Spin-mechanics with trapped diamonds

Gabriel Hetet

Invited Talk

Spin-controlled quantum interference of levitated nanorotors

Cosimo Rusconi

In this presentation, I will describe how to prepare an electrically levitated nanodiamond in a superposition of orientations via microwave driving of a single embedded nitrogen-vacancy (NV) centre, (Fig. 1). The spin of the NV centre couples to the spatial orientation of the nanodiamond via an external applied magnetic field. I will show that for a suitable orientation of the NV centre and of the applied field, the spin-orientation coupling reaches the regime of ultrastrong coupling, thus enabling single spin control of the particle's orientation. In the libration regime - when the diamond's orientation oscillates about an equilibrium direction - the dynamics of the system can be described by a spin-oscillators Hamiltonian. I will present a protocol to create and observe quantum interference in the particle's libration by monitoring the spin population, and I will show that such protocol is robust against the initial temperature of the libration dynamics. I will discuss the impact of decoherence and argue that this proposal can be realistically implemented with near- future technology. More information on these results can be found in the following pre-print arXiv:2203.11717.

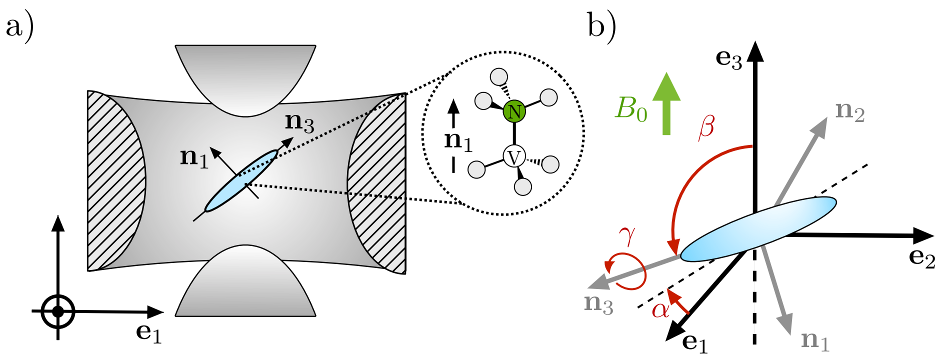


FIG. 1. a) Illustration of an electrically levitated nanomagnet in a ring Paul trap with an embedded NV centre: the axis of the NV centre is orthogonal to the symmetry axis of the particle. b) Degrees of freedom of the nanodiamond: the orientation of the particle is described by the three Euler angles α, β, and γ which relate the position of the body-fixed frame $O\mathbf{n}_1\mathbf{n}_2\mathbf{n}_3$ to the laboratory fixed frame $O\mathbf{e}_1\mathbf{e}_2\mathbf{e}_3$.

New technologies and techniques for levitating particles and sharing ideas

James Millen

Invited Talk

Testing fundamental physics with charged nanoparticle oscillators

Peter Barker

Invited Talk

Testing quantum mechanics and gravity with levitated systems

Hendrik Ulbricht

Invited Talk

Ferromagnetic Gyroscopes for Tests of Fundamental Physics

Pavel Fadeev

The coupling between the magnetization and the lattice of a ferromagnet gives rise to interesting dynamics. Specifically, in low magnetic fields a levitated magnet should precess. Such behaviour will enable the use of a ferromagnet as a gyroscope, as a system to test for exotic bosons, and, in the future, to test experimentally the gyrogravitational ratio. Recently, a collaboration arose to build a proof of principle prototype: LEMAQUME is a European Union’s QuantERA project. In my talk, I will present the motivation to explore such magnet's dynamics and the ongoing experimental efforts and plans of the collaboration. https://www.lemaqume.org/

Searches for dark matter with levitated optomechanical sensors

David Moore

Invited Talk

Stabilizing a coherent optical levitation system with photothermal cancellation

Giovanni Guccione

In optomechanical systems, the "optical spring effect" is a notable form of control. It can be used to optically trap a small mirror [1], or even levitate it to fully isolate it from an external thermal environment [2]. This same phenomenon, however, may become a double-edged sword by introducing parametric gain together with its restoring force [3]. Parametric instability may ensue within the optomechanical system as a consequence. Light will interact with the mechanical dynamics in a dramatic way that destabilises the system or drags the system away from the desired operation point. An additional complication in high-power optomechanical systems is given by photothermal effects. These result from the absorption of light by the object and the ensuing thermal expansion or thermo-optic refractive index change, which alters the phase response of the system. Left unchecked, parasitic photothermal effects will introduce unwanted feedback dynamics that may drive the system into strongly nonlinear regimes and even further deteriorate the stability of the optomechanical system [4, 5].

