Levitated Systems for Directional Direct Dark Matter Detection

Peter Barker, Prof Chamkaur Ghag, Fiona Alder, Jonathan Gosling, Robert James

Levitated quantum optomechanics provides a novel platform for tests of fundamental physics. The isolation afforded by levitation in vacuum, coupled with the ability to cool particles to the quantum ground state, opens 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. We present the progress made towards the development of a levitated optomechanical direct dark matter experiment, capable of resolving collisions in all three dimensions by utilising nanoparticles (10^-18 kg) 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 sensitivity projections competitive with world-leading dark matter constraints. Finally, we present planned work to enhance sensitivity to unexplored parameter space in the search for dark matter using alternative levitated systems.

Squeezed light from free space levitated nanoparticle at room temperature

Victor A. Camarena-Chavez, Lorenzo Magrini, Constanze Bach,Aisling Johnson, Markus Aspelmeyer

Quantum measurements of mechanical systems can produce optical squeezing via ponderomotive forces. Its observation requires high environmental isolation and efficient detection, typically achieved by using optical cavities and cryogenic cooling. Here we realize these conditions by measuring the position of an optically levitated nanoparticle at room temperature and without the overhead of an optical cavity. We use a fast heterodyne detection to reconstruct simultaneously orthogonal optical quadratures, and observe a noise reduction of 9% ± 0.5% below shot noise. Our experiment offers a novel, cavity-less platform for squeezed-light enhanced sensing. At the same time it delineates a clear and simple strategy towards observation of stationary optomechanical entanglement.

Cavity optomechanics implemented using levitating superconductors and Josephson microwave circuits

P. Schmidt, J. Hofer, G. Higgins, S. Minniberger, J. Hansen, S.Z.D. Plachta, R. Claessen, M. Trupke, and M. Aspelmeyer

Experimental investigation of quantum mechanics with macroscopic objects is an important goal in the study of the limits of quantum mechanics and its connection to gravity. Current techniques, utilising optical levitation, have achieved ground state cooling of the mechanical motion of microparticles of femtogram masses . However, optical traps can introduce decoherence from photon scattering and heating of the levitated particle. Superconducting magnetic traps could overcome this and be made free of dissipation. Further challenges for the quantum control of heavier objects are posed by the need to decouple the quantum object from environmental influences, while maintaining a high control of the object, a challenge increasing with the mass of the object.

The approach of superconducting microspheres (of the order of 6 μg) in a magnetic field trap, allowing for a mass independent levitation, is implemented in an attempt to overcome the aforementioned challenges. By inductively coupling the mechanical motion to resonant superconducting quantum circuits, we aim to reach sufficiently high optomechanical coupling rates to enable quantum states of motion in a completely new regime of masses. This poster discusses the prospects and challenges of the envisioned approach along with the current status of our experiment and read-out system.

Ultra-Strong Coupling in Levitated Cavity Optomechanics

Kahan Dare, Jannek J. Hansen, Iurie Coroli, Aisling Johnson, Uros Delic, and Markus Aspelmeyer

Levitated nanoparticles have long been heralded as an excellent platform for quantum sensing. Recent proposals have sought to utilize instability due to ultra-strong coupling via coherent scattering but this regime has been out of reach to experimental systems. We report the first levitated optomechanical system to operate in the ultrastrong coupling regime, reaching a maximum coupling of gx/\Omega x = 0.5 operating in the resolved sideband regime using the radial motion of the nanoparticle in an optical tweezer. Additionally, we can realize deep strong coupling of the axial mode reaching gz/\Omegaz = 1.2. Finally, we demonstrate a simple extension to this realization which can dramatically improve the coupling rates.

Programmable trap array of levitated nanoparticles

Manuel Reisenbauer, Livia Egyed, Anton Zasedatelev, Henning Rudolph,
Klaus Hornberger, Ben Stickler, Markus Aspelmeyer, Uros Delic

Arrays of coupled mechanical oscillators have been proposed for studies of collective effects such as non-reciprocal phonon transport, investigation of topological phases or multipartite entanglement. However, typical experimental architectures are usually either based on fabricated structures or use an optical cavity to mediate the interaction between multiple mechanical modes, thus limiting the maximal number of elements and their interaction tunability, as well as prohibiting individual detection of the oscillators. Here, we present a novel approach by creating a tunable trap array of levitated nanoparticles. Our platform allows for independent control and individual readout of the particles motion. In contrast to standard cavity-mediated setups, we exploit the light-induced dipole-dipole interactions to couple the particles directly. The ability to control the non-reciprocal particle interaction allows for interesting and versatile multiparticle dynamics. We will present first results on the dynamics of two particles and discuss further extensions.

Eliminating cavity mediated hybridisation and frequency shifts from levitated cavity optomechanics

Hayden Fu, Julian Iacoponi, Antonio Pontin, Tania Monteiro, Peter Barker

Coherent Scattering (CS) has proven to be a ground-breaking technique in the field of levitated cavity optomechanics [1]. With recent works demonstrating ground-state cooling of one Centre of Mass (CoM) motion [2], and very low phonon occupancies in two CoM degrees of freedom [3]. In this poster, we showcase our experiment exploring two-dimensional motional cooling of silica nanoparticles, using a monolithic tweezer assembly and a high finesse cavity. Our results exploit CS to demonstrate the cooling of a silica nanosphere (of nominal diameter 120nm), in the two axes of the tweezer polarisation plane, down to 21±1 and 34±1 phonons. These preliminary results bring us very close to the quantum regime. Currently, our system has ample margins for improvement and there is a clear path forward to reach the two-dimensional ground state in the near future.

Utilising the same CS setup, we can sweep the position of the nanosphere across the cavity standing wave. As the nanosphere is moved from the node to the antinode, the resultant CS field can oppose both: the optical spring shifts to the 2D motional frequencies of the nanosphere; and the hybridisation of these mechanical modes. An optimal cancellation point for both these effects is experimentally demonstrated to be approximately at the midpoint of the node and antinode, matching well with the theoretical predictions, and showing the possibility of strongly cooling and controlling the unperturbed modes. Successfully suppressing the hybridisation of these modes (and thus, leaving them uncorrelated) shows the potential of using CS set-ups for directional force sensing.

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[2] Delic, Uros, et al. "Cooling of a levitated nanoparticle to the motional quantum ground state." Science 367.6480 (2020): 892-895.
[3] Ranfagni, A., et al. "Two-dimensional quantum motion of a levitated nanosphere." arXiv preprint arXiv:2112.11383 (2021).

Suppression of Rayleigh Scatter in Levitated Optomechanics

Rafal Gajewski

Advanced sensing applications utilising levitated particle systems require the creation of large spatial superpositions of the trapped nanoparticle, which suffer from rapid decoherence due to the trapping laser. The laser photons which the particle scatters, randomly perturb the particle's motion. In this work we theoretically predict that the scattering rate of a point polarisable particle trapped at the centre of a large hemispherical mirror can be fully suppressed. A potential experimental configuration is also presented, addressing some of the experimental challenges.

Cavity optomechanics with levitated nanoparticles and atomic ions

Florian Goschin, Dmitry S. Bykov, Lorenzo Dania, Nina Erhart, Katharina Heidegger, Max Meusburger, Tracy E. Northup

The generation of non-classical states of motion of macroscopic objects is thought to be a crucial step to experiments investigating the interaction of gravity and quantum mechanical systems and the development of ultra-sensitive force detectors. In order to prepare such a quantum state of motion, we plan to take advantage of the highly non-linear properties of a single calcium atom and couple it to a macroscopic mechanical oscillator in the motional ