Fotonica e Nanotecnologie)

Hot Topic Talk

We levitate a permanent micromagnet in a superconducting trap and spin it to ultrahigh rotation speed by means of synchronous driving enabled by SQUID detection. We achieve a maximum rotation speed beyond 2 MHz for a neodymium-alloy micromagnet with diameter 60 m, close to the limits imposed by the material and the SQUID bandwidth. We can stably spin the magnet at temperature T=4.2 K and pressure down to 10^{-5} mbar. The free rotation speed slows down exponentially, with decay time up to several hours, corresponding to a mechanical quality factor up to . We can detect the spinning-top-like precession motion induced by the restoring torque provided by the superconductor. Levitated magnet microrotors can be used in a number of applications in sensing (gyroscopes, pressure sensors) fundamental physics and material science.

Vacuum levitation and motion control on chip

Nadine Meyer (Nanophotonic Systems Laboratory ETH Zurich)

Hot Topic Talk

Levitation in vacuum evolved into a versatile technique that already benefited diverse scientific directions, from force sensing, thermodynamics to material science and chemistry. It also promises to advance the study of quantum mechanics in the unexplored macroscopic regime. Hereby, on-chip integration is anticipated to enhance the control over the particle motion through a more precise engineering of optical and electric fields. Here, we present levitation and motional control of a silica nanoparticle at the surface of a hybrid optical-electrostatic chip. By combining lens-free, fiber-based optical trapping and sensitive position detection with cold damping through planar electrodes, we cool the particle motion to a few hundred phonons.

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Light-mediated interactions in atomic and optomechanical systems

Philipp Treutlein (University of Basel)

Invited Talk

Many of the breakthroughs in quantum science and technology rely on engineering strong Hamiltonian interactions between quantum systems. Typically, strong coupling relies on short-range forces or on placing the systems in high-quality electromagnetic resonators, which restricts the range of the coupling to short distances. In this talk I will show how a loop of laser light can generate Hamiltonian coupling over a distance [1] and report experiments using this approach to strongly couple a nanomechanical membrane oscillator and an ultracold atomic spin ensemble across one meter through a room-temperature environment [2]. We observe spin-membrane normal mode splitting, coherent energy exchange oscillations, two-mode thermal noise squeezing, and dissipative coupling with exceptional points [2]. We furthermore realize an optical coherent feedback loop and use it for cooling of the membrane vibrations to below the cavity dynamical backaction cooling limit [3,4]. Our experiments demonstrate the versatility and flexibility of light-mediated interactions, a powerful tool for quantum science that offers many further possibilities and is readily applicable to a variety of different systems.

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Nonlinear Dynamics of Nanomechanical Drum Resonators due to Casimir Force

Pinara Evren Korkmazgil (Aalto University)

Poster

Microwave optomechanical systems often employ stressed mechanical resonators that comprise of two closely spaced metallic surfaces. These devices can exhibit nonlinear dynamics arising from their tension state. This phenomenon is known as geometric nonlinearity. However, proximity forces can also contribute nonlinearity. In particular, the Casimir force—an attractive interaction arising from quantum vacuum fluctuations of the electromagnetic field between conducting surfaces—introduces a nonlinear potential [1].

In this work, we investigate the nonlinear dynamics of aluminium drum resonators coupled to a superconducting microwave cavity under the influence of a Casimir potential [2]. We measure the mechanical response through optomechanical techniques and observe a pronounced softening nonlinearity in the optomechanical response. We simulate the system's dynamics using MatCont, a MATLAB toolbox for continuation and bifurcation analysis of dynamical systems [3,4]. This method allows us to demonstrate that our observations align with the expected magnitude of Casimir force. Contrastingly, we show that an electrostatic residual force or a force generated by potential patch distributions fails to account for the magnitude of the observed effects. Finally, by analyzing geometric nonlinearity we establish that the Casimir force is the dominant mechanism determining the nonlinear response of these optomechanical devices [5]. The existence of the Casimir force is also shown to have a very significant impact on the resonance frequency of the oscillator and on its rest position. Our work shows that the Casimir force should be considered in microwave optomechanical devices to account for the relationship between mechanical and optomechanical parameters.

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On-chip levitation of superconducting microparticles for quantum experiments and sensing

Fabian Resare (Chalmers University of Technology)

Poster

The goal of our project is to test macroscopicity limits of quantum mechanics, pushing from nano- to microparticles while also developing a device for quantum force/acceleration sensing. For our experiments, we construct a chip-based superconducting magnetic levitation device operating at mK temperatures. Magnetically levitated superconducting particles provide an environment with extremely low decoherence, possibility of engineering potentials, and options for coupling the trap to superconducting quantum circuits for readout and control. We present our chip-based magnetic levitation devices, which allowed us to demonstrate quality factors of 10^5 and frequency tunability between 90-160 Hz for levitated particles of 48 μm diameter. Further, we present studies of adhesion forces between various substrate surfaces and particles. These experiments aim at finding surface-particle combinations that minimize the attractive contact force, which must be overcome by the magnetic levitation force. Our results pave the way for a reliable levitation of micrometer-sized superconducting particles at mK temperatures and with that further studies of the sensitivity and dissipation limits of magnetic levitation.

Cavity-free cooling of a mechanical oscillator by feedback

Alexandre Huot de Saint-Albin (University of Basel)

Poster

Quantum feedback is a powerful technique for controlling quantum systems. The conventional strategy relies on quantum-limited measurements followed by classical processing and feedback actuation onto the system. However, quantum mechanics also allows coherent feedback of quantum signals. Such coherent feedback may exploit the information stored in non-commuting observables, while circumventing the decoherence and backaction noise associated with a measurement. Coherent feedback has thus the potential to improve quantum control and provide new capabilities in a broad range of physical systems. We first experimentally demonstrate measurement-based feedback control in a cavity-free configuration of a mechanical oscillator with a quality factor of 70 million. Using this scheme, we demonstrate cooling of the motion of the mechanical oscillator by a cooling factor of three thousand from room temperature to 90 mK. We are now trying to demonstrate coherent feedback control in the same cavity-free configuration.

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Mechanical Two-mode Squeezing and SU(1,1) Interferometry

Max-Emanuel Kern (ETH Zürich)

Poster

Mechanical resonators are highly versatile tools for quantum information processing due to their bosonic nature. The modes of these resonator can be manipulated using tunable bilinear interactions, such as beam splitter and squeezing operations. These interactions can be engineered by coupling the resonator modes to a nonlinear element, such as a transmon ancilla, and driving the system with two parametric tones [1]. Recently, beam splitter and single-mode squeezing operations have been demonstrated, completing a universal gate set for continuous-variable quantum information processing within a single circuit quantum acoustodynamics (cQAD) system [2, 3].

In this poster, we present the realization of two-mode squeezing (TMS) of the bosonic modes of a mechanical resonator. This interaction enables the implementation of an active SU(1,1) interferometer [4], with promising applications in quantum sensing. The SU(1,1) interferometer consists of an initial TMS operation, followed by a second TMS operation that imprints a phase [5].

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Towards coupling two magnetically levitated superconducting microparticles on a chip

Seyed Alireza Hashemi (Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, Göteborg SE-412 96, Sweden)

Poster

Levitating micrometer-sized superconducting particles provides a novel platform for studying fundamental aspects of quantum physics and for developing highly sensitive sensors. Levitating multiple particles allows exploring and exploiting collective effects for these purposes. We present initial work towards coupling of two or more superconducting microparticles on a chip.

Self induced oscillations in a non-linearly coupled magnetomechanical system

Shivangi Dhiman (Karlsruhe Institute of Technology, Germany)

Poster

Backaction effects in optomechanical systems can be exploited to efficiently cool thermally excited mechanical states towards their ground state. However, within specific operational regimes, the resulting backaction can give rise to a negative damping rate, consequently leading to heating of the mechanical mode and subsequently to a break-down of the linear theory. The interplay of nonlinear effects and dissipation can lead to self induced oscillations with a fixed amplitude.

Our current study focuses on the theoretical modeling of a nonlinear magnetomechanical system that exhibits self-induced oscillations. In such inductively-coupled electromechanical systems, the interaction between the mechanical mode and the microwave cavity mode is effectively mediated via a SQUID loop, thus the nonlinear aspect of the system is strongly enhanced as the cavity mode is itself nonlinear. This non-linearity gives us access to bistable regime at much low powers, making it an important aspect to consider while obtaining the correct photon numbers. We compare our theoretical predictions with experimental data.

Towards mechanical quantum state control in suspended carbon nanotubes

Eneko Mateos Madinabeitia (ICFO - The Institute of Photonic Sciences)

Poster

Mechanical resonators have impactful applications such as ultraprecise sensing, and are promising candidates for quantum information processing. For experiments in the quantum regime to be controllable, high coherence times are required. In particular, ultra-clean suspended carbon nanotubes (CNTs) hosting gate-tunable quantum dots are excellent platforms for these applications because they combine high mechanical quality factors with a large zero-point-motion, the latter being interesting for the exploration of the so-called ultra-strong coupling regime in the context of cQED. In our work, we couple double quantum dots to mechanical vibrations of the CNTs, and readout the system via superconducting resonators. Our work aims to improve the coherence of this hybrid system allowing us to prepare quantum states that are predominantly mechanical.

Phonon phase shifter

Jan Niklas Kirchhof (TU Delft)

Poster

The goal of this project is to dynamically control the propagation of traveling phonons in silicon-based waveguide devices and thereby realize a phonon phase shifter [1]. In combination with recently developed phonon waveguides [2,3] and a beamsplitter [4], we thereby complete the toolbox needed for performing linear quantum operations using phonons -- analog to linear optical quantum computing [5]. With this toolbox, we obtain full coherent control over traveling acoustic modes on-chip, which can be used to distribute quantum information between various quantum systems and therefore act as a transducer for hybrid quantum systems. Our approach relies on manipulating the phononic dispersion relation by introducing strain to the suspended phononic waveguides. To experimentally induce the required strain in the waveguide, we implement piezoelectric elements on both sides of the phononic waveguides. Our simulations predict that applying a voltage of ±50V to a 300 μm-long waveguide will induce a phase shift of $\Delta\Phi = \pm\pi/2$. We furthermore present the design, fabrication, and initial characterization of our devices.