In this work, we investigate how photothermal effects influence an optomechanical levitation cavity and how they affect its stability. The cavity, designed for coherent levitation of a macroscopic milligram-scale mirror, was previously shown to be highly unstable and susceptible to nonlinear dynamics [6]. By modifying the photothermal properties to have photothermal interaction cooperate with radiation pressure, we achieve stabilisation and robust control of this system. This technique of "photothermal cancellation", named after the neutralization of the photothermal coefficient at the heart of system's dynamics, proved successful where other established forms of active control failed before. This new approach provides a compelling pathway for optical control and precision metrological applications, specifically in macroscopic and high-power optomechanical system that are particularly susceptible to parasitic photothermal effects.

[1] T. Corbitt et al., Phys. Rev. Lett. 98: 150802 (2007).
[2] G. Guccione et al., Phys. Rev. Lett. 111: 183001 (2013).
[3] P. A. Altin et al., Sci. Rep. 7: 1, 1–8 (2017).
[4] R. Lecamwasam et al., Phys. Rev. A 101: 053857 (2020).
[5] Ma, J. et al., Optica 8: 2, 177–183 (2021).
[6] Ma, J. et al., Commun. Phys. 3: 197 (2020).

High frequency gravitational wave detection with optically levitated nano objects

George Winstone

Invited Talk

Levitodynamics in a drop tower

Christian Vogt

Levitated optomechanics are a promising candidate to study the interface between the theory of general relativity and quantum mechanics. Both are very successful in their respective fields, but cannot be unified because of their different foundations. One way to approach a regime in which both are required is to observe a coherent superposition for increasingly heavy masses. While this has been successfully demonstrated for complex molecules up to 2.5·104 amu using near-field interferometry, nanoparticles could access the parameter space of 106-1010 amu. This technique is based on the Talbot effect, in which interference leads to a self-image of a coherently illuminated grating. The distance between this image and the grating depends on the wavelength of the incident wave and therefore increases with mass. This Talbot distance can be easily converted into a Talbot time after which the interference pattern appears. During this time, the particle must not be optically levitated, since absorption of photons from the trapping field would lead to decoherence. The targeted regime requires several seconds of free fall, which is not possible in a laboratory setup.

The NaiS- project will bring the technique of levitated optomechanics into the microgravity environment of the drop tower Bremen. This 146-meter-tall facility allows for up to 9.3 s of free fall, with very low residual vibrations. I will show that the size, weight, and power consumption requirements can be easily met with the designed experimental setup. The transfer from a ground-based laboratory to a microgravity environment also supports efforts to put such systems into space, as proposed in the Maqro mission. The feasibility of levitated optomechanics in microgravity will first be demonstrated by simple force measurements. Therefore, the particle will be motionally cooled by parametric or linear feedback cooling and afterwards released into free fall. The sensitivity of this measurement is dominated by the interrogation time of the testparticle with the force field, and strongly benefits from long free-fall times.

In this talk I will present the experimental design of our setup, explain the different available microgravity platforms, compare levitodynamics with other spaceborne quantum mechanical experiments, talk about the challenges for precise force measurements in free fall and introduce a simplified version for observing coherence from single measurements.

The 2022 proposal of the MAQRO space mission

Rainer Kaltenbaek

Invited Talk

Stroboscopic High-Order Nonlinearity for Levitated Optomechanics

Andrey Rakhubovsky

High-order quantum nonlinearity is an important prerequisite for advanced quantum technology leading to universal quantum processing with large information capacity of continuous variables. Levitated optomechanics, a field where the motion of dielectric particles is driven by precisely controlled tweezer beams, can attain the required nonlinearity via engineered potential landscapes of mechanical motion. Importantly, to achieve nonlinear quantum effects, the evolution caused by the free motion of mechanics and thermal decoherence has to be suppressed. For this purpose, we devise a stroboscopic application of a highly nonlinear potential to a mechanical oscillator that leads to the motional quantum non-Gaussian states exhibiting nonclassical negative Wigner function and squeezing of a nonlinear combination of mechanical quadrature [1]. We test the method numerically by analysing highly unstable cubic potential with relevant experimental parameters of the levitated optomechanics, prove its feasibility within reach, and propose an experimental test. The method paves a road for experiments instantaneously transforming a ground state of mechanical oscillators to applicable nonclassical states by nonlinear optical force.

[1] A.A. Rakhubovsky and R. Filip, Stroboscopic high-order nonlinearity for quantum optomechanics, npj Quantum Information 7, 120 (2021).

