Exploiting Levitated Particles in the Quantum Regime

794. WE-Heraeus-Seminar

04 – 08 September 2023

at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 794. WE-Heraeus-Seminar:

The Wilhelm and Else Heraeus seminar on "Exploiting levitated particles in the quantum regime" brings together leading scientists and young researchers working in the field of levitated quantum opto- and electromechanics. The aim of the seminar is to provide a platform to discuss the most recent experimental and theoretical advances, as well as promising future directions in the quantum physics of levitated particles. The seminar will bring together experts from the field of levitated optomechanics with experts from related fields in the atomic, molecular, and optical physics community.

Levitating nanoscale particles in ultra-high vacuum and cooling them to the quantum regime provides a unique platform for quantum experiments with massive objects, for ultra-precise force and torque sensing, and for the exploration of physics beyond the standard model. The recent experimental breakthroughs of cooling a nanoscale dielectric sphere to its motional quantum ground state by cavity and feedback cooling paves the way for the first experimental observation of mechanical quantum superpositions in these systems. This seminar will discuss the recent breakthroughs and promising future directions with levitated nanoparticles in the quantum regime, ranging from quantum control of levitated objects, collective effects in particle arrays, magnetic and electric trapping platforms, nanoscale quantum rotations, to prospects of testing dark matter models and quantum gravity.

Scientific Organizers:

Prof. Dr. Benjamin Stickler, University of Ulm /Germany
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Introduction

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Registration:

Mojca Peklaj (WE Heraeus Foundation)
at the Physikzentrum, Reception Office
Sunday (17:00 h - 21:00 h) and Monday morning

Program

Program *(CEST)*

Sunday, 03 September 2023

17:00 – 21:00	ARRIVAL and REGISTRATION	
18:00	*BUFFET SUPPER*	

Monday, 04 September 2023

08:00	*BREAKFAST*	
08:50 – 09:00	Organizers	**Introduction**
09:00 – 09:45	Markus Aspelmeyer	**Levitated Solids in the Quantum Regime - from Ground state Cooling to Quantum Sources of Gravity**
09:45 – 10:30	Martin B. Plenio	**Aspects of Low Energy Tests of Quantum Gravity**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Andrew Geraci	**Precision Sensing and Searches for New Physics with Optically-levitated Dielectric Particles**
11:45 – 12:30	Tongcang Li	**Rotational Optomechanics with Levitated Nanoparticles in Optical Tweezers and Ion Traps**
12:30 – 12:45	**Conference Photo (outside at the main entrance)**	
12:45 – 14:00	*LUNCH BREAK*	
14:00 – 14:45	Francesco Marin	**Quantum Spectral Signatures of a Two-dimensional Optomechanical System**
14:45 – 15:30	James Millen	**Levitated Electromechanics**

Program *(CEST)*

15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Klemens Hammerer	**Predicting the Future, Remembering the Past: Stationary Entanglement in Optomechanics**
16:45 – 17:30	Pavel Zemánek	**Multidimensional Effects with Levitated Objects**
17:30 – 18:00	**Poster Flash Presentations**	
18:00 – 19:30	*DINNER*	
from 19:30	**Poster Session 1**	

Program *(CEST)*

Tuesday, 05 September 2023

08:00	*BREAKFAST*	
09:00 – 09:45	Oriol Romero-Isart	**Macroscopic Quantum Superpositions via Dynamics in Wide Nonharmonic Potentials**
09:45 – 10:30	Romain Quidant	**Controlled Dynamics of a Levitated Nanoparticle in a Hybrid Optical / RF Integrated Platform**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Klaus Hornberger	**Probing Quantum Mechanics with Nanoparticles**
11:45 – 12:30	Yiwen Chu	**Schrödinger Cat States of an Acoustic Resonator**
12:30 – 14:00	*LUNCH BREAK*	
14:00 – 14:45	Hendrik Ulbricht	**Testing Fundamental Physics with Levitated Mechanics**
14:45 – 15:30	Flaminia Giacomini	**Quantum Systems as Gravitational Sources: Which Quantum Aspects of Gravity Can We Test?**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:30	Murad Abuzarli	**Non-Hermitian Dynamics in Arrays of Optically Coupled Levitated Particles**
16:30 – 17:00	Henning Rudolph	**Quantum Theory of Non-Hermitian Optical Binding Between Nanoparticles**
17:00 – 17:30	Peiran Yin	**Challenging Theories of Dark Energy with Levitated Force Sensor**
17:30 – 18:00	Nikolai Kiesel	**Fast Quantum Interference of a Nanoparticle via Optical Potential Control**
18:00	*DINNER*	

Program *(CEST)*

Wednesday, 06 September 2023

08:00	*BREAKFAST*	
09:00 – 09:45	Christiane Koch	**Quantum Control of Molecular Rotation**
09:45 – 10:30	Martin Frimmer	**Probing the Physics of Nanoscale Rotations with Levitated Nanoparticles**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Peter Barker	**Characterisation and Control of Single Levitated Nanoparticles**
11:45 – 12:30	**Poster Flash Presentations**	
12:30 – 14:00	*LUNCH BREAK*	
14:00	**Excursion**	
18:00	*HERAEUS BARBECUE at the Physikzentrum (with complimentary drinks)*	
from 19:30	**Poster Session 2**	

Program *(CEST)*

Thursday, 07 September 2023

08:00	*BREAKFAST*	
09:00 – 09:45	Gabriel Hétet	**Spin-mechanics with Trapped Diamonds**
09:45 – 10:30	David Moore	**Levitated Optomechanical Sensors for Nuclear and Particle Physics**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Tracy Northup	**Co-trapping an Ion and a Nanoparticle in a Two-frequency Paul Trap**
11:45 – 12:30	Peter Rabl	**Phase Transitions and Universal Scaling in Bosonic Transport**
12:30 – 14:00	*LUNCH BREAK*	
14:00 – 14:45	Vanessa Wachter	**Coupled Spin Mechanics in Levitated Nanoscale Particles**
14:45 – 15:30	Carlos Gonzalez-Ballestero	**Quantum Light-matter Interaction with a Dielectric Sphere: Toward 3D Ground-state Cooling**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:30	Mitsuyoshi Kamba	**Nanoscale Feedback Control of Six Degrees of Freedom of a Near-sphere**
16:30 – 17:00	Thomas Agrenius	**Interaction between an Optically Levitated Nanoparticle and Its Thermal Image: Internal Thermometry via Displacement Sensing**
17:00 – 17:30	Jakob Hüpfl	**Multi-Particle Active Feedback Cooling Using Shaped Wave-Fronts**
17:30 – 18:00	Antonio Pontin	**Simultaneous Cooling of All Six Degrees of Freedom of an Optically Levitated Nanoparticle by Elliptic Coherent Scattering**
18:00 – 18:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**

Program *(CEST)*

18:15 – 19:30	*DINNER*	
19:30 – 20:15	Markus Arndt	**Universal Matter-wave Interferometry Across Mass and Complexity Scales**
20:15	**Poster Awards**	

Program *(CEST)*

Friday, 08 September 2023

08:00	*BREAKFAST*	
09:00 – 09:45	Helmut Ritsch	**Controlling Interaction Forces Towards General Quantum Simulations with Trapped Particles**
09:45 – 10:30	Philipp Kunkel	**Engineering Spatial Entanglement and Graph States of Atomic Ensembles via Photon-Mediated Interactions**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Jayadev Vijayan	**Cavity Quantum Optomechanics with Levitated Nanoparticles**
11:45 – 12:00	Organizers	**Closing Remarks**
12:00	*LUNCH*	

End of Seminar / Departure

Posters

Posters

Bruno Fernando Abreu de Melo	**Single Nanoparticle Control on a Chip: Trapping, Detection, and Cooling**
Seyed Khalil Alavi	**Quantum Levitodynamics with a Photonic Crystal Nanocavity**
James Bateman	**Backaction Suppression in Levitated Optomechanics**
Ines Ben Yedder	**Optical Levitation of Nanoparticle in Engineered Non-linear Potentials**
Alexander Bott	**Light-matter Interaction with Single-photon Transitions for Sensing Beyond the Standard Model**
Igor Brandao	**Magnetically Levitated mm-Sized Helium-3 Spheres as an Optomechanical Platform for Free Quantum Rotations**
Quentin Deplano	**Towards Molecular Entanglement Control**
Alrik Durand	**Toward Spin-mechanical Coupling in Levitating 2D Material**
Matteo Fadel	**Macroscopic Quantum Test with Bulk Acoustic Wave Resonators**
Jonathan Gosling	**Novel Quantum Levitated Sensors for Directional Dark Matter Detection**
Alexey Grinin	**High Mass Matter-Wave Interference and Submicron Gravity Tests with Levitated Nanospheres**
Thiago Guerreiro	**Quantum Optomechanics of Gravitational Waves**

Posters

Bas Hensen	**On-chip Diamagnetic Levitation and Cooling for Gravity Mediated Entanglement**
Jack Homans	**Demonstrating Optical and Magnetic Levitation in Space**
Sungkun Hong	**Hybrid Optomechanical Systems Consisting of Optically Levitated Nanoparticles and Silica Microtoroid Optical Cavity**
Yanhui Hu	**Structured Transverse Orbital Angular Momentum Probed by a Levitated Optomechanical Sensor**
Cyril Laplane	**Towards Absolute Cooling in Levitodynamics Using Optically Active Nanocrystals**
Monika Leibscher	**Controllability of Driven Quantum Rotors: A Graph-theoretical Approach**
Stefan Lindner	**Hollow-core Fiber Loading of Optically Levitated Nanoparticles into Ultra-high Vacuum**
Vojtěch Liška	**Cold Damping of Levitated Optically Coupled Nanoparticles**
Lukas Martinetz	**Surface-induced Decoherence and Heating of Charged Particles**
Miriam Martínez Flórez	**Cooling of Particles with Internal Degrees of Freedom**
Andraz Omahen	**Quantum Gravitational Wave Detector Based on High Overtone Bulk Acoustic Wave Resonators**
Thomas Penny	**Searching for Sterile Neutrinos Using Radioactive Levitated Nanoparticles**

Posters

Johannes Piotrowski	**Cavity Quantum Optomechanics with Levitated Nanoparticles**
Markus Rademacher	**Characterising Nanoparticle Anisotropy through Angularly Resolved Rayleigh Scattering in Optically Levitated Particles**
Andrey Rakhubovsky	**Broadcasting Quantum Nonlinearity to a Linear System**
Dennis Rätzel	**Using (Levitated) Optomechanical Systems to Test Gravitational Theory - Possibilities and Limitations**
Rafael Mufato Reis	**Bimodal Thermal States of Levitated Nanoparticles**
Fabian Resare	**Levitated Superconductive Particles On-chip for Testing Foundations of Quantum Mechanics and Sensing**
Jakob Rieser	**Tunable Light-induced Dipole-dipole Interaction Between Optically Levitated Nanoparticles**
Marc Rodà Llordés	**Macroscopic Quantum Superpositions in a Wide Double-Well Potential**
Loïc Rondin	**Shortcuts to Equilibrium with a Levitated Particle in the Underdamped Regime**
Pedro Rosso Gomez	**Optical Metasurfaces for Levitodynamics Experiments**
Jonas Schäfer	**Decoherence of Rigid Rotors due to Emission of Thermal Radiation**
Surangana Sengupta	**Josephson Optomechanics**

Posters

Marit O. E. Steiner	**Testing Spontaneous Collapse Models with Levitated Particles Under Free Evolution**
Daniel Tandeitnik	**Perturbative Nonlinear Levitodynamics**
Shilu Tian	**Engineering Q Factor of Diamagnetically Levitated Graphite Resonator**
Germain Tobar	**Testing Spontaneous Wavefunction Collapse with Quantum Electromechanics**
Stephan Troyer	**Towards an Experimental Platform for the Control of Biological Nanoobjects**
Christian Vogt	**Levitated Optomechanics with Reduced Gravity**
George Winstone	**Detecting High Frequency Gravitational Waves with Optically Levitated Micro Disks**
Nabil Zerradi	**Electrical Levitation of Micromagnetic Particle Coupled to Superconducting Quantum Circuit**

Abstracts of Lectures

(in alphabetical order)

Non-Hermitian dynamics in arrays of optically coupled levitated particles

M. Reisenbauer[1], L. Egyed[1], M. Abuzarli[1], A. Zasedatelev[1], H. Rudolph[2], K. Hornberger[2], M. Aspelmeyer[1,3], B. Stickler[2] and U. Delić[1]

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Collective effects are at the heart of many interesting phenomena, such as pattern formation out of equilibrium, topological effects, self-organization, and phase transitions. Recently, strong tunable dipole-dipole and electrostatic interaction have been demonstrated between two levitated particles [1]. This makes arrays of optically levitated dielectric particles a prime candidate for exploring some of the aforementioned effects.
Our platform enables independent control and readout of individual particle dynamics and the dipole-dipole interactions together. We employ an anti-reciprocal (dissipative) coupling to engineer non-Hermitian dynamics and observe a mechanical lasing transition once a threshold coupling rate is achieved, supported by our analytical model [2].
Our work showcases the versatility of the platform and has possible applications for sensing and metrology. Finally, we will discuss the scalability of our system to large arrays of trapped particles.