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Superconducting flip-chip and flux-tunable resonators for flux sensing the motion of a magnetically levitated microparticle

Achintya Paradkar (Chalmers University of Technology)

Poster

Magnetic levitation of a superconducting microparticle provides a tunable, passive trapping with ultra-low dissipation of their center-of-mass (COM) motion [1], paving the way for realizing macroscopic quantum states significant for fundamental physics and sensing applications. Previously, we demonstrated an on-chip magnetic trap [2] with a flux-based readout of the particle's motion by coupling it to a DC-SQUID [3]. To enhance control over the particle's motion, we explore flux-based coupling to flux-tunable superconducting resonators (FTRs), enabling the use of cavity magnetomechanics techniques [4] for ground-state cooling of the particle's COM motion.

To realize an efficient coupling between the levitated particle and the FTR, we have developed novel methods for modulating FTRs using both flip-chip and on-chip configurations. We first present a simplified fabrication and bonding process for superconducting flip-chip devices using indium microspheres as the interconnects [5]. This flip-chip assembly utilizes Au-passivated superconducting Nb or NbN, achieving chip separations of 20–50 μm with high alignment accuracy, and supports supercurrents of tens of microamperes at millikelvin temperatures.

We then present our results on FTRs realized as quarter-wave coplanar

waveguide resonators terminated by a DC-SQUID, featuring large SQUID

loops (100 μm) and large Josephson junctions (1 μm). We demonstrate flux

modulation of the FTRs via an input coil placed above the SQUID loop via

flip-chip bonding. Additionally, we showcase an on-chip flux modulation approach using an air-bridge-based input coil concentric to the SQUID. Future work aims to couple the FTR to the COM motion of the levitated superconducting microparticle, thereby aiming toward its quantum control.

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A novel BAW resonator design for optimizing electromechanical coupling and coherence

Stefano Marti (ETH Zurich)

Poster

Coupling different solid-state quantum systems into a hybrid device can often lead to additional loss channels for the individual components. In circuit quantum acoustodynamics devices such as the ħBAR [1], the coupling between superconducting qubits and high-overtone bulk acoustic resonators (HBARs) is mediated by piezoelectricity. It has been observed that qubit coherence times decrease substantially after being combined with an HBAR[2], which is a limiting factor in current experiments. The decrease might be due to coupling of the qubit to unconfined mechanical modes [3] and additional dielectric loss [4].

Here, we present a novel design of an HBAR to mitigate these losses by spatially separating the piezoelectric excitation and the confinement of the mechanical modes for resonators in which the paraxial approximation holds.

This allows for the optimization of electromechanical couplings. We show through simulations that our design leads to more selective coupling to specific mode profiles. Furthermore, we have fabricated and measured a proof-of-concept device in a dilution refrigerator. Preliminary results demonstrate the potential of this new type of resonator.

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Phonon Thermometry for Searches of New Physics

Andraz Omahen (ETH Zurich)

Poster

A key prerequisite for control and operation of a quantum system is its initialization in a simple state, for example the ground state, be it for quantum computing, cryptography, or sensing. Here, we precisely measure the steady-state thermal population of a high-overtone bulk acoustic resonator (HBAR) coupled to a superconducting qubit [1]. The measurement protocol consists of swapping the population in the first excited state of the mechanical mode into the qubit, followed by measurement of Rabi oscillations between the first and second excited states of the qubit [2]. We find that the excited state population of the HBAR mode is lower than 0.01% for all four modes measured and is limited by thermalization of the qubit during the swap operation and by pulse infidelities.

The measurement results enable the first searches for gravitational waves and scalar dark matter in the GHz frequency range using a mechanical sensor, as well as insights into the generalized uncertainty principle [3-6]. For instance, we establish an upper bound on the amplitude of gravitational waves on resonance with the mechanical mode of $h < 2.610^{-18}$, which could be improved by, for example, increased qubit coherence in the future.

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Investigating different dc SQUID geometries for coupling to magnetically-levitated superconducting microparticles

Paul Nicaise (Chalmers University of Technology)

Poster

Levitating a superconducting microparticle at low temperatures is a promising platform for demonstrating quantum behavior of mesoscopic objects. We aim towards measuring the center-of-mass (COM) motion of magnetically levitated superconducting microparticles and apply feedback cooling to reach their ground state of motion. In our experiment, the microparticle is levitated using a superconducting on-chip magnetic trap in an anti-Helmholtz configuration. The microparticle's COM motion is translated into flux variation, which can be measured by a flux-tunable resonator (FTR) made from a quarter-wave CPW resonator terminated by a dc SQUID. We have fabricated and characterized FTRs with Qi = 10^4 that can be modulated over more than one magnetic quantum using an external bias coil. However, feedback cooling on the particle is still limited by multiple factors such as ambient flux noise, Kerr nonlinearity and flux transfer efficiency. We address these limitations by implementing three different SQUID loop geometries. First, in a series gradiometric SQUID, the parasitic flux threading both loops will circulate in opposite directions and cancel out. Second, a washer SQUID would increase the effective area and increase coupling to a multi-loop flux transformer while reducing the SQUID loop inductance. Finally, a series gradiometric washer SQUID could address all these limitations in a single configuration.

Dispersive Readout of nanoSQUIDs for Optomechanical Cooling

Richard Wagner

Poster

Diamagnetic levitation of superconducting picogram particles could serve as a promising technique for fundamental tests with large mass quantum systems. To cool the motion of these massive particles to their mechanical ground state, we propose to enable the dispersive readout of nanoSQUIDs to combine the enhanced sensitivity and magnetic field resilience of these sensors with sideband cooling techniques. In this project, we explore how to fabricate and characterize these circuits. Moreover, we aim to measure what optomechanical coupling strength we can achieve by detecting the motion of a magnetized cantilever.

Towards quantum electro-optic transduction using a MHz-frequency mechanical resonator

Luca Talamo (JILA)

Poster

Entangling microwave-frequency quantum processors through optical fibers would allow for distributed quantum information processing over long distances. By coupling MHz-frequency high-stress silicon nitride membranes to microwave and optical resonators we can achieve high-efficiency and low-noise transduction of information between the two electromagnetic regimes. Despite this, remaining noise still prevents transduction of quantum signals with a fidelity high enough to generate useful entanglement. I will present our efforts to isolate and eliminate various noise sources in our transducer while operating in a dry dilution refrigerator. I will also present progress towards pitching quantum signals from superconducting single-photon sources to optical single photon detectors, which can bound the total thermal noise added in the complete transduction chain from source to detector.

Multimode Parametric Control of Quantum Acoustic Resonators

Takuma Makihara (Stanford University)

Poster

Nanomechanical systems coupled to superconducting qubits can extend the capabilities of pure microwave systems owing to the long lifetimes, compact size, and low crosstalk of acoustic resonances. Simultaneously addressing many mechanical modes can further reduce hardware overhead by increasing the available Hilbert space. Parametric control is ideally suited for coupling microwaves and mechanics owing to the fast rates and tailorable interactions. However, parametrically controlling many modes is difficult with the traditional 4-wave mixing Josephson Junction nonlinearity owing to self-Kerr and cross-Kerr couplings. In this poster, I will discuss recent progress towards multimode parametric control of mechanical resonators using a 3-wave mixing circuit element, the Asymmetrically Threaded SQUID (ATS). Namely, we couple multiple Lithium Niobate phononic crystal defect resonators to one ATS and demonstrate parametric readout of the acoustic mode.

Simulating quantum spacetimes with optomechanical systems

Germain Tobar (Stockholm University)

Poster

We develop an experimental proposal to simulate the model for spacetime superpositions proposed by Foo, Arabaci, Zych, and Mann in Phys. Rev. Lett. 129, 181301 (2022) , using an optomechnical experiment. This is achieved through the creation a superposition of boundary conditions, which is the core feature of the proposed quantum gravitational model, in a laboratory experiment. We focus in particular on what setups could realistically implement this superposition of boundary conditions, by for example, preparing one mirror of an optical cavity in a spatial superposition, or delocalised much larger than the mirror's zero point motion, and examine the implications for both witnessing Casimir physics and extracting signatures of superposed spacetimes.

Cooling and Self-Sustained Oscillations in Non-Linear Cavity-Optomechanics

Korbinian Rubenbauer (Walther-Meißner-Institute)

Poster

Quantum sensing is set to exploit quantum properties for sensing applications. Advanced systems, which consist of a sensing element coupled to a readout system, allow to implement quantum measurement protocols with the potential to beat the standard quantum limit. They also enable backaction evasion and thereby achieve sensitivity at or even below the Heisenberg uncertainty limit. Optomechanical systems allow to explore such quantum measurement concepts. One particular realization employs superconducting microwave resonators coupled dispersively to a mechanically compliant element, which defines the sub-field of cavity-optomechanics.

In this work, we present a superconducting quantum circuit featuring a mechanically compliant string integrated into the superconducting quantum interference device (SQUID) of a flux-tunable microwave resonator. This design enables large tunable single-photon optomechanical coupling strengths, reaching up to 55 klHz.

We explore several key phenomena enabled by the large g_0 They include (i) ultra-low power red sideband cooling of the mechanical oscillator approaching its quantum ground state, (ii) the emergence of mechanical instabilities originating from the non-linear response of the microwave resonator and (iii) signatures indicating the presence of few magnetic vortices detected via a mechanical signature. We also discuss the prospects of reaching the single-photon strong-coupling regime with our concept.