Spatiotemporal control of levitated nanoparticles

Nikolai Kiesel

Invited Talk

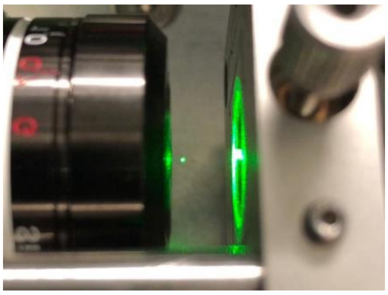
Shortcuts to equilibrium with a levitated particle

Damien Raynal

During any transformation between equilibrium states, a system remains out of equilibrium for a characteristic relaxation time τr. Mastering this transient regime is of prime importance for optimizing power in nano-physical and biological systems. Recently, state-to-state transformations faster than the system's natural relaxation time τr have been demonstrated for an overdamped Brownian particle [1]. The experimental extension of such shortcut to equilibrium protocols to more generic cases is thus of importance both fundamentally and applications- wise [2].

Using an optically levitated particle in moderate vacuum, we demonstrate the first shortcuts to equilibrium in the general case of the underdamped regime (see Figure). Besides taking advantage of the three-dimensional nature of the system, we address the robustness of the studied protocols over the different trap axes. These results are crucial for developing state-to- state transformations protocols in multimode systems.

Our work paves the way for developing general optimal protocols for state-to-state transformations, with a natural application to the study of nano-heat engines efficiency, in the classical or quantum regime [3].



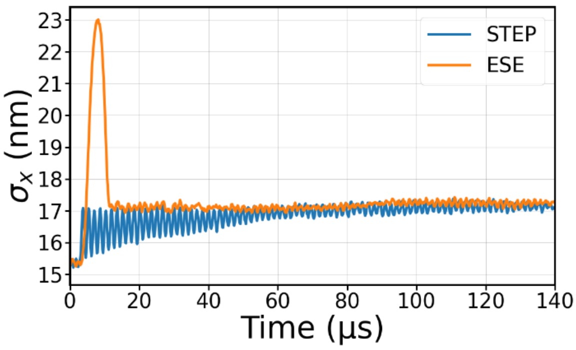


Figure : (Left) Picture of the setup with a levitated particle (bright green spot) in front of the trapping objective (black). (Right) Mean squared displacement σ_x for the levitated particle after a sudden decompression (blue line, STEP) and under a shortcut protocol for the same decompression (orange line, ESE). The shortcut protocol reached the equilibrium (*i.e.* steady σ_x) 15 times faster than natural relaxation time.

[1] I.A. Martinez et al., Engineered swift equilibration of a Brownian particle, Nat. Phys. 12 843–6 (2016)
[2] M. Chupeau et al., Engineered swift equilibration for Brownian objects: from underdamped to overdamped dynamics, New J. Phys. 20 075003 (2018)
[3] A. Dechant, N. Kiesel, E. Lutz, All-optical nanomechanical heat engine. Phys. Rev. Lett. 114, 183602 (2015)

Ultra-coherent levitodynamics with squeezed light

Carlos Gonzalez-Ballestero

Recent experiments have achieved active feedback ground-state cooling of a center-of-mass degree of freedom of an optically levitated dielectric nanosphere in free space. This achievement requires (i) to efficiently measure the light scattered by the nanoparticle in order to extract all the information it carries about the center-of-mass position, and (ii) that the motional noise is dominated by the measurement back-action, that is, laser recoil heating. After ground-state cooling, the coherence time of the quantum mechanical degree of freedom of an optically levitated nanoparticle is still limited by measurement back-action despite the fact that efficient position measurement is not needed anymore. To achieve coherence times beyond what laser recoil heating allows, one needs to either (a) switch off the laser light or (b) suppress the amount of information about the nanoparticle position that is carried by the scattered light.

In this work, we propose a method to achieve (b) using vacuum-squeezed light. We theoretically show that by squeezing a particularly chosen collective electromagnetic field mode, the quantum electrodynamical light-matter interaction can be optimally modified to reduce or enhance the information carried by the scattered light about a given mechanical degree of freedom. Consequently, laser recoil heating can be reduced by an amount proportional to the overlap between the squeezed mode and the angular distribution of the inelastically scattered photons. We argue that our results can be tested by current experiments and show how they apply to both center-of-mass and librational degrees of freedom in optically trapped nanospheres and nanorotors, respectively. Our work promotes squeezed light as a novel tool to explore the quantum regime of levitodynamics.

TBA

Oriol Romero-Isart

Invited Talk

Towards deep laser cooling of the internal an external motion of trapped nanoparticles

Christian Tomás Schmiegelow

We present our road-map and advances towards cooling the internal and external degrees of freedom of a levitated nano-particle via laser methods. We study cooling of rare-earth doped nano-crystals trapped in quadrupole Paul trap and discuss the benefits, challenges and progress in this field and in our lab. Cooling the bulk of crystals dopped with Ytterbium has been achieved for centimeter-sized as well as for nano-sized objects to temperatures in the range of 100 K. This minimum temperature is the result of competing heating and cooling mechanisms. Heating processes are mainly determined by the presence of impurities in the crystals in ppm concentrations as well and by inhomogeneous broadening of the dopants in the crystal. This spurious heating could be limited in small nano-particles if both the dopants and the impurities could be spectrally addressed individually to enhance cooling and avoid heating. On the other hand, cooling power is limited by the fine linewidth of the dopant transition, which could be broadened by co-doping with atoms with resonant levels and faster transitions, such as in the Er-Yb up-conversion pair.

We also study laser cooling of the center of mass of a rare-earth doped nano-crystal, via the Doppler mechanism. We conclude that unless an efficient mechanism is found to increase the coupling of the dopant to the driving field, cooling rates are too low to compete even with electrical noise or black body radiation heating rates.

Finally we will share our advance in building an ultra high-vacuum compatible system to trap and cool nano-particles in a linear Paul trap with a blade design. We have tested a laser induced acoustic desorption loading mechanism and are setting up an electrical center-of-mass feedback cooling system as a first stage before laser cooling.

Environmental Decoupling and Enhanced Force Sensitivity in Levitated Optomechanical Systems

Julen Pedernales

One of the most fascinating prospects offered by levitated optomechanical systems is the possibility of gaining experimental access to the high-mass regime of quantum mechanics. In the most-advanced envisioned experiments, this would allow, for example, testing collapse models or exploring quantum aspects of gravity with tabletop setups. However, like for any other quantum platform, the feasibility of such ambitious experiments relies on whether the running times of the designed protocols can be made shorter than the coherence times attainable in practice. While levitated setups lack some of the dissipation mechanisms that affect their tethered counterparts, they are still sensitive to a plethora of uncontrolled environments that limit their coherence times. This together with the long times typically required to operate objects of such sizes, calls for the development of innovative experimental protocols that can both extend the coherence times and shorten the duration of the experiments.

In my presentation, I want to introduce a collection of proposed experimental techniques to achieve both of these goals. First, I will focus on decoupling the levitated nanoparticle from its environment while retaining sensitivity to a signal of interest. Here, I will discuss both active decoupling techniques, where the dynamics of the system is modulated to average out slowly fluctuating noise, as well as passive experimental arrangements that are inherently less sensitive to their environments. Second, I will present techniques to enhance the interaction of a levitated oscillator with either a signal of interest or a second oscillator. This reduces the required experimental times in experiments aiming at detecting a weak force, or at generating entanglement between two levitated nanoparticles. Interestingly, the latter can be used to gain insight into the nature of the force mediating the interaction.

[1] J. S. Pedernales, G. W. Morley, and M. B. Plenio, Motional dynamical decoupling for interferometry with macroscopic particles, Physical Review Letters 125 (2), 023602 (2020).
[2] F. Cosco, J. S. Pedernales, and M. B. Plenio, Enhanced force sensitivity and entanglement in periodically driven optomechanics, Phys. Rev. A 103, 061501 (2021).
[3] J. S. Pedernales, K. Streltsov, and M. B. Plenio, Enhancing Gravitational Interaction between Quantum Systems by a Massive Mediator, Phys. Rev. Lett. 128 (11), 110401 (2022).
[4] J. S. Pedernales and M. B. Plenio, Robust Macroscopic Matter-Wave Interferometry with Solids, arXiv:2107.14794 (2021).

Ground-State Cooling of Levitated Magnets in Low-Frequency Traps

Kirill Streltsov

We present a ground-state cooling scheme for the mechanical degrees of freedom of mesoscopic magnetic particles levitated in low-frequency traps. Our method makes use of a binary sensor and suitably shaped pulses to perform weak, adaptive measurements on the position of the magnet. This allows us to precisely determine the position and momentum of the particle, transforming the initial high-entropy thermal state into a pure coherent state. The energy is then extracted by shifting the trap center. By delegating the task of energy extraction to a coherent displacement operation we overcome the limitations associated with cooling schemes that rely on the dissipation of a two-level system coupled to the oscillator. We numerically benchmark our protocol in realistic experimental conditions, including heating rates and imperfect readout fidelities, showing that it is well suited for magnetogravitational traps operating at cryogenic temperatures. Our results pave the way for ground-state cooling of micron-scale particles.