References

[1] J. Rieser, M. A. Ciampini, H. Rudolph, N. Kiesel, K. Hornberger, B. A. Stickler, M. Aspelmeyer, and U. Delić, Tunable light-induced dipole-dipole interaction between optically levitated nanoparticles, Science **377**, 987 (2022)

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Interaction Between an Optically Levitated Nanoparticle and Its Thermal Image: Internal Thermometry via Displacement Sensing

Thomas Agrenius, **Carlos Gonzalez-Ballstero, Patrick Maurer, Oriol Romero-Isart**

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We propose and theoretically analyze an experiment where displacement sensing of an optically levitated nanoparticle in front of a surface can be used to measure the induced dipole-dipole interaction between the nanoparticle and its thermal image. This is achieved by using a surface that is transparent to the trapping light but reflective to infrared radiation, with a reflectivity that can be time modulated. This dipole-dipole interaction relies on the thermal radiation emitted by a silica nanoparticle having sufficient temporal coherence to correlate the reflected radiation with the thermal fluctuations of the dipole. The resulting force is orders of magnitude stronger than the thermal gradient force and it strongly depends on the internal temperature of the nanoparticle for a particle-to-surface distance greater than two micrometers. We argue that it is experimentally feasible to use displacement sensing of a levitated nanoparticle in front of a surface as an internal thermometer in ultrahigh vacuum. Experimental access to the internal physics of a levitated nanoparticle in vacuum is crucial to understand the limitations that decoherence poses to current efforts devoted to prepare a nanoparticle in a macroscopic quantum superposition state.

Phys. Rev. Lett. **130**, 093601 (2023)

Universal matter-wave interferometry across mass and complexity scales

M. Arndt

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In 1923 we celebrate the Louis de Broglie conception of matter waves which inspired Schrödinger's wave equation and a century of studies on quantum foundations and technologies. And while de Broglie believed to have solved "probably … all problems related to quanta"[1], the very nature of the quantum wave has remained a matter of debate throughout the entire century. And though we tend to assume our macroscopic world to be 'non-quantum' we have not found any hard borderline between a coherent quantum evolution and our classical experience.
With our Quantum Nanophysics group at the University of Vienna we have been running experiments with atoms[2], polyaromatic hydrocarbons[3], clusters of organic molecules[4], vitamins[5], neurotransmitters[6], antibiotics[7], macromolecules[8] and polypeptides[9] in more than half a dozen of different matter-wave interferometers, searching for indications of violations of quantum linearity as well as applications in bio-physical chemistry. In all these experiments quantum mechanics has been correct and it even applies to objects that were deemed too complex or too agitated still thirty years ago.
I will review these efforts and describe our ongoing explorations in universal matter-wave interferometry with nanoparticles – focusing here on objects of high mass and complexity and entire material classes that have remained unexplored hitherto [10]. I will discuss how to exploit the matter-wave nature of metal nanoparticles[11] and large biomolecules to gain new insight into materials science and biophysical chemistry[12].

References

[1] L. De Broglie, Nature **112** 540-540 (1923).
[2] Y. Y. Fein, et al., Phys. Rev. X **10** 011014 (2020).
[3] Y. Y. Fein, et al., Phys. Rev. Lett. **129** 123001 (2022).
[4] P. Haslinger, et al., Nature Physics **9** 144 (2013).
[5] L. Mairhofer, et al., Angew. Chem. Int. Ed. **56,** 10947 (2017).
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[7] C. Brand, et al., Phys. Rev. Lett. **125**, 033604 (2020).
[8] Y. Y. Fein, et al., Nature Phys. **15,** 1242 (2019).
[9] A. Shayeghi, et al., Nat. Communs. **11,** 1447 (2020).
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[12] S. Gerlich, et al., Otto Stern's Legacy in Quantum Optics: Matter Waves and Deflectometry, Molecular Beams in Physics and Chemistry (2021).

Levitated Solids in the Quantum Regime - from ground state cooling to quantum sources of gravity

Markus Aspelmeyer[1,2]

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[2] *IQOQI Vienna, Austrian Academy of Sciences, Vienna, Austria*

The quantum optical control of solid-state mechanical devices, quantum optomechanics, has emerged as a new frontier of light-matter interactions [1]. Objects currently under investigation cover a mass range of more than 17 orders of magnitude - from nanomechanical waveguides to macroscopic, kilogram-weight mirrors of gravitational wave detectors. Extending this approach to levitated solids opens up complete new ways of coherently controlling the motion of massive quantum objects in engineerable potential landscapes [2]. In turn, this provides access to an unprecedented parameter regime of large delocalization, mass and coherence time [3].
I will briefly review experimental advances in quantum controlling levitated solids, including cavity- [4] and feedback-based [5] demonstrations of the motional quantum ground state of optically trapped room-temperature nanoparticles, and demonstrations of controlling micron-scale levitated magnets [6] and superconductors [7] at ultra-low environment temperatures. I will then discuss the perspective to explore new regimes of macroscopic quantum physics, in particular ones that include quantum systems as sources of gravity [8].

References

[1] M. Aspelmeyer, T. Kippenberg, F. Marquardt, Rev.Mod.Phys. **86**, 1391 (2014)
[2] J. Millen et al., Rep. Prog. Phys. **83**, 026401 (2020); C. Gonzalez-Ballestero et al., Science **374**, eabg3027 (2021)
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[4] U. Delic et al., Science **367**, 892 (2020); A. Ranfagni et al., Phys. Rev. Res. **4**, 033051 (2022); J. Piotrowski et al., Nat. Phys. **19**, 1009 (2023)
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Characterisation and control of single levitated nanoparticles

P.F. Barker[1], M. Rademacher[1], J.M.H. Gosling[1], A. Pontin[1], M. Toroš[2], J.T. Mulder[3], A.J. Houtepen[3], and T. S. Monteiro[1]

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Fast control, detection and characterisation of single nanoparticles such as viruses, airborne aerosols and colloidal particles are considered to be particularly important for medical applications, material science and atmospheric physics as well as for understanding the detailed understanding of optomechanics experiments [1–7]. In particular, non-intrusive optical characterisation, which can be carried out in isolation from other particles, and without the deleterious effects of a substrate or solvent, are seen to be particularly important. Optical characterisation via the scattering of light does not require complicated sample preparation and can in principle be carried out in-situ. We describe the characterisation of single nanoparticle shape based on the measurement of their angular scattering patterns as well as their rotational and oscillatory motion when optically levitated within vacuum. Using a range of particles, including colloidally grown YLF nanocrystals of different sizes trapped in a single beam optical tweezers, we demonstrate the utility of this method verified by the calculation of these dynamics. We show that size differences as small as a few nanometers could be resolved using this technique offering a new optical spectroscopic tool for non-contact characterisation of single nanoparticles.
Lastly, given time, I will also describe the creation of an optical centrifuge for nanorotors levitated within an optical tweezer. I will discuss optimal schemes to achieve this by rapid control of the laser polarization to well-defined rotational frequencies using a fast in-line polarization controller.

References

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Schrödinger cat states of an acoustic resonator

Y. Chu[1], M. Bild[1], M. Fadel[1], Y. Yang[1], U. von Lüpke[1], P. Martin[1], A. Bruno[1]

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One of the fundamental unanswered questions in quantum physics is why we do not observe macroscopic objects to be in superpositions of states that can be distinguished by some classical property. Various experiments have tried to explore this question by creating so-called "Schrödinger cat states" in systems ranging from SQUIDs to atom interferometers. I will present our work that demonstrates the preparation of a mechanical resonator in Schrödinger cat states of motion, where the constituent atoms oscillate in a superposition of two opposite phases [1]. The acoustic resonator has an effective mass of 16 micrograms, and can be controlled and measured through its coupling to a superconducting quantum circuit. I will also discuss potential applications of our system to quantum sensing and studies of fundamental physics.

References

[1] M. Bild, M. Fadel, Y. Yang, U. von Lüpke, P. Martin, A. Bruno, and Y. Chu, Science **380**, 274 (2023).

Precision sensing and searches for new physics with optically-levitated dielectric particles

A.Geraci[1] and the LSD collaboration

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Despite the great successes of the Standard Model of particle physics, many basic phenomena surrounding us remain without any satisfactory explanation, including the nature of Dark Matter and Dark Energy, which together make up 95 percent of the matter-energy content of our universe. Complementary to high-energy particle colliders or large-scale detectors, ultra-sensitive tabletop experiments are well suited to discover a wide range of new phenomena beyond the Standard Model, where feeble interactions require precision measurements rather than high energies. In high vacuum, optically levitated dielectric nanospheres can achieve excellent decoupling from their environment, making force sensing at the zeptonewton level (10-21 N) achievable. In this talk I will describe our recent efforts using both spherical and plate-like dielectric objects supported by radiation pressure as precision sensors to search for quantum effects related to gravity, high-frequency gravitational waves, and Dark Matter.

References

[1] Cris Montoya, Eduardo Alejandro, William Eom, Daniel Grass, Nicolas Clarisse, Apryl Witherspoon, and Andrew A. Geraci, Appl. Opt. 61, 3486-3493 (2022).

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Quantum systems as gravitational sources: which quantum aspects of gravity can we test?

Flaminia Giacomini
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Understanding the fundamental nature of gravity at the interface with quantum theory is a major open question in theoretical physics. Recently, the study of gravitating quantum systems, for instance a massive quantum system prepared in a quantum superposition of positions and sourcing a gravitational field, has attracted a lot of attention: experiments are working towards realising such a scenario in the laboratory, and measuring the gravitational field associated to a quantum source is expected to give some information about quantum aspects of gravity.

However, there are still open questions concerning the precise conclusions that these experiments could draw on the nature of gravity. Will experiments in this regime be able to test more than the Newtonian part of the gravitational field? More generally, which quantum aspects of gravity can be tested in this regime?

In my talk, I will argue that a full answer to this question requires a combination of different techniques and tools derived from quantum information. On the one hand, I will show how a careful analysis of physical situations using a weak-field description of the gravitational field allows us to identify specific quantum features of gravity. For instance, when two particles become entangled via the Newtonian field and are spacelike separated, in a linearized quantum gravity model it is necessary to introduce quantum properties of gravity (vacuum fluctuations and emission of radiation in a quantum state) to avoid faster-than-light signalling. On the other hand, a theory-independent approach allows us to derive no-go theorems which help us to constrain the possible theories compatible with a certain experimental outcome.

A solid theoretical investigation of these aspects is necessary to identify quantum properties of gravity that could be observed in the future.