Reaching the resolved sideband regime in magnetomechanics

Christian Dejaco (IQOQI)

Poster

The approach of inductively coupling an AFM cantilever to a SQUID microwave resonator offers the advantage of in-situ tunable optomechanical coupling. With such a system, we were able to reach the single photon strong coupling regime and demonstrated that the SQUID's intrinsic nonlinearity can be exploited to enhance backaction cooling in the unresolved sideband regime. However, the sideband resolved regime, which allows ground state cooling, remained unattainable with the achieved resonator quality factor of only about 5,000.

To reach the resolved sideband regime, a new batch of frequency tunable SQUID resonators, fabricated on a higher resistivity Si wafer was characterized. With intrinsic quality factors of up to 35,000, the new batch outperforms the previous batch. To determine the participation ratio and the flux shielding parameter of the SQUID, a fitting routine for the observed hysteretic frequency tuning behavior has been worked out. An implemented circle fit routine for nonlinear scattering data allows to determine the Kerr constant.

Despite the initial improvement in resonator quality factor, the losses introduced after placing the AFM cantilever with a magnetic particle close to the SQUID still place our system in the sideband unresolved regime. To address this limitation, we currently pursue several approaches, including coupling the unresolved system to an auxiliary high-Q cavity or using in-house fabricated high-Q SQUID resonators coupled to the mechanical resonator via a flux transformer (See Posters by R. Sathyanarayanan, B. Thyagarajan and talk by L. F. Deeg).

Reaching the resolved-sideband regime in magnetomechanics

Raamamurthy Sathyanarayanan (member@uibk.ac.at staff@uibk.ac.at student@uibk.ac.at)

Poster

Superconducting circuits have shown great promise as a platform for the control and measurement of mechanical systems — in particular, they can be used to create quantum states in macroscopic mechanical oscillators, allowing for high precision sensing experiments and tests of fundamental physics. However, such protocols require that the mechanical oscillator be first cooled to the ground state. This, in turn, requires that the optomechanical system be in the sideband-resolved regime, which requires a cavity of sufficiently high quality; unfortunately, the addition of a mechanical system and a coupling mechanism to a superconducting circuit invariably worsens the circuit, bringing us further from this regime. We present three strategies for mitigating these effects in our inductively-coupled optomechanical setup. First, we fabricate magnetic-field resilient flux-tunable resonators through the use of niobium constriction junctions; these offer high quality factors but set challenging requirements on our lithography process. Second, we demonstrate that a flux transformer can be used to transmit a flux bias; this allows us to separate the mechanical system from the circuit, suppressing losses due to the mechanics and the magnet. Third, we demonstrate a more general approach of coupling a high-quality 3D cavity with a low-quality optomechanical system such that their modes are hybridized — creating an artificial sideband-resolved system in the high-Q mode. These latter strategies place new limits on the photon-enhanced optomechanical coupling, and we explore these limits through theory and experiment.

Kerr enhance optomechanical cooling with an auxiliary cavity in the unresolved regime.

Gustavo Elias Kufatty Anton

Poster

Different strategies have been developed for cooling an optomechanical system in the unresolved regime. Among them, the addition of an auxiliary cavity produces a Fano-resonance enhancing the balance between Stokes and Anti-Stokes rates. Similarly, a recent wok was able to achieve cooling by using a Kerr nonlinear cavity in the unresolved regime. In the current work, we aim to combine both techniques with the goal of achieve a better cooling limit

Quantifying the quantum delocalization of a 1-milligram torsional pendulum for gravity experiments

Sofia Agafonova (IST Austria)

Poster

Milligram-scale optomechanical experiments open a new direction for bridging quantum mechanics and gravitational physics by aiming to strike a balance between the ease of achieving two competing desires: 1) making gravitational couplings of the controlled objects dominant and 2) making the motions of these objects quantum noise dominated. With the aim of exploring whether gravitational fields should obey the quantum superposition principle, one further finds the prerequisite of working with low-frequency dynamics that is typically quantum-unfriendly, but needed to maximize the dimensionless figure-of-merit in the problem, quantifying the ability to generate quantum entanglement gravitationally.

In this talk, I will share recent exciting results for tackling these problems. In particular I will begin by focusing on our first 1-milligram suspended torsional pendulum operating at 18 Hz, and the successful laser cooling its motion to an unprecedented 240 μK for this mass range [1]. I will explain how the resulting boost in the quantum delocalization of the pendulum benchmarks a state-of-the-art quantum-gravity figure-of-merit with an unparalleled improvement potential. These results open a frontier for explorations of quantum aspects of gravity, establishing milligram-scale torsional pendulums as a leading platform. I will conclude by describing our initial demonstration of a new concept: a 'zig-zag optical cavity' for sensing and controlling the torsional motion of our pendulums to tap further into the unparalleled potential at the quantum-gravity interface [2].