Chip-based magnetic levitation of superconducting microparticles

Witlef Wieczorek

Invited Talk

Integrated single-spin magnetomechanics with levitated micromagnets via in-situ micromanipulation

J DaLi Schaefer

Coupling quantum nonlinearities to mechanics is an outstanding challenge in the field of quantum science. Realizing such a system would prove useful for applications in quantum metrology and quantum information. We demonstrate a levitated system consisting of micromagnets over a type-II superconductor. The magnet's center of mass is shown to be trapped in three dimensions, resulting in modes at more than 10 kHz and quality factors of ~10^6. Additionally, the modes can be adjusted by changing the conditions of the system before cooldown. We also demonstrate the coupling of the levitated magnet to the spin of a single nitrogen-vacancy center in diamond, ~0.048(2) Hz. This proof-of-principle is the first step towards a spin-mechanics system in coupling regimes relevant for quantum applications. In addition, we will also discuss our roadmap towards this goal via in-situ micromanipulated magnet loading and superconductor traps integrated with diamond.

Quantum optomechanics with a levitated nanoparticle in free space

Massimiliano Rossi

Invited Talk

A levitated nanosphere in the strong optomechanical coupling regime

Francesco Marin

Invited Talk

Cooling through parametric modulations and phase-preserving quantum measurements

Sofia Qvarfort

In this talk, I will outline a proposal for a cooling protocol in the quantum regime that uses phase-dependent modulations of the trapping potential at parametric resonance and phase preserving quantum measurements to cool a quantum harmonic oscillator to near its quantum-mechanical ground-state. We derive the optimal phase control for cooling, and show that the protocol provides an average cooling power proportional to the mean quanta in the oscillator. We demonstrate the robustness of our cooling protocol against dissipation as well as phase errors in the feedback loop. Our work has implications for the cooling of mechanical resonators in the quantum regime and as a quantum refrigerator that can be integrated into circuits.

Quantum signature in the dynamics of a single oscillator

Valerio Scarani

When considering "what is quantum" in a harmonic oscillator, first comes to mind the discreteness of energy levels. Also, one can prepare non-classical states (although, strictly speaking, states are independent of the dynamics). By contrast, the time evolution of harmonic oscillators is supposed to be as classical as it gets: it is just the usual precession in phase space. Based on an unnoticed work by Tsirelson [1], I shall show how to detect the quantumness of an oscillator by looking at its "trivial" time evolution [2]. This unexpected observation is state-dependent and comes from the basic fact that position and momentum do not commute. The only assumption needed for this certification is that the system is indeed undergoing a uniform precession, and that the same variable is being measured in all the rounds (at possibly different times in every round). The idea can be extended to measures of entanglement between different oscillators.

[1] B. Tsirelson, https://arxiv.org/abs/quant-ph/0611147
[2] L.H. Zaw, C. Aw, Z. Lasmar, V. Scarani, in preparation

Light-induced dipole-dipole interaction between nanoparticles

Uros Delic

Invited Talk

Strong Optomechanical Coupling of Levitated Nanoparticles to an Optical Cavity

Andres de los Ríos Sommer

After a decade of experimental efforts, the milestone of preparing the centre of mass motion of a levitated nanoparticle in its ground state was recently achieved [1,2,3,4]. Enabling coherent optomechanical control of this motion is now paramount. In this work we use coherent scattering [5,6] to demonstrate the strong coupling regime (SCR) between the motion of an optically levitated nanoparticle to an optical cavity mode, a necessary condition for coherent control. The SCR is characterized by the optomechanical coupling strength (OCS) exceeding both the mechanical and optical dissipation rates. We observe normal mode splitting of the particle's motion, an unambiguous signature of the SCR [7], and extract a maximum value of $2\pi * 23$ kHz for the OCS, which is more than twice the optical decay rate. We also show that the OCS can be modulated by varying experimental parameters such as the particle's position or the detuning between the optical trap and cavity resonance. This modulation is crucial for coherent optomechanical control which can be attained by reducing the thermal decoherence rate to magnitudes routinely reached by similar experiments [1, 2, 3, 4, 8].

[1] Delić U. et al, Science, 367, 6480, (2020)
[2] Magrini L. et al, Nature, 595, 373, (2021)
[3] Tebbenjohanns F. et al, Nature, 595, 378, (2021)
[4] Ranfagni A. et al, arXiv:2112.11383 (2021)
[5] Delić U. et al, PRL, 122, 123602, (2019)
[6] Windey D. et al, PRL, 122, 123601, (2019)
[7] Groblacher S. et al, Nature, 460, 724-727, (2009)
[8] Meyer N. et al, PRL, 123, 153601, (2019)