Quantum light-matter interaction with a dielectric sphere: toward 3D ground-state cooling

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The interaction of light with a dielectric sphere is core to multiple fields of research, including levitated optomechanics [1]. Recent experiments demonstrating ground-state motional cooling of optically levitated nanospheres [2-7] have opened the door to the quantum regime. These experiments have been limited to ground-state cooling of only one or two motional degrees of freedom – the latter only with the aid of an optical cavity – of subwavelength silica nanoparticles, whose electrodynamical response can be approximated by a point dipole. Within this point-dipole approxima-tion, understanding how light interacts with the motion of the nanoparticle (e.g. laser recoil heating rates, information radiation patterns) has been key to predict, optimize, and understand ground-state cooling. This theory, however, is limited and not easily extended to particles beyond the point-dipole approximation. Thus, it is unclear if and how can large dielectric spheres be cooled to the ground state.

In our recent work [8] we develop a quantum electrodynamical theory of the interaction between the electromagnetic field and a dielectric sphere of arbitrary size and refractive index. We derive expressions for the three core quantities in levitated optomechanics, namely optomechanical coupling rates, recoil heating rates, and information radiation patterns, for arbitrary configuration of incoming laser fields. Furthermore, we simplify such expressions analytically which enables us to evaluate them efficiently. I will show how in two relevant examples, namely a Gaussian laser beam and two Gaussian beams in a standing wave configuration, our theory predicts a wide range of parameters (sphere size, numerical apertures of focusing lenses,…) where one, two, and even three-dimensional ground-state cooling is achievable in free space. Our work provides a complete theoretical toolbox to describe the interaction of light with levitated dielectric objects in the quantum regime.

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Predicting the Future, Remembering the Past: Stationary Entanglement in Optomechanics

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Consider a quantum system subject to a continuous measurement that was started at a certain point in time. Based on the record of the continuous measurement, what information can be obtained about the quantum state the system was in at that initial time? I will give an introduction to the problem of retrodiction of quantum states and its solution in terms of retrodictive Positive Operator Valued Measures. The general formalism will be illustrated in its application to optomechanical systems. E.g. I will explain how an ideal quadrature measurement of the mechanical oscillator can be realized that provides direct access to the marginal distribution of the oscillator position or momentum and thus the basis for a complete, albeit destructive, quantum state tomography. Retrodiction is the temporal mirror image of the more familiar prediction of quantum states, via e.g. the stochastic Schrödinger equation, conditioned on measured photocurrent. I will draw an intriguing connection between the temporal mode functions relevant for retrodiction and prediction, and stationary entanglement of mechanical oscillators and light.

Spin-mechanics with trapped magnetic particles

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Observing and controlling macroscopic quantum systems has long been a driving force in research on quantum physics. To this end, many groups are investigating platforms for coupling the motion of levitating particles to the spin of atomic electrons at the quantum level. The angular degrees of freedom of levitating diamonds coupled to embedded Nitrogen-Vacancy (NV) centers offer bright prospects towards this purpose [1]. Levitating magnets are also promising for high sensitivity magnetometers. I will present our experimental progress in this direction.

First, I will present our results on coherent manipulations of the spin of NV centers [2] and of the spin-dependent torque and spin-cooling of the angular motion of diamonds levitating in a Paul trap [3]. I will also show how the negative magnetic susceptibility enables microwave-free magneto-optical alignment of the diamond main axes along the magnetic field [4], offering prospects towards spin-levitation and angular control of diamonds under liquid environments. Last, I will present our recent observations of the spin-detection of fully rotated diamond particles.

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Probing quantum mechanics with nanoparticles

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Levitated optomechanics provides a platform for testing the validity of the quantum superposition principle at increasingly macroscopic scales. But how can the degree of macroscopicity achieved in an optomechanical superposition be objectively compared to other experiments, using for intance superconductors, free matter waves, or bulk acoustic resonators?
In this talk, I will first discuss a measure of macroscopicity applicable to any quantum mechanical superposition test [1,2]. Motivated by this, I will propose to create orientational superpositions of nanoparticles using the intrinsic nonlinearity of their rotational dynamics [3,4], and will discuss how to predict the impact of environmental decoherence based on the dielectric properties of their material [5].

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Multi-Particle Active Feedback Cooling Using Shaped Wave-Fronts

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Levitated particles offer a unique and controlled platform for precise investigations of various physical effects while minimizing external influences. The potential to perform high-precision force sensing experiments and explore quantum phenomena using cooled particles has emerged as an intriguing possibility. However, to fully unlock the complexity and capabilities of these systems, the simultaneous trapping and cooling of a large number of particles is crucial. This poses a challenge as existing techniques rely on controlled environments, making the scaling up to larger systems challenging due to intricate interactions between individual particles. Here, we propose a novel multi-particle cooling approach utilizing a generalization of the Wigner-Smith time-delay operator [1,2]. By establishing a connection between the eigenvalues of this operator and system changes, we leverage advancements in spatial light modulators to introduce an active feedback cooling scheme. Our scheme utilizes far-field information from the electromagnetic field to generate a sequence of customized input wave-fronts, which simultaneously cool the translational and rotational center-of-mass motion for all particles in parallel. Remarkably, our approach decouples the degrees of freedom of the field from those of the particles, naturally leading to good scaling properties. To validate the scalability of our approach, we conducted numerical simulations demonstrating its effectiveness across a wide range of particle numbers, sizes, and shapes. Based on these findings, we propose an experimental implementation wherein continuously shaped wave-fronts cool an ensemble of levitated objects, with the goal to observe and analyze the cooling effects in a practical setting using state of the art equipment.

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Nanoscale feedback control of six degrees of freedom of a near-sphere

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Nanoparticles levitated in a vacuum by laser beam (levitated nanoparticles) have the characteristic of being extremely well isolated from the environment, and by controlling their center-of-mass (CoM) and rotational motions, they are expected to be used in various applications such as acceleration sensors and stage for quantum phenomena of macroscopic objects.

Recently, significant progress has been made in developing effective cooling methods for the CoM motion [1]. With optical cavities, it is now possible to cool the CoM motion in two dimensions to extremely low temperatures, approaching the ground state [2]. However, cooling the CoM motion in multiple dimensions to the ground state with feedback cooling remains challenging. Furthermore, rotational motion of nanoparticles also has attracted much attention in recent years and has been studied for anisotropic particles, such as dumbbell-shaped particles. Although it has recently become possible to cool three degrees of rotational motion with optical cavities [3], feedback cooling of rotational degree is limited to control of up to two degrees of freedom [4].

In this study, we have succeeded in feedback cooling all of the external degrees of freedom of electrically neutral and nearly spherical nanoparticle trapped by one dimensional optical lattice [5]. The three degrees of CoM motion are cooled to near ground state by an optical feedback cooling [6]. The minimum occupation number is 0.69(18). We also have succeeded in confinement of nanoparticle’s orientation by anisotropic confinement with a one-dimensional optical lattice, and also observe three librational motions of nanoparticles. We have successfully cooled three librational motion to temperatures below 0.03 K by applying a feedback torque proportional to the angular velocity to the nanoparticles.

These results will set the stage for investigating the effect of librational motion on the CoM motion of nanoparticles cooled to near the ground state [7].

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Fast Quantum Interference of a Nanoparticle via Optical Potential Control

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Optical micromanipulation in the liquid phase has been extremely successful in demonstrating motional control of colloids and microfabrication techniques. Recently, researchers have started to exploit the versatile potential of optical tweezers beyond simple single particle harmonic traps in optical levitation. To what extend this approach will lead to enhanced control of QUANTUM states of mesoscopic systems is still an open question for two major reasons: On an technical level, due to the challenge of control in an ultra-low friction environment, and on a fundamental level due to the intrinsic measurement performed by light field itself on the object's motion.
I will argue for the feasibility of such experiments by discussing a specific experimental scheme: We propose to prepare and detect non-Gaussian quantum states of an optically levitated particle via the interaction with a light pulse that generates cubic and inverted potentials. We show that operating on short time- and length scales will significantly reduce the demands on decoherence rates in such experiments. Specifically, our scheme predicts interference of nanoparticles with a mass above 10^{8} amu delocalised over several nanometers when operated at vacuum levels around 10^{-10} mbar and at room temperature. I will discuss the experimental implementation, specific challenges and an outlook to future steps in this direction.

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Quantum control of molecular rotation

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The angular momentum of molecules, or, equivalently, their rotation in three-dimensional space, is ideally suited for quantum control [1]: Molecular angular momentum is naturally quantized, time evolution is governed by a well-known Hamiltonian with only a few accurately known parameters, and transitions between rotational levels can be driven by external fields from various parts of the electromagnetic spectrum. Molecules without any improper axis of rotation, more specifically chiral molecules belonging to the C_1 symmetry point group, offer a particularly interesting avenue for quantum control.

These molecules possess a permanent dipole moment with nonzero components along all three principal axes of inertia. They are necessarily chiral such that the two stereoisomers, also termed enantiomers, are nonsuperposable mirror images of each other. Intriguingly, observables that are sensitive to the handedness of the molecules exist even in ensembles of molecules with random orientation, as is typical in gas phase experiments. We have identified the number and types of electric fields necessary to completely control the rotational dynamics [2]. The insight on chiral-sensitive control can also be used to design excitation schemes that induce chirality in an ensemble of initially achiral molecules [3]. Further possibilities for chiral-sensitive control arise when considering the coupled rotational-vibrational motion [4].

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Engineering Spatial Entanglement and Graph States of Atomic Ensembles via Photon-Mediated Interactions

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Programming the spatial structure of entanglement is an essential prerequisite for quantum computation. While many experiments with neutral atoms focus on bottom-up approaches combining local interactions with position control, all-to-all interactions together with local operations provide a complimentary top-down approach to achieve full control over the entanglement structure. In our experiment, we use an optical cavity and local spin rotations to mediate programmable long-range interactions within a 1D array of atomic ensembles. Driving the cavity with light induces all-to-all interactions between the spin-1 atoms, creating atom pairs and quantum correlations within a single spatially extended mode of the collective spin. In this case, we measure spin-nematic squeezing and verify the generation of entanglement between spatially separated ensembles by quantifying the correlations in two non-commuting observables. By employing local spin rotations we selectively couple different spatial modes to the cavity and thus control the structure of the generated quantum correlations. This capability allows tailoring the spatial entanglement structure from local entanglement to graph states, a valuable resource for quantum computation and sensing.

Rotational optomechanics with levitated nanoparticles in optical tweezers and ion traps

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A non-spherical nanoparticle levitated in a vacuum provides an exceptional setting for investigating quantum rotations and serves as an extremely sensitive torque and force detector [1]. Recently, we optically levitated a silica nanodumbbell in a vacuum at about 430 nm away from a sapphire surface and drove it to rotate at GHz frequencies [2]. By levitating a nanodumbbell near a gold nanograting, we probed near-field intensity distributions beyond the optical diffraction limit. Additionally, we demonstrated the successful levitation of a nanodiamond with nitrogen-vacancy centers in high vacuum using a surface ion trap and drove it to rotate at MHz frequencies. Our research contributes to the understanding of spin-mechanical coupling and brings us one step closer to realizing quantum superposition of nanodiamonds.

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Quantum spectral signatures of a two-dimensional optomechanical system

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Levitated nanoparticles in cavity optomechanical experiments allow to study quantum phenomena beyond the usual limit of one-dimensional, weakly coupled mechanical oscillator. In our experiment, the motion of a levitated nanosphere is coupled to the cavity field by coherent scattering, and heavily cooled in the plane orthogonal to the tweezer axis [1], achieving the two-dimensional strong and coherent quantum optomechanical coupling regime [2]. Here, we show that the motional sideband asymmetry that reveals the quantum nature of the dynamics is not limited to mere scaling factors between Stokes and anti-Stokes peaks, as customary in quantum optomechanics, but assumes a peculiar spectral dependence. Its shape traces out the spectral features of the quantum fluctuations in the cavity field, which are thus explored over a wide spectral range [3]. Moreover, we show that in the two-dimensional mechanical system the quantum backaction, generated by these vacuum fluctuations, is strongly suppressed within a narrow spectral region due to destructive interference in the overall susceptibility.

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Levitated Electromechanics

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In this talk I will introduce an all-electrical interface for the quantum control of levitated particles, and discuss technical advances in particle bath engineering, and the cooling of arrays of particles for sensing applications.

The use of optical fields to levitate nanoparticles enables precise control, to the level where ground-state cooling has been achieved [1,2]. Optical levitation faces challenges, including absorption [3,4], photon recoil [5] and relatively low optical trap depths necessitating feedback control when operating in vacuum. Hence, research has explored the use of magnetic or oscillating-electric fields for levitation.

The latter, whereby charged particles are levitated within a Paul trap, offers extremely large trap depths, lends itself to miniaturization and benefits from the mature technologies developed by the atomic ion trap community. We have developed the framework for the coupling of charged particles to the electrodes of a Paul trap [6] for cooling and sensing, and further developed a scheme to coherently couple charged particles to a qubit [7] for quantum networking and the exploration of macroscopic quantum mechanics.

The levitation of charged particles also allows bath engineering and the straightforward levitation of arrays of interacting particles. We will present progress from the lab on both single- and multi-particle cooling and control.

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Levitated optomechanical sensors for nuclear and particle physics

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Levitated optomechanical sensors operated in the quantum regime can enable novel searches for new fundamental particles and interactions [1]. As an intiial demonstration of such applications, I will describe an initial search for dark matter using an optically levitated nanogram mass sensor, which can exceed the sensitivity of even large underground detectors for certain classes of dark matter candidates in a few days of exposure [2]. If a signal were detected, such sensors would also be able to correlate its direction with earth's motion through the galaxy, allowing definitive confirmation that such a signal arose from dark matter. The same techniques can also permit new laboratory searches for sterile neutrinos, potentially probing orders-of-magnitude smaller mixings with active neutrinos than previous experiments in the keV-MeV mass range. I will also describe recent proposals to perform such searches using optically trapped nanoparticles doped with beta emitters [3]. Future extensions of these techniques have substantial potential to provide new insight into major unanswered quetions in nuclear and particle physics.

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

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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. Such quantum states have already been realized with superconducting qubits coupled to clamped mechanical oscillators. We are interested in achieving an analogous coupling between a spin and a levitated oscillator — namely, a silica nanoparticle in a linear Paul trap — in order to take advantage of a levitated system's extreme isolation from its environment. In this case, we envision an atomic ion as the spin qubit.

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 the particle's 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.

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Aspects of low energy tests of quantum gravity

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This talk delves into the theoretical and practical aspects of levitated particles operating in the quantum regime, with a primary focus on measuring gravitational effects. We will commence with a concise examination of the force sensitivity inherent in non-classical quantum states, such as cat-states or squeezed states. Building upon this foundation, we will present some ideas aimed at enhancing the force sensitivity of levitated particles [1, 2].

Moreover, we may delve into more fundamental aspects, exploring the potential impact of hypothetical non-linear extensions of quantum mechanics on tests of the quantum character of gravity [3] and investigating entanglement-free tests of the quantum nature of an interaction [4, 5].

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Simultaneous cooling of all six degrees of freedom of an optically levitated nanoparticle by elliptic coherent scattering

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There has been significant interest in controlling the motional degrees of isolated, single nanoparticles, trapped within optical fields in high vacuum. These systems are ideal candidates for exploring the limits of quantum mechanics in new mass regime and they are also massive enough to be considered for future laboratory tests of the quantum nature of gravity. The translational motion of trapped particles has entered the quantum regime [1] and there is significant interest in extending this control to all observable degrees of freedom, including their orientational motion. We report on the control and cooling of all translational and rotational degrees of freedom of a nanoparticle trapped in an optical tweezer exploiting cavity cooling via coherent elliptic scattering [2]. Translational temperatures in the 100 μK range were demonstrated, thus approaching the quantum regime. At the same time temperatures as low as 5 mK were attained in the librational degrees of freedom. This work represents an important milestone in controlling all observable degrees of freedom of a levitated particle and opens up future applications in quantum science and the study of single isolated nanoparticles via diffractive methods, free of interference from a substrate.

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Controlled dynamics of a levitated nanoparticle in a hybrid optical / RF integrated platform

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The study and control of levitated nano- and micro-objects has gained considerable attention over the last decade owing to its potential to advance both fundamental science and technology. While early levitation experiments made use of optical potentials and weakly absorbing dielectric polarizable particles, the toolbox expanded in recent years to include techniques borrowed from the atom trapping community. The development of electrostatic and magnetic levitation made it possible to overcome excessive photoheating of the trapped specimen and extended levitation to a broader range of particles, including particles with internal degrees of freedom. Furthermore, on-chip integration has been identified as key to interface levitodynamics with other existing technologies, to increase platform robustness and compatibility with cryogenic conditions, and to devise autonomous and portable sensors.

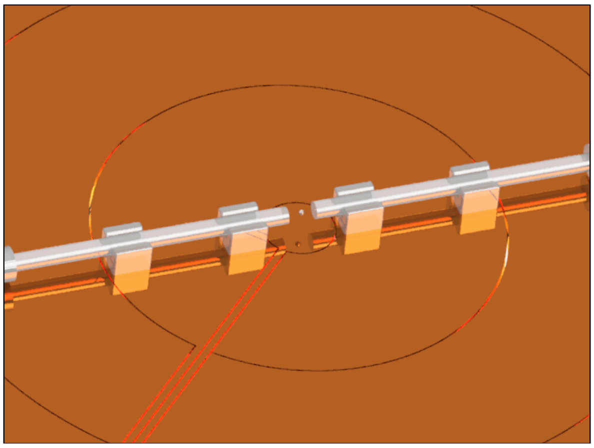

Figure 1: Artistic representation of an integrated levitation platform interfacing plan RF electrodes with optical trapping and readout.

In this presentation we discuss our most recent advances in the development of integrated hybrid levitation platforms combining RF planar electrodes with integrated photonics. We focus on two different experiments. The first one explores the potential of levitated microparticles for inertial sensing. The second experiment focuses on free-fall dynamics in a dark double-well potential.

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Phase transitions and universal scaling in bosonic transport

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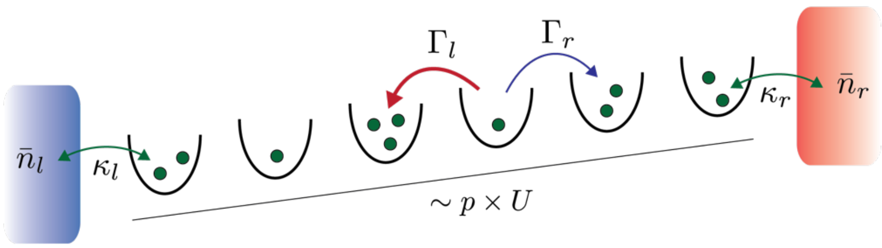
Optomechanical and levitated systems offer exquisite control over isolated bosonic excitations, including mechanical, optical and magnetic degrees of freedom. Continued experimental advances in this field will soon allow us to control whole networks of such isolated modes and explore new physical phenomena, such as transport. In this talk I will discuss the directed transport of bosons along a one dimensional lattice with asymmetric hopping rates. In spite of its simplicity, this model already exhibits many intriguing features, which arise from the combination of directionality and the underlying bosonic particle statistics. In particular, I will describe the appearance of boundary condensation phenomena in thermal transport scenarios as well as the asymptotic scaling of current fluctuations in a freely expanding system and how they can be explained in terms of a surface-growth model. Finally, I will propose different setups and mechanisms that could potentially be used to study these effects in the context of opto- and magnetomechanics.



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Controlling interaction forces towards quantum simulations with trapped particles

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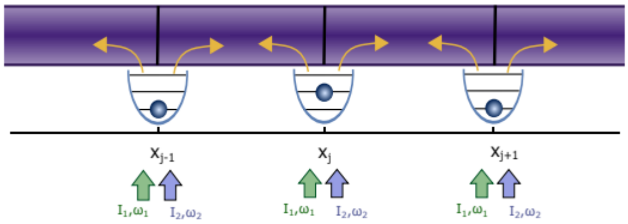

The transversely confined propagating light modes of a nano-photonic optical waveguide or nanofiber can mediate effectively infinite-range forces. We show that for a linear chain of particles trapped within the waveguide's evanescent field, transverse illumination with a suitable set of laser frequencies should allow the implementation of a coupled-oscillator quantum simulator with time-dependent and widely controllable all-to-all interactions. At the example of the energy spectrum of oscillators with simulated Coulomb interactions we show that different effective coupling geometries can be emulated with high precision by proper choice of laser illumination conditions. Similarly, basic quantum gates can be selectively implemented between arbitrarily chosen pairs of oscillators in the energy basis as well as in a coherent-state basis. Key properties of the system dynamics and states can be monitored continuously by analysis of the out-coupled fiber fields.

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Macroscopic Quantum Superpositions via Dynamics in Wide Nonharmonic Potentials

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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 (arXiv:2303.07959) that employs fast quantum dynamics in nonharmonic potentials to meet the stringent requirements imposed by environmentally-induced decoherence.

Quantum theory of non-hermitian optical binding between nanoparticles

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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]. Motivated by this, I will present the quantum theory of small dielectric objects interacting via the forces and torques induced by scattered tweezer photons [2]. 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 with optical binding.

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Testing Fundamental Physics with Levitated Mechanics

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We will report on progress with levitated experiments and theoretical ideas for using such sustems for testing fundamental physics at Southampton and with partnering institutions. In more detail, we will report on using metalenses for optical trapping and controlling rotation of silica nanoparticles as well as the implementation of squeezing protocols in optical experiments, using superconducting levitation of micrometer ferromagnets for measruing magnetic fields and gravity, as well as using rotation of metallic objects for amplification of electromagnetic waves.

Cavity quantum optomechanics with levitated nanoparticles

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The quantum ground state of motion of a massive mechanical system is a stepping stone for exploring macroscopic quantum science and building high fidelity mechanical sensors. We describe our results on two-dimensional ground-state cooling of the motion of an optically levitated nanoparticle, entering the quantum regime with cavity-based cooling via coherent scattering [1]. Recently, levitated optomechanical systems have also entered the multi-particle regime with demonstrations of simultaneous cooling [2] and short-range interactions [3].
Combining the capabilities of controlling multiple particles and the optomechanical coupling provided by a coherent scattering setup, we now demonstrate for the first time truly long-range interactions between levitated nanoparticles. Tuning our experimental parameters allows us to adjust the interaction strength, choose which mechanical modes are coupled, and rapidly switch the coupling on and off. Engineering such long-range interactions is a powerful tool for the investigation of out-of-equilibrium phenomena and the generation of non-local correlations. Our work paves the way towards generating entanglement [4,5] and exploring non-local many-body effects in levitated nanoparticles, as well as building arrays of interacting sensors for optomechanical sensing.

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Coupled spin mechanics in levitated nanoscale particles

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Dielectric particles levitated in vacuum offer an ideal playground to control and study the dynamics of micro- and nanoresonators due to the high isolation from environmental noise and decoherence. Magnetically ordered dielectrics introduce magnetization as an additional degree of freedom. Due to the reduced moment of inertia of nano- to microscale particles, the Einstein–de Haas effect and its reciprocal, the Barnett effect, can play a dominant role in the dynamics of such systems. These two effects are macroscopic manifestations of the internal angular momentum origin of magnetization, describing how a change in the magnetization of a freely moving body causes a change in the mechanical rotation and vice versa. We theoretically study different systems of levitated nano- and micrometer sized dielectric particles in the presence of a static magnetic field in order to investigate the interplay of magnetization and mechanical dynamics. In particular, we emphasize on the spin origin of the magnetization and focus on the coupling between spin and rotational motion of levitated nanomagnets and -diamonds with an embedded nitrogen-vacancy center [1, 2]. To additionally study the interaction of light with such coupled spin-mechanics we combine the fields of levitated optomechanics and cavity optomagnonics by considering a levitated Faraday-active dielectric microsphere driven by an external laser - a novel system within which light, magnetism and angular motion are intertwined. We show that light can be used as a sensitive probe of the coupled spin-mechanics [3].

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Challenging theories of dark energy with levitated force sensor

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The nature of dark energy is one of the most outstanding problems in physical science, and various theories have been proposed. It is therefore essential to directly verify or rule out these theories experimentally. Despite substantial efforts in astrophysical observations and laboratory experiments, previous tests have not yet acquired enough accuracy to provide decisive conclusions as to the validity of these theories. Here, using a diamagnetically levitated force sensor, we carry out a test on one of the most compelling explanations for dark energy to date, namely the Chameleon theory, an ultra-light scalar field with screening mechanisms, which couples to normal-matter fields and leaves a detectable “fifth force” [1]. Diamagnetically levitated mechanical oscillator is an emerging system for ultra-sensitive force detection at sub-milligram scales [2,3,4]; in addition, we have made sophisticated structure design for the experiment system. Our results extend previous results by nearly two orders of magnitude to the entire physical plausible parameter space of cosmologically viable chameleon models. We find no evidence for such a “fifth force”. Our results decisively rule out the basic chameleon model as a candidate for dark energy. Our work, thus, demonstrates the robustness of laboratory experiments in unveiling the nature of dark energy in the future. The methodology developed here can be further applied to study a broad range of fundamental physics.

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Multidimensional effects with levitated objects

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Recent experimental progress in the control of the mechanical motion of a single levitated particle opens new ways to investigate more complex configurations in more dimensions or with more levitated and interacting particles. Optical levitation offers relatively easy tunability of the key parameters of the system (oscillating frequency, the strength of the optical coupling between particles, damping, etc.), over several orders of magnitude and merging with other non-optical types of interactions (e.g. external electric field). Similarly, the methods of cooling of mechanical degrees of freedom can be extended from a single particle case to a multiparticle case.

We provide a few experimental examples of optical levitation of more particles where their optical coupling (referred to as optical binding) plays a key role. We demonstrate a synchronization of two limit cycles formed from two levitated particles orbiting in the lateral plane [1,2] where the non-conservative optical spin force, coming from the circularly polarized beam, plays the dominant role. Additionally, in a similar geometry with two levitated particles in two independent standing wave traps, we employ a feedback loop based on an electric field and cooled the normal modes of both optically coupled particles [3]. Finally, we analyze the optical levitation of several particles optically coupled in the longitudinal direction in counter-propagating laser beams [4].

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Abstracts of Posters

(in alphabetical order)

Single Nanoparticle Control on a Chip: Trapping, Detection and Cooling

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In recent years, optically levitated micro and nanoparticles in high vacuum have been used in a variety of experiments, both in fundamental and applied research. Preparing their quantum ground state opened a new path for exploring the boundaries between quantum and classical [1, 2], while their isolation from the environment makes them excellent force [3] and acceleration sensors [4].
Thus far, optical levitation setups have relied on free space optics, making them bulky and susceptible to long term drifts. As an alternative, we demonstrate optical trapping, detection and cooling of nanoparticles on an integrated chip-based platform at 1e-6 mbar. The on-chip optical trapping is based on two orthogonal standing waves created by opposing optical fibers. We use two photon polymerization to ensure robust and accurate positioning of the optical fibers close to a planar electrode layout. The electrode layout comprises a planar Paul trap and additional electrodes used for cooling the center of mass in three directions by means of cold damping. The light collected by the optical fibers is used to measure the particle's position via homodyne detection.
Our fiber-based platform enables the realization of levitodynamics experiments on a chip for a large range of particle sizes, promising the compactness and long-term stability required in applications such as experiments in space, drop towers, cryostats and in industry.

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Quantum levitodynamics with a photonic crystal nanocavity

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Optically levitated nanoparticles, being coupled to optical cavities, have emerged as a promising platform to explore light-matter interaction at the quantum level. In such an optomechanical system, the particle's mechanical motion is coherently coupled to the cavity's optical field, allowing precise and efficient control of the motion of the levitated particle. Breakthrough experiments revealed the merits of such a platform by showing the cooling of particle's motion to the ground state using standard Fabry–Pérot cavities [1-2]. Micro- and nano-scaled optical cavities are attractive alternatives, where the small dimensions of these cavities facilitate the integration of such compact system with other elements, forming a more complex optomechanical system with higher functionalities. Moreover, a high degree of optical field confinement allows for strong optomechanical coupling. Single-photon optomechanical coupling of up to 10 kHz has been demonstrated with a stand-alone photonic crystal nanocavity (PCN) [3]. Nevertheless, the susceptibility of the system to optical absorption and mechanical perturbation hindered further progress toward the quantum regime. Here, we introduce a new platform based on on-chip PCN to achieve this goal. This new architecture significantly improves mechanical and thermo-optic stability, enabling experiments to be conducted in high vacuum conditions and with a substantial number of intracavity photons. In this contribution, we highlight our recent results towards achieving a quantum cooperativity value exceeding one.

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Backaction suppression in levitated optomechanics

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Backaction is the unavoidable consequence of measurement in quantum mechanics. Rayleigh scatter from a point-like dipole in a focused laser field has been shown to reveal sufficient information to attain the Heisenberg limit [1] and this is consistent with the stochastic force noise arising from photon recoil [2] as it must be through the imprecision--backaction product [3].

The above results are derived in free-space. To study geometries which include metallic boundary conditions, we compute the force noise on a point-like dipole directly using stochastic electrodynamics [4,5], which provides a formalism to incorporate quantum fluctuations of the electromagnetic field in an otherwise classical theory. We reproduce the free-space result and then study the specific geometry of a particle near the geometric center of a large spherical mirror.

We find that for some arrangements of focused laser field it is possible, by choice of mirror radius, to ensure not only that no linear position information is available in the scattered field but also that the force noise on the particle reduces to zero. This corresponds to complete suppression of recoil heating, as has been explored by alternative means elsewhere [6].

These calculations are first-order in polarisability, ignore internal heating, and assume a perfectly reflecting mirror. We describe an experimental protocol, discuss the suppression we expect under realistic conditions, and report on experimental progress.

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Optical levitation of nanoparticle in engineered non-linear potentials

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Dynamical control of non-harmonic potentials of a levitated particle is an essential step toward the generation of advanced quantum states, enhanced force sensing, and modelling of thermodynamics at the nanoscale.

Here we present an approach to generate arbitrary 1D optical trapping potential of a levitated particle based on the controlled superposition of an ensemble of laser beams [1]. Specifically, we focus on the opportunity to handle the non-harmonicity of the potential by the simple superposition of two spatially shifted laser trapping beams using an acousto-optic modulator (AOM).

We study the particle dynamics while the potential is tuned from harmonic to bistable, through almost quartic.

Our work is a step forward for controlling optical potentials toward studying non-equilibrium dynamics in complex potentials and generating non-Gaussian superposition states for mesoscopic particles [2].

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Light-matter interaction with single-photon transitions for sensing beyond the Standard Model

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Atom interferometers have been successfully employed for high-precision measurements of various quantities, for instance accelerations [1] as well as fundamental constants [2]. Differential measurements with atom interferometers are a promising avenue for demanding sensing applications such as the detection of gravitational waves [3] and light scalar dark matter [4]. Most current atom interferometers rely on two-photon transitions used for Raman or Bragg diffraction. Single-photon transitions driven by a single laser are a hopeful alternative for such differential detectors as they offer a natural mitigation of laser phase noise [5].

In our contribution we derive an effective atomic two-level model for both Raman and single-photon transitions, including perturbations from effects beyond the Standard Model; in particular we include violations of the Einstein equivalence principle and effects of light scalar dark matter. We obtain a description of the time-evolution of such effective atomic two-level systems during their interaction with light. Therefore, we determine phase contributions imprinted by the Standard Model violations on the atoms interacting with the lasers in an atom interferometer.

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Magnetically levitated mm-sized helium-3 spheres as an optomechanical platform for free quantum rotations

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Ground state cooling has been achieved in a plethora of optomechanical systems in recent years. Most prominently, setups using optically levitated nanoparticles made rapid progress on this front given their unprecedented isolation. However, the high optical power needed to trap and manipulate the particles leads to photon recoil rates which limit the achievable mean phonon number and mechanical coherence times. Combined with the relatively small single photon coupling rates realized in these systems, subsequent state preparation has been limited to the linearized regime and Gaussian states. Magnetic levitation of liquid helium is an attractive alternative since it removes this decoherence channel. The choice to levitate mm-sized liquid helium drops instead of silica (SiO2) solid spheres, allows us to use the levitated object itself as the optical cavity. This can be achieved using the optical whispering gallery modes (WGM) which couple directly to the drop's surface waves and rotational modes. Surface waves may achieve the single-photon strong-coupling regime, and have been the subject of preliminary experimental studies in superfluid helium-4 drops at temperature ~ 300 mK. Rotational coupling can be achieved in helium-3, which undergoes rigid-body rotation at similar temperatures. This coupling is predicted to be dominated by the centrifugal force experienced by the drop, which would induce a shape deformation. This detunes the optical WGM by an amount proportional to the square of the drop's angular momentum, adding a new form of interaction to the toolbox of levitodynamics. Here, we report the first magnetic levitation of helium-3 drops, and describe our ongoing efforts to study their optomechanical and optorotational behavior.

Towards molecular entanglement control

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Arrays of entangled delocalized emitters trapped in condensed matter such as quantum dots [1], colored defects in diamond [2] or fluorescent molecules trapped in a matrix [3] are promising systems to study quantum collective processes and enlighten some path towards scalable, integrated quantum technologies. Among those systems, molecules trapped in an organic crystalline matrix are particularly attractive. Brought to liquid helium temperature, they are very well modeled by two-level systems and display a lifetime-limited transition. In this work, we are using such fluorescent molecules as a test bench to demonstrate full optical, coherent, sub-nanosecond manipulation of one single emitter.

Moreover, by using a far-field nanoscopy method [4], we report the observation of more than ten pairs of entangled molecules coupled through the resonant dipole-dipole interaction. We measure the lifetimes of the sub- and super-radiant states emerging from the coupling as a function of the entanglement degree and show the selective addressing of the long-lived subradiant state [5].

Our study paves the way to the dynamical control of entangled molecular qubits as well as the investigation of the decoherence in delocalized ensembles.

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Toward spin-mechanical coupling in levitating 2D material

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We aim to investigate spin-mechanical coupling in levitating hBN particles with boron vacancy spin defects held in Paul traps. The substantial spin count and the potentially large angular confinement in these micro-particles may offer a new way to probe the physics of spin-defects in 2D materials.

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Macroscopic Quantum Test with Bulk Acoustic Wave Resonators

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Recently, solid-state mechanical resonators have become a platform for demonstrating non-classical behavior of systems involving a truly macroscopic number of particles. Here, we perform the most macroscopic quantum test in a mechanical resonator to date, which probes the validity of quantum mechanics by ruling out a classical description at the microgram mass scale. This is done by a direct measurement of the Wigner function of a high-overtone bulk acoustic wave resonator mode, monitoring the gradual decay of negativities over tens of microseconds. While the obtained macroscopicity of $\mu = 11.3$ is on par with state-of-the-art atom interferometers, future improvements of mode geometry and coherence times could test the quantum superposition principle at unprecedented scales and also place more stringent bounds on spontaneous collapse models.