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A two-dimensional optomechanical crystal for quantum transduction

Samuel Gyger (Stanford University)

Poster

Integrated optomechanical systems are one of the leading platforms for manipulating, sensing, and distributing quantum information. The temperature increase due to residual optical absorption sets the ultimate limit on performance for these applications. In this work, we demonstrate a two-dimensional optomechanical crystal (OMC) geometry that alleviates this problem through increased thermal anchoring to the surrounding material. Our mechanical mode operates at 7.4 GHz, well within the operation range of standard cryogenic microwave hardware and piezoelectric transducers. The eight times better thermalization over state of the art one-dimensional OMCs combined with the large optomechanical coupling rates, $g_0 / 2\pi \approx 880$ kHz, and high optical quality factors, $Q_{opt} = 2.4 \cdot 10^5$, enables the ground-state cooling of the acoustic mode to phononic occupancies as low as $n_m = 0.32$ from an initial temperature of 3 K, as well as entering the optomechanical strong-coupling regime. Finally, we perform pulsed sideband asymmetry of our devices at a temperature below 10 mK and demonstrate ground-state operation $n_m < 0.45$ for repetition rates as high as 3 MHz corresponding to a photon-phonon pair generation rate of $\approx$147 kHz. Our results extend the boundaries of optomechanical system capabilities and establish a robust foundation for the next generation of microwave-to-optical transducers with entanglement rates overcoming the decoherence rates of state-of-the-art superconducting qubits.

A preprint is available at https://arxiv.org/abs/2406.14484v1

Bandwidth-tunable Telecom Single Photons Enabled by Low-noise Optomechanical Transduction

Liu CHEN (Technical University of Delft)

Poster

Single-photon sources are of fundamental importance to emergent quantum technologies. Nano-structured optomechanical crystals provide an attractive platform for single photon generation due to their unique engineering freedom and compatibility with on-chip silicon fabrication. However, optical absorption heating has thus far prevented these systems from being widely used in practical applications. Here, we overcome this limitation through the use of a quasi-two-dimensional optomechanical crystal structure and demonstrate an on-chip source of single photons natively at telecom wavelength. We verify the low thermal noise and resulting high purity of the generated single photons through a Hanbury Brown-Twiss experiment with $g^2(0)=0.35\{+0.10-0.08\}$. Furthermore, we perform Hong-Ou-Mandel interference of the emitted photons showcasing the indistinguishability and coherence of photons generated from our source with visibility V=0.52±0.15 after 1.43 km of fiber delay line. With the possibility of using the mechanical mode as a quantum memory, we can retrieve the single photons on-demand. Crucial for applications, the optomechanical interaction at the heart of our device allows the bandwidth of emitted single photons to be tuned over a large range from 100 kHz to several hundreds of MHz, which makes them directly compatible with leading quantum memory platforms.

Magnon-microwave backaction noise evasion in cavity magnomechanics

Victor Augusto Sant Anna V Bittencourt (University of Strasbourg)

Poster

In cavity magnomechanical systems, magnetic excitations couple simultaneously with mechanical vibrations and microwaves, incorporating the tunability of magnetism and the long lifetimes of mechanical modes. Applications of such systems, such as thermometry and sensing, require precise measurement of the mechanical degree-of-freedom. In this paper, we propose a scheme for realizing backaction evading measurements of the mechanical vibrations in cavity magnomechanics. Our proposal involves driving the microwave cavity with two tones separated by twice the phonon frequency and with amplitudes satisfying a balance relation. We show that the minimum added imprecision noise is obtained for drives centered around the lower frequency magnon-microwave polaritons, which can beat the standard quantum limit at modest drive amplitudes. Our scheme is a simple and flexible way of engineering backaction evasion measurements that can be further generalized to other multimode systems.

Fluctuating drive of coupled classical oscillators can simulate dissipative qubits

Lorenzo Bernazzani (Universität Konstanz)

Poster

We investigate a system composed of two coupled oscillators subject to stochastic fluctuations in its internal parameters. In particular, we answer the question whether the well-known classical analogy of the quantum dynamics of two-level systems (TLS), i.e. qubits, provided by two coupled oscillators [1] can be extended to simulate the dynamics of dissipative quantum systems. In the context of nanomechanics, the analogy in the dissipation free case has already been tested in multiple experimental setups, e.g., doubly clamped or cantilever string resonators and optically levitated particles [2,3]. A well-known result of this classical analogy is that the relaxation and decoherence times of the analog quantum system must be equal, i.e. $T_1=T_2$, in contrast to the general case of quantum TLS. We show that this fundamentally quantum feature, i.e. $T_1 \neq T_2$, can be implemented as well in the aforementioned classical systems by adding stochastic fluctuations to their internal parameters [4]. Moreover, we show that these stochastic contributions can be engineered in the control apparatus of those systems, discussing, in particular, the application of this theory to levitated nanoparticles and to nanostring resonators. However, a limit of this improved quantum-classical analogy is that the analog Bloch vector of our system (see figure) always collapses to the center of the sphere, i.e., the state corresponding to an effective infinite temperature [4]. Eventually, we discuss possible ways to extend the present model to simulate classical analogs of finite-temperature quantum states and possible implications of this for directional sensing [5].

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Josephson Gravimeter - Gravity Sensing by Quantum Tunneling in Superconducting Circuit

Martin Zemlicka (Institute for Quantum Optics and Quantum Information - Vienna of the Austrian Academy of Sciences)

Poster

Recent theoretical studies [1, 2] in quantum gravity and dark matter detection have proposed challenging electrical systems that aim to observe gravitational influence on quantum tunneling within a superconducting Josephson junction (JJ). The main principle suggests that gravity affects the potential difference across the electrodes of the junction, which can have a measurable influence on the tunneling of charge carriers (electron Cooper pairs). A finite potential energy difference across the JJ's tunneling barrier results in the generation of an alternating electromagnetic field – AC Josephson effect, where the potential energy of the electron pairs is converted into the energy of emitted photons. Here, we present an idea for applying this effect to detect gravity with high precision. If the JJ is aligned with the direction of gravity, the gravitational potential energy of electron pairs is maximized, that maximizes the frequency of the electromagnetic (EM) signal induced by gravity. Such a signal might be detectable within reasonable time scales if the circuitry and detection system are optimally designed and well-calibrated. If successful, this system will offer a new platform for detecting gravity with extreme precision and resolving gravitational potential differences at the atomic scale. Besides advancing our understanding of quantum gravity and dark matter, it has the potential application in the fields of nanotechnology, material science, geophysics, planetary science and navigation systems.

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Hybrid Atom-Optomechanical System in the Quantum Regime

Gian-Luca Schmid (Universität Basel)

Poster

Coherent feedback stabilises a system towards a target state without the need of a measurement, thus avoiding the quantum backaction. In our experiment, we employ optical coherent feedback to remotely cool a nanomechanical membrane oscillator using the collective spin of an atomic ensemble as controller. Direct time-controlled manipulation of the spins allows us to tune the spin-membrane interaction from strong coupling to an overdamped regime. By applying a stroboscopic cooling, the cooling rate can be increased such that we can cool the membrane from room-temperature to 216 mK in 200 μs. The coherent feedback on the macroscopic membrane paves the way towards more elaborate quantum protocols such as the generation of non-classical states.

Quantum control of a small-scale multi-mechanical device

Shlomi Kotler (The Hebrew University of Jerusalem)

Poster

Quantum control of single mechanical elements using opto-mechanics is well established by now. These techniques can be extended to multi-mechanical devices, with some careful considerations as to the larger Hilbert space and its inadvertent practical complexity. We show initial results of multi-mechanical readout and control that might serve as a basis for a small-scale quantum communication testbed in the microwave regime.

Optomechanics Inside a Levitated Superfluid Helium-4 Drop

Igor Brandao Cavalcanti Moreira (Yale University)

Poster

Quantum control over micromechanical systems has been achieved with center of mass motion of levitated solids in high vacuum [1] and bulk modes of solid-state mechanical devices [2]. Here, we present ongoing experiments expanding the scope of coherent control to shape oscillations of liquid microdrops coupled to their optical whispering gallery modes (WGMs). Thus, our optomechanical platform is entirely hosted inside a magnetically levitated superfluid Helium-4 drop.

Trapping in ultrahigh vacuum ($\leq 3 \cdot 10^{-11}$ mbar) provides environmental isolation, passive evaporative cooling to sub-Kelvin temperatures, and means for the liquid's surface tension to mold itself into a highly spherical shape. We have measured the frequencies of oscillation of the drop's free surface with agreement to ~ 1 part in 10^4 with ab initio theory, providing precise measurement of its diameter (~ 800 um), evaporation rate (≥0.3 pm/s) and bulk temperature (≈ 270 mK).

The spherical geometry allows for standing waves of light (WGMs) to exist within the dielectric drop, serving as our optical cavity. We find that free-space laser beams couple to a variety of WGMs over a wide range of drop sizes. By modulating their optical paths with coherently driven surface oscillations, we have observed WGMs with finesse up to 1000, characterized their linewidths and polarization dependence, and calibrated the absolute amplitude of the surface oscillation (≤ 5 nm).

Ab initio calculations, however, also predict yet unobserved ultrahigh finesse WGMs $F > 10^7$ [3]. Our ongoing efforts focus on enhanced detection of higher-finesse WGMs, and quantifying their single photon optomechanical coupling strength with the drop's surface oscillations, which are predicted to surpass the mechanical frequency [3].

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Towards All-Optical Coherent Quantum Backaction Cancellation via an Effective Negative Mass

Bernd Wolfgang Schulte (Institute of Gravitational Physics, Leibniz University Hanover)

Poster

Optomechanical systems, such as gravitational wave detectors, face limitations imposed by the standard quantum limit (SQL) of interferometry. Coherent Quantum-Noise Cancellation (CQNC) suggested by M. Tsang and C. Caves [1] presents an approach to surpassing the SQL formed by quantum backaction noise and shot noise at all frequencies. Different to [1] our CQNC scheme involves in series coupling of an all-optical effective negative mass oscillator/system (eNMO/ eNMS) to an optomechanical system (OMS - containing a positive mass oscillator) to mitigate the quantum backaction noise seen by the OMS. This poster/talk shows the details of our cascaded CQNC scheme, explaining why the eNMO is formed by a cavity containing a beam splitter and down-conversion process and on which requirements our all-optical CQNC scheme relies [2]. Furthermore, the optomechanical system (OMS), specifically the Membrane at the Edge (MatE) system containing a commercial SiN membrane, and its characterisation through Optomechanically Induced Transparency (OMIT) and Dynamical Backaction (DBA) are presented [3]. The necessity of cryogenic environment and soft clamped membranes to build a quantum backaction noise limited OMS and their implementations is shown. Additionally, progress in realising and characterising the effective negative mass oscillator (eNMO) via squeezing measurements and squeezed state tomography is demonstrated.

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Nonharmonic potential modulation for levitated nanoparticles in the quantum regime

Piotr T. Grochowski (Palacký University Olomouc)

Poster

Levitated high-mass quantum systems offer entrance to unprecedented regimes for both fundamental science and technological applications. However, the generation and manipulation of quantum non-Gaussian states that would enable full access to the quantum advantage of such platforms are still elusive. We theoretically propose a method that enables the preparation of a massive particle's center-of-mass motion in a variety of quantum states, including Fock and Schrödinger cat states, without utilizing auxiliary couplings to two-level systems. We combine nonharmonicity enhancement through motional delocalization and optimal control techniques to fully exploit a weakly nonharmonic trapping potential landscape. The time-dependent modulation of linear potential contribution in the presence of leading static cubic nonharmonicity allows full control of the center-of-mass mode. We analyze state preparation protocols utilizing such a control, providing bounds for the amount of nonharmonicity, delocalization, and decoherence levels that are needed to generate a given non-Gaussian state. The proposed optimal control scheme can be readily generalized to quantum operations beyond single-particle state generation, including logical gates or two-particle systems, and be implemented in other weakly nonharmonic physical systems.

Towards quantum control of an electromechanically coupled levitated superconductor

Remi Claessen (University of Vienna)

Poster

In our approach towards quantum mechanical control of macroscopic objects, we levitate superconducting microspheres with a mass of 6 µg in a magnetic trap, enabling mass-independent levitation with ultralow dissipation [1]. In a recent evolution of the experiment, we have inductively coupled the mechanical motion of the levitating microsphere to a resonant superconducting quantum circuit [2], thereby demonstrating a tunable electromechanical interaction. This allows us to define a quantitative path towards ground-state cooling and quantum control of levitated particles with Planck-scale masses at millikelvin environment temperatures. This contribution will discuss the prospects and challenges of the envisioned approach, along with the current status of our experiment and readout system.

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Interferometric readout of magnetically levitated micromirrors in a superconducting trap

Jannek Hansen (Vienna Center for Quantum Science and Technology)

Poster

An experiment is described in which we combine magnetic levitation of superconductors and optical interferometry.

The magnetic levitation of superconducting masses on the µg scale has shown to be well decoupled from the environment with Q-factors up to $2.6\cdot10^7$ at mK temperatures. The aim is to create non-classical states of objects which are sufficiently massive for the observation of gravitational coupling.

We are developing high-precision position readout to enable feedback cooling of the centre-of-mass motion into its quantum ground state.

In a first proof-of-concept experiment, we have demonstrated that our readout scheme is on par with existing, state-of-the-art magnetic readout schemes. The limiting factor that prevents us from reaching the back-action regime is the relatively poor reflectivity of the superconductor, which leads to internal heating through absorption.

In an improved version of the experiment, we demonstrate that we can levitate micro-mirrors supported by a superconducting structure and can cool their centre-of-mass motion through magnetic feedback. This platform can be equipped with a high reflectivity coating to reduce the absorption by several orders of magnitude. This reduction will allow to increase the optical power to the backaction regime and cool the oscillator to its ground-state occupation, opening the possibility for quantum state preparation.

Hot Schrödinger Cat States

Thomas Agrenius (University of Innsbrcuk)

Poster

The observation of quantum phenomena often necessitates sufficiently pure states, a requirement that can be challenging to achieve. In this study, our goal is to prepare a non-classical state originating from a mixed state, utilizing dynamics that preserve the initial low purity of the state. We generate a quantum superposition of displaced thermal states within a microwave cavity using only unitary interactions with a transmon qubit. We measure the Wigner functions of these 'hot' Schrödinger cat states for an initial purity as low as 0.06. This corresponds to a cavity mode temperature of up to 1.8 Kelvin, sixty times hotter than the cavity's physical environment. Our realization of highly mixed quantum superposition states could be implemented with other continuous-variable systems e.g. nanomechanical oscillators, for which ground-state cooling remains challenging.