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Novel quantum levitated sensors for directional dark matter detection

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Levitated quantum optomechanics provides a novel platform to test fundamental physics. These systems, providing both isolation from the environment and the ability to cool particles to the quantum ground state, open up the potential for extremely sensitive measurements of weak forces at both short and long range. One such application provides a unique directional dark matter direct detection technique to explore alternative parameter space to that being investigated by large scale experiments deployed underground, providing a complementary search for particulate dark matter [1]. In particular, due to the movement of our solar system through the “dark matter halo” of the Milky Way, this additional directional discrimination will allow for unambiguous confirmation of a galactic signal.

We present the results from a proof-of-principle experiment, capable of resolving collisions in all three dimensions, utilising nanoparticles (10^-18kg), for composite dark matter searches in the 10 MeV – 10 GeV mass range. We describe the experimental apparatus, data analysis framework and profile likelihood ratio based statistical techniques to present projected sensitivity results competitive with world-leading dark matter constraints [2]. Finally, we present studies into improving momentum transfer sensitivity through calibration of the experimental setup, and increasing detection efficiency through data analysis, enhancing sensitivity to unexplored parameter space in the search for dark matter in near future science runs.

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High Mass Matter-Wave Interference and Submicron Gravity Tests with Levitated Nanospheres

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Demonstration of Matter-Wave Interference with ever larger particles not only goes side-by-side with the development of Quantum Mechanics but also results in crucial imaging and measurement methods for essentially every new particle brought to interference.

The current mass record for matter-wave interference is around 25kDa [1]. Optically levitated nanospheres have the potential to push this boundary by several orders of magnitude due to their efficient decoupling from the environment and the ability to feedback-cool the center of mass degrees of freedom even down to the motional ground state [2,3,4].

Similarly, the strong decoupling from the environment and the mesoscopic size of the objects can be exploited to bring nanoobjects close to a surface and measure short-range forces at distances where even a millionfold strong deviation from Newtonian gravity has not been ruled out experimentally.

I will report on the progress of our fully cryogenic, extremely high vacuum (EHV), and vibration-isolated setup. We have implemented optical levitation and parametric feedback cooling of nanospheres, designed a submicron gold-coated silicon nitride membrane to trap less than a micron away from the source mass, realized repeatable EHV compatible launching of nanoparticles [5], and demonstrated zeptonewton force sensitivity [6].

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Quantum optomechanics of gravitational waves

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Abstract: Einstein's theory of gravity admits a low energy effective quantum field description from which predictions beyond classical general relativity can be drawn. As gravitational wave detectors improve, one may ask whether non-classical features of such theory can be experimentally verified. Here we argue that nonlinear effects in black hole ringdowns can be sensitive to the graviton number statistics and other quantum properties of gravitational wave states. The prediction of ringdown signals, potentially measurable in the near future, might require the inclusion of quantum effects. This offers a new route to probing the quantum nature of gravity and gravitational wave entanglement. The implications to optomechanics and the program of detecting the gravitational field of macroscopic quantum superpositions will be discussed.

On-chip diamagnetic levitation and cooling for gravity mediated entanglement

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Understanding the interface between quantum mechanics and general relativity is one of the key challenges of modern physics. What happens to the space-time metric when a massive particle is in a spatial superposition? A recent proposal [1] to test these questions experimentally, based on detecting gravity mediated entanglement, has gained a lot of momentum. However, the experimental requirements for such a test are very challenging. I will present our ideas and progress towards building an experimental platform based on Meisner levitated microparticles to address those challenges. I will discuss our chip-based device designs to levitate superconducting microparticles of different sizes, as well as progress towards testing superconducting microwave resonator based cooling of a magnetic microparticles attached to a mechanical cantilever resonator. Finally, I will discuss our work towards reducing vibrations at millikelvin temperatures.

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Demonstrating Optical and Magnetic Levitation in Space

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While the excellent environmental isolation provided by levitated optomechanical systems has allowed for the examination of various fundamental phenomena, almost all current experiments are Earth-bound and subject to gravitational forces. We propose the first experimental platform to conduct compact, autonomous, and low power experiments in a micro-*g* low Earth-orbit (LEO) space environment, using both optical and magnetic levitation regimes.
Working in collaboration with various start-ups and other universities, we plan to construct both optical and magnetic trapping sites in multiple miniaturized, passively pumped permanent vacuum chambers, and load nanoparticles in-flight using a piezo loading system[1].
We aim to conduct multiple experiments during the 30 minute flight, including squashing the nanoparticle's motion[2], attempting matterwave interferometry via both free waveform evolution and a Talbot-Lau interferometry setup[3], and assessing the potential of optically and magnetically[4] levitated nanoparticles as accelerometers for inertial navigation and gravimetry[5].

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Hybrid optomechanical systems consisting of optically levitated nanoparticles and silica microtoroid optical cavity

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An optically levitated dielectric nanoparticle coupled to an optical cavity has recently emerged as a promising quantum optomechanical system with various unique features. The field has shown rapid progress in the past few years. Recent breakthroughs include ground-state cooling of the particle's motion. For further advancement, it is desirable to develop a system that allows for enhanced coupling and stability.
Here we present a new cavity levitodynamics system comprising a nanoparticle in an optical tweezer coupled to monolithic optical microcavities. Specifically, we employ a silica microtoroid as an optical cavity, which exhibits an ultrahigh quality factor of up to 100 million. The system will allow us to reach the resolved sideband regime with enhanced optomechanical couplings compared to previously achieved systems based on macroscopic mirror cavities. We discuss our progress and the prospects in this research direction.

Towards absolute cooling in levitodynamics using optically active nanocrystals

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Levitated mesoscopic particles, with their intrinsic low coupling to the environment, are ideally suited as hybrid quantum platforms of mesoscopic size and mass. In vacuum, the only coupling to the environment is the levitation field itself, resulting in a mechanical oscillator with a very high-quality factor. Optically levitated systems in vacuum have recently entered the quantum realm with demonstration of cooling to the motional quantum ground state using passive and active feedback methods [1 - 3]. The levitated particles in most of these experiments are optically inert such as SiO2 nanospheres. Here we are interested in studying and developing techniques suitable for the stable levitation of optically active nanoparticles, in particular, rare-earth ion activated nanocrystals.

Rare-earth ion doped crystals are one of the few materials enabling laser refrigeration through anti-Stokes fluorescence which is particularly relevant for levitation in vacuum as it enables control over the internal temperature of the levitated nanoparticle [4]. This is particularly relevant since the internal temperature of the particle will limit the coherence of the oscillator.

We will present the absolute spectroscopy (of the oscillator and the optically active ensemble) of different nanoparticle designs. In particular we will show refrigeration down to 150k from room temperature of a levitated nanocrystal. We will also show control of the temperature of the oscillator paving the way to absolute cooling of a levitated nanoparticle. Our approach would enable access to advanced tools for the quantum manipulation of levitated mesoscopic systems, opening up new avenues for accessing fundamental physics.

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Controllability of driven quantum rotors: a graph-theoretical approach

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Controlling the dynamics of a quantum asymmetric top by external field has many applications ranging from quantum information to enantio-selective manipulation of chiral molecules. A challenge for the control of quantum rotors is their inherent degeneracy caused by the rotational symmetry of randomly oriented tops. We present a graphical method to analyze the controllability of a quantum asymmetric top and to determine the number, polarization and frequencies of the external fields which are required to fully control the rotational or ro-vibrational dynamics of randomly oriented molecules [1,2]. Moreover, we show how to apply this strategy to observe and control chiral properties in randomly oriented molecules.

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Hollow-core fiber loading of optically levitated nanoparticles into ultra-high vacuum

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As experiments involving levitated nanoparticles move towards the quantum regime, minimizing the effect of environmental decoherence on these systems becomes increasingly relevant. Lowering the pressure such experiments are conducted at and therefore decreasing the decohering effect of gas collisions is in many cases hindered by the choice of particle loading mechanism. Here we present a novel method for loading nanoparticles via hollow-core photonic crystal fibers which allows direct placement into traps at pressures in the ultra-high vacuum (UHV) regime.
An optical conveyor belt is created by guiding two counter-propagating beams of light through a hollow-core fiber. This fiber connects a main UHV vacuum chamber to an ambient or low vacuum "loading chamber". By detuning one of the two beams, nanoparticles can be transported from the loading chamber through the fiber directly into the optical trap in the main vacuum chamber. Using this method, we have successfully demonstrated transfers of particles at pressures of $7{\cdot}10^{-10}$mbar, effectively opening the door to experimental regimes where decohering gas collisions happen at a sub-kHz rate.

Cold damping of levitated optically coupled nanoparticles

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Methods for controlling the motion of single particles, optically levitated in vacuum, have developed rapidly in recent years [1-3]. The technique of cold damping makes use of feedback-controlled, electrostatic forces to increase dissipation without introducing additional thermal fluctuations. This process has been instrumental in the ground-state cooling of individual electrically charged nanoparticles [3,4]. Here we show that the same method can be applied to a pair of nanoparticles, coupled by optical binding forces. These optical binding forces are about three orders of magnitude stronger than typical Coulombic inter-particle force and result in a coupled motion of both nanoparticles characterized by a pair of normal modes. We demonstrate cold damping of these normal modes, either independently or simultaneously, to sub-Kelvin temperatures at pressures of 5×10^{-3} mbar. Experimental observations are captured by a theoretical model which we use to survey the parameter space more widely and to quantify the limits imposed by measurement noise and time delays. Our work paves the way for the study of quantum interactions between meso-scale particles and the exploration of multiparticle entanglement in levitated optomechanical systems.

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Surface-induced decoherence and heating of charged particles

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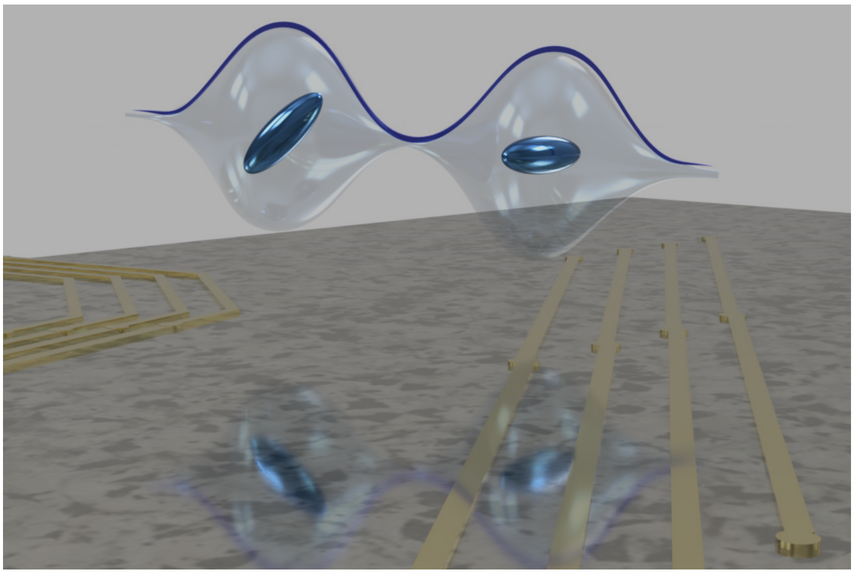
Levitating charged particles in ultrahigh vacuum provides a preeminent platform for quantum information processing, for quantum-enhanced force and torque sensing, for probing physics beyond the standard model, and for high-mass tests of the quantum superposition principle. Existing setups, ranging from single atomic ions to ion chains and crystals to charged molecules and nanoparticles, are crucially impacted by fluctuating electric fields emanating from nearby electrodes used to control the motion. We present a theoretical toolbox for describing the rotational and translational quantum dynamics of charged nano- to microscale objects near metallic and dielectric surfaces, as characterized by macroscopic dielectric response functions. The resulting quantum master equations describe the coherent surface-particle interaction due to image charges and Casimir-Polder potentials as well as surface-induced decoherence and heating with the experimentally observed frequency and distance scaling. We explicitly evaluate the master equations for relevant setups, thereby providing the framework for describing and mitigating surface-induced decoherence as required in future quantum technological applications.



Cooling of Particles with Internal Degrees of Freedom

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Levitated optomechanics involves the interaction of light and mechanical motion without physical contact with the external environment. High-quality-factor mechanical oscillators based on levitated particles have the potential to advance fundamental physics and act as sensitive detectors for weak forces [1]. However, fully exploiting the capabilities of levitated systems in vacuum requires simultaneous control over the center-of-mass motion and the internal temperature of the particles. The former is crucial for preparation of quantum states of motion [1], while the latter is linked to the decoherence of the particle's state [2].

Our research specifically focuses on achieving hybrid cooling, targeting the simultaneous damping of translational motion and reduction of the internal temperature of nanoparticles levitated in a Paul trap. As nanoparticles, we use YLF nanocrystals doped with ytterbium ions, which have two distinct electronic level manifolds separated by a significant energy difference (1.2 eV). This characteristic enables excellent optical cooling results [3, 4], making Yb^{3+} well-suited for cooling of solids. Furthermore, by comparing the fluorescence spectra in different environments, namely on a substrate and in vacuum, we aim to gain insights into the temperature dynamics of the levitated crystals.

Through our study, we anticipate achieving precise control over the cooling of internal degrees of freedom. This advancement is an essential step towards the full control of levitated particles for future quantum experiments.

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Sensing directional forces in levitated optomechanics

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Optomechanical devices are being harnessed as sensors of ultraweak forces for applications ranging from inertial sensing to the search for the elusive dark matter; For the latter, the focus is on detection of either higher energy single recoils or ultralight, narrowband sources; a directional signal is expected. However, the possibility of searching for a directional broadband signal need not be excluded; with this and other applications in mind, we investigate experimentally the effect of applying a stochastic signal with a well defined direction, Ψ to a trapped and cooled levitated nanosphere. We find that cross-correlation power spectra offer a calibration-free "smoking-gun" signature of the presence of a directional force, and its orientation quadrant, unlike normal power spectral densities (PSDs). With calibration we are able to accurately measure the angle Ψ, akin to a force compass in a plane.

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Quantum gravitational wave detector based on high overtone bulk acoustic wave resonators

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There are numerous predictions for gravitational wave sources in the GHz frequency range that come from physics beyond the standard model or early universe [1]. To investigate them, we propose a quantum (high frequency) gravitational wave detector based on the high overtone bulk acoustic wave resonator (HBAR). The device would consist of an HBAR, piezoelectrically coupled to a transmon qubit, which is then read out using a microwave cavity [2].

This would allow for quantum non-demolition measurements that can surpass the standard quantum limit. Unlike previous resonant mass detectors, it would operate in the quantum ground state and not be limited by thermal noise. Furthermore, HBARs have an (effective) mass in the microgram range, which puts them among the heaviest quantum objects. High mass means that the detector would also have a large absorption cross-section for gravitational waves.

In addition to using the HBARs as a telescope for observing the universe, the quantum nature of the device could also open the possibility of detecting quantum effects of gravity and probing the phonon-graviton interaction [3, 4].

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Searching for sterile neutrinos using radioactive levitated nanoparticles

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The repeated measurements of neutrino oscillations over the last few decades confirm that neutrinos have non-zero masses which are not accounted for in the Standard Model. The observed small neturino masses can be explained by introducing a massive right-handed "sterile neutrino" that does not interact through the weak force. One class of experiments searching for sterile neutrinos utilise radioactive decays to generate neutrinos and search for deviations in the recoil energy spectra of the daughter nucleus that would suggest mixing between Standard Model neutrinos and a sterile neutrino. We present a new experiment that is currently being realised that utilises levitated nanoparticles doped with a radioactive isotope to measure the momentum of the recoiling daughter nucleus and reconstruct the momentum of the emitted neutrino. Measuring momentum rather than energy significantly reduces the impact of low or zero mass backgrounds and secondary emissions. This search will improve sensitivity to sterile neutrinos in the mass range 100 keV - 2 MeV compared to previous experiments. Interestingly, a sterile neutrino within this mass range could explain almost all observed dark matter. We also show initial results from a proof-of-principle experiment attempting to measure the momentum recoil of an optically levitated silica microsphere due to an alpha decay.

Characterising Nanoparticle Anisotropy through Angularly Resolved Rayleigh Scattering in Optically Levitated Particles

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Significant progress has been made in the cooling and control of optically levitated nanoparticles.[1–3]. Levitated nanoparticles showed significant promise for quantum-limited sensing [4] and the creation of non-classical states of motion[5]. However, a detailed knowledge of the structural and geometric properties of these particles is required to understand the detailed dynamics of these systems for comparison of experiments with theoretical predictions[6, 7].
This poster introduces a method for characterising nanoparticles by analysing their inherent light scattering patterns. This technique aligns and orients single optically levitated nanoparticles in a vacuum using trapping light and then examines the ensuing angularly resolved Rayleigh scattering patterns. Our approach accommodates a broad range of particle geometries, from spherical nanodroplets to octahedral nanocrystals, enabling the detection of shape differences down to a few nanometers.
Our technique utilises laser Rayleigh scattering theory, and our experimental results are validated through a comparison with finite-difference time-domain simulations of the scattered field. Notably, our approach addresses the yet unexplored challenge of leveraging the scattering behaviour of optically trapped nanoparticles to study the shape and geometry of individual particles in-situ [8, 9].
Although our method is utilised in low-damping environments, it can also be used in traditional overdamped fluids commonly used in optical tweezers. This novel approach opens up a new path for determining nanocrystal geometries and for precision measurements in levitated optomechanics.

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Broadcasting quantum nonlinearity to a linear system

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There is active research aimed at exploring the nonlinear dynamics of levitated nanoparticles in the quantum regime. Harnessing nonlinearities can be fruitful for fundamental studies and quantum sensing, thermodynamics, and information processing. Recently we showed that it is possible to implement an approximate nonlinear phase gate on a motional quantum state of a levitated nanoparticle given a nonlinear trapping potential.

Here, we argue that such a nonlinear phase gate can be broadcast to an otherwise fully linear harmonic oscillator using only linear Gaussian operations. That is, using a sequence of linear quantum non-demolition (QND) coupling between the linear oscillator and the nanoparticle, and an approximate phase gate on the latter, it is possible to implement an approximate nonlinear phase gate on the linear oscillator. Importantly, this broadcasting does not require a quantum state swap (which would be a suboptimal strategy of broadcasting). QND-based nonlinearity broadcasting, by carefully optimized individual quadrature processing, allows overcoming limitations of the state swap. Furthermore, it is possible to enhance the effective strength of the phase gate using the Gaussian coupling strength as a resource. Finally, given stringent requirements on the loss and noise associated with Gaussian operations, the overall broadcasting operation can be made insensitive to the initial quantum state of the nanoparticle.

Using (levitated) optomechanical systems to test gravitational theory - possibilities and limitations

Dennis Rätzel

ZARM - University of Bremen
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More than 100 years after the first development of a relativistic theory of gravity, there is an ever-increasing amount of predicted, yet untested, phenomena and unsolved scientific puzzles revolving around gravity. There are many proposals to apply quantum sensors to test for such phenomena or experimentally resolve some of the puzzles. I will present my perspective on three proposals based on (levitated) optomechanical systems: measurement of the gravitational field of light and relativistic particle beams, obtaining bounds on Chameleon-field dark energy models, and testing for quantum properties of the gravitational field. I will give a short introduction to the models involved and discuss fundamental constraints.

Bimodal thermal states of levitated nanoparticles

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Classical bimodal states of the mechanical oscillator can be generated with a protocol combining two elements: laser power modulation and optical potential nonlinearity. The thermal squashing technique[1], created by non adiabatic changes in the laser power, makes the thermal state to elongates, transforming the usual circular Gaussian state into a thinner and longer ellipsoidal figure. As the vertex of the ellipse becomes sufficiently elongated the particle starts to sample nonlinear sites of the optical potential. With extended amplitude the particle's effective period of oscillation is slower, and it falls behind compared to harmonic behavior near the centre. Consecutive squashing pulses changes the ellipsoid into a spiral shape and as the protocol goes on the figure aggregates into two distinct clusters rotating in phase space.

The experimental platform involves an amplitude modulation element of the trapping laser and a FPGA to create custom signals. Computer simulations were used to find a set of parameters to guide the experiment in progress. With extraneous nonlinearities added, this protocol could prepare non-Gaussian states with low occupation number for interference experiments in the future[2].

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Levitated superconductive particles on-chip for testing foundations of quantum mechanics and sensing

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In it's original form, unitary quantum mechanics contain no reference to the scale of the systems it describes. The objective of our experiment is to test macroscopicity limits of quantum mechanics, pushing from nano- to microparticles while also developing a device for quantum force/acceleration sensing. In 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 quantum circuits for readout and control. A chip-based approach has the advantage of ensuring accuracy across multiple devices and readily allows for coupling the motion of multiple levitated particles together. In our devices, we have demonstrated quality factors of 10^5 and fast tunability by supply current of trapping frequencies between 90-160 Hz for levitated particles of 48 µm diameter . We readout the motion of the particle using a DC SQUID, using integrated gradiometric pickup coils. We show that the potential landscape explored by the particle is consistent with what we obtain from FEM simulations of the trap. The particle is able to levitate for several days in the trap. We have identified cryostat vibrations as a source of noise driving the particle and designed a vibration isolation system to counteract this. To be able to cool to the particle to its motional ground state, we highlight the need for additional vibration isolation and improvements in readout efficiency.

Tunable light-induced dipole-dipole interaction between optically levitated nanoparticles

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By coupling mechanical systems one can observe collective effects, such as topological phonon transport or, when operating in the quantum regime, the possibility of entanglement. Current optomechanical experiments utilize an optical cavity mode to mediate interactions [1-2], which limits the tunability of the system. Here we are interested in directly coupling parties using scattered light in a finely controlled manner.

It has been known that optically levitated microparticles can interact through light -- optically bind -- and form self-organized patterns that resemble crystals [3-5]. In my contribution, I will present coherent, direct interaction between two dielectric nanoparticles levitated in a trap array. In contrast to previous optical binding studies, the interparticle coupling is inherently non-reciprocal. I will show how tuning the relative optical phase, laser powers, and the particle distance gives us full control of the optical interactions. Finally, we will demonstrate how we can suppress the optical coupling using the light polarization, in which case we can observe electrostatic interactions. Together these capabilities will be instrumental when exploring entanglement and topological effects in arrays of levitated nanoparticles.

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Macroscopic Quantum Superpositions in a Wide Double-Well Potential

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We present an experimental proposal for the rapid preparation of the center of mass of a levitated particle in a macroscopic quantum state, that is a state delocalized over a length scale much larger than its zero-point motion and that has no classical analog. This state is prepared by letting the particle evolve in a static double-well potential after a sudden switchoff of the harmonic trap, following initial center-of-mass cooling to a sufficiently pure quantum state. We provide a thorough analysis of the noise and decoherence that is relevant to current experiments with levitated nano- and microparticles. In this context, we highlight the possibility of using two particles, one evolving in each potential well, to mitigate the impact of collective sources of noise and decoherence. The generality and scalability of our proposal make it suitable for implementation with a wide range of systems, including single atoms, ions, and Bose-Einstein condensates. Our results have the potential to enable the generation of macroscopic quantum states at unprecedented scales of length and mass, thereby paving the way for experimental exploration of the gravitational field generated by a source mass in a delocalized quantum state.

Shortcuts to equilibrium with a levitated particle in the underdamped regime

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We report on speeding up equilibrium recovery in the previously unexplored general case of the underdamped regime using an optically levitated particle. We accelerate the convergence towards equilibrium by an order of magnitude compared to the natural relaxation time. We then discuss the efficiency of the studied protocols, especially for a multidimensional system. These results pave the way for optimizing realistic nanomachines with application to sensing and developing efficient nano-heat engines.

Optical metasurfaces for levitodynamics experiments

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Optical metasurfaces have been a hot topic of current research due to their ability to manipulate light at sub-wavelength scale [1]. By assembling a periodic or quasi-periodic array of carefully chosen light scatterers [2], one can engineer phase, amplitude, and polarization of incoming light, thus creating arbitrary complex phase profiles [3]. Furthermore, it offers the possibility to control the near-, intermediate, and far-field [4].

These metasurfaces can be used to redesign classical optical components. For example, high NA lenses with negligible aberration can further improve the focusing of optical tweezers and the detection of levitated nanoparticles [5]; polarization-sensitive metasurfaces can be used to create different intensity profiles based on the incoming light polarization, particularly suitable for classical nonlinear dynamics [4]; achromatic and dispersion engineered metasurfaces pave the way for polychromatic laser driving in which only one beam is focused [6].

Integrated photonic components promise multifunctional optics at smaller volumes for more intricate experiments. In addition, the miniaturized setup offers enhanced interaction of the particles with the much stronger electromagnetic fields, which could be used to reach higher coupling regimes for mode hybridization and nonlinear effects. Here we present a silicon-on-insulator metalens design to optically trap a nanoparticle.

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Decoherence of Rigid Rotors due to Emission of Thermal Radiation

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Recent advances in the control of levitated nanoparticles open the door for fundamental tests and sensing applications exploiting their rotational degrees of freedom [1]. This poster presents the quantum master equation of rotational and translational decoherence of internally hot dielectric particles of arbitrary size and shape emitting thermal radiation. We find that even highly symmetric objects, such as spheres, exhibit orientational decoherence since the internal excitations sourcing the emitted fields break the symmetry of the particle. We quantify the resulting decoherence rates for upcoming experiments with nanoscale to microscale objects.

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Josephson Optomechanics

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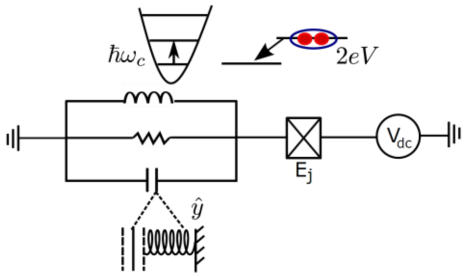

Optomechanical phenomena can be investigated in the microwave regime using a circuit-QED setup combining superconducting microwave cavities and a mechanical degree of freedom. A Josephson junction biased by a DC source, in series with an LC oscillator can be used as a bright source of quantum microwave light. The inherent nonlinearity of the Josephson junction can, at special parameter points, restrict the cavity dynamics to the N lowest states, with the transition to the (N+1) level blockaded [1]. In the most extreme case, N=2, the strongly driven two-level cavity shows a Mollow triplet [2] in the spectrum. For N>2 the system shows similar nonlinear behaviour, with sidebands appearing in the spectrum.

The mechanics, in turn, is driven by the nonlinear radiation and can be cooled or heated at these sidebands in novel ways. We find that, in the nonlinear regime, the unusual nonlinear sideband cooling is much more efficient than the usual cooling mechanism using a red-detuned drive. The behaviour of this unusual cooling rate is a non-monotonic function of detuning and can change sign, when the mechanical mode is heated, even when the drive is red-detuned.

In the Poster, I will theoretically describe the quantum dynamics of the super-conducting microwave circuit and show the heating or cooling rates obtained for an engineered N-level cavity (N∈ [2,6]).

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Testing Spontaneous Collapse Models with Levitated Particles Under Free Evolution

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We propose an experimental protocol to test the linearity of quantum mechanics at macroscopic scales using levitated nanoparticles. Our design leverages the dynamical control of the trapping fields offered by many levitated optomechanical setups, and works by combining only two types of dynamics: free evolution and harmonic trapping. In this manner we are able to exploit the dispersion of the wave packet under free evolution to reach a large spatial delocalization, and then revert its evolution by the application of suitably timed trapping fields. The recovery of the initial state at the end of the protocol flags the coherence of the system over the spatial extent reached by the free-evolution part of the protocol. This would allow us to set bounds on the free parameters of theories that postulate forms of fundamental decoherence for largely delocalized massive particles, like, for example, spontaneous collapse models. We perform an analysis of the potential sources of environmental decoherence and control errors, and estimate the required degree of experimental precision and isolation to set bounds that are more stringent than existing ones.

Perturbative nonlinear levitodynamics

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Using electric feedback, we artificially create nonlinear potentials for an optically trapped nanoparticle. Tuning the strength of the artificial potential, we study the effects of nonlinear forces upon an underdamped Brownian particle across different regimes. Notably, we measure the effects of the nonlinear force on the particle's power spectrum and two-point position correlations manifest in the perturbative regime as a shift in the resonance frequency. Our results agree with path integral calculations [1], opening the way to precision measurements of stochastic thermodynamics of levitated particles.

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Engineering Q factor of diamagnetically levitated graphite resonator

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Levitation can isolate objects from the environment to suppress mechanical dissipation, which shows promise for applications such as ultra-precise sensors, levitated positioners and actuators and the exploration of fundamental aspects in quantum mechanics including the superpositions of massive objects and theories of quantum gravity. Many levitation techniques require active driving which may introduce extra noise or heating, while diamagnetic levitation is attracting more attention which requires no energy input and also has the capacity to trap massive objects.

Highly oriented pyrolytic graphite (HOPG) is one of the strongest diamagnetic materials and centimeter-sized slabs can easily be levitated over a checkerboard array of permanent magnets. However, since graphite is a good electrical conductor, eddy currents are induced as it moves through the magnetic field. These eddy currents dampen the plate's motion and heat the graphite, leading to very low motional Q factors even in high vacuum conditions. We describe a method to engineer the Q factor of a diamagnetically levitated/trapped graphite resonator over a wide range by carving narrow through-cut slots into the resonator to interrupt the eddy current flow. The through-cut slots allow us to systematically control the motional quality factor in a highly predictable manner, with excellent agreement between theory and experiment [1].

We designed circular slot patterns with 80 μm-width slots which can cut off the main current path. Different densities of slots were cut into the graphite slabs by femtosecond laser machining. In the sample with the highest density of slots, the eddy damping is reduced by a factor of 40, leading to an increase in the resonator Q factor from around 65 to 2500. Our experimental results matched very closely with our FEM/Mathematica simulations. The ability to engineer the eddy damping while retaining its structural integrity and strong diamagnetic susceptibility will permit researchers in a wide range of disciplines to apply such conducting diamagnetic materials to situations where fast motional control is required. We will also discuss recent results where by using material processing techniques we experimentally demonstrate motional Q factors above 10^5 in high vacuum and at room temperature for cm-sized resonators.

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Testing spontaneous wavefunction collapse with quantum electromechanics

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Theories of spontaneous wavefunction collapse offer an explanation of the possible breakdown of quantum mechanics for macroscopic systems. However, resolving collapse-induced anomalous heating above background noise has limited previous tests of collapse models. Here, we propose to overcome this challenge using quantum control and measurement of a superconducting qubit coupled to a macroscopic mechanical resonator. Specifically, our proposal outlined in Ref. [1] adapts a previously developed electromechanical quantum system [2] to the challenge of measuring signatures of collapse-induced spontaneous heating [3]. We show that the electromechanical system can amplify the weak signals from collapse-induced heating and simultaneously suppress qubit noise, initializing the qubit close to its ground state. Combined, this could provide a stringent test of collapse models.

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I will also briefly present some of my more recent work, which examines how single graviton signatures can be observed in laboratory experiments [4]. We propose an experiment that uses quantum sensing techniques to witness the exchange of a single graviton between matter and gravitational waves. Under the assumption of energy conservation at the level of individual discrete transitions between energy eigenstates, the proposed experiment could provide the first evidence of quantum features of the gravitational field.

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Towards an Experimental Platform for the Control of Biological Nanoobjects

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In the last few years, significant advances have been made in the control of levitated dielectric nanoparticles [1]. However, the application of these methods to biological objects, which represent an unexplored material class, remains a challenge.

Recent experiments have demonstrated matter-wave interference with polypeptides [2]. Future experiments with massive biological nanoobjects will require novel techniques [3] to prepare their center of mass motion sufficiently well localized.

We discuss progress towards an experimental platform for optical trapping and cooling of dielectric nanoparticles. This platform allows the combination of feedback cooling [4] and cavity cooling [5] and will also enable sympathetic cooling [6] on optically or electrodynamically trapped particles.

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Levitated Optomechanics with Reduced Gravity

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Levitated optomechanics is a promising platform to investigate quantum mechanical behaviour with 'large' masses or measure tiny forces [1,2].
To observe quantum phenomena, particles must be largely isolated from their environment. Collisions with gas atoms and interaction with thermal photons can be minimized by high vacuum and cryogenic environments respectively. Nevertheless, optically trapped particles will always absorb a small fraction of the trapping beam, but untrapped particles will fall under gravity.
One approach is to minimize the necessary free evolution time by inflating the wave packet [3], the other is to cancel gravity and move to a weightlessness environment like drop towers or space. We are following the latter approach.

We will present a fully autonomous experimental setup for the operation in the Bremen Drop Tower, which allows for up to 9.3 s of microgravity time at a low repetition rate, or 2.5 s for almost 1000 times per day [4]. The system is capable of parametric cooling of Silica particles to the milli Kelvin regime and will start with first release and recapture experiments in weightlessness, by the end of the year.

We will present the advantages of anharmonic potentials to measure static forces and how they can benefit from weightlessness conditions.

Last but not least, there will be a short outlook towards the CubeSat mission we are preparing with teams from Southampton and Surrey and Twin Paradox Labs.

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Detecting high frequency gravitational waves with optically levitated micro disks

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We will present an update on the Levitated Sensor Detector (LSD) project for detection of high frequency (10-100kHz) gravitational waves above the region previously probed by LIGO. Well motivated sources of gravitational waves in this frequency band include superradiance from QCD axion clouds around black holes and PBH mergers. The experiment makes use of optically-levitated micron-scale flat disk-likes with the advantage of reduced photon recoil heating; these are highly novel objects in the levitated optomechanical parameter space. We discuss experimental trapping results of high aspect ratio NaYF4 hexagonal plates and our recent milestone of increasing the test mass by an order of magnitude. Finally, we examine the progress of the 1-meter prototype that is in construction at Northwestern University.

Electrical levitation of micromagnetic particle coupled to superconducting quantum circuit

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Cavity optomechanics, where photons are coupled to mechanical motion, provides the tools to control mechanical motion near the fundamental quantum limits. Reaching single-photon strong coupling would allow to prepare the mechanical resonator in non-Gaussian quantum states. Preparing massive mechanical resonators in such states is of particular interest for testing the boundaries of quantum mechanics. This goal remains however challenging due to the small optomechanical couplings usually achieved with massive devices.
Here, we use levitated micro-magnetic particles with a **Paul trap** as mechanical resonators. In this case, we are **coupling** the mechanical motion **magnetically** to the microwave cavity via a **SQUID** (Superconducting QUantum Interference Device). The levitated particle provides high factors quality that increase the coherence of the resonator once in the quantum regime. Moreover, this approach offers the advantage of decoupling the manipulation of the particle which is done electrically with the Paul trap and the coupling mechanism which is done magnetically via the quantum interference device. Our experiment is mounted on the base plate of a dilution refrigerator to provide the environment needed to perform quantum experiments. Our main goal is to achieve the **single-photon strong coupling regime** where a complete exchange between the electromagnetic radiation and the oscillator occurs within the lifetimes of the mechanical and microwave cavity, allowing the generation of states of macroscopic quantum superposition of the mechanical oscillator. This experimental platform will be used both for fundamental studies (preparation of **macroscopic quantum states**) as well as for technological applications such as **quantum memory** where information is encoded in mechanical resonators.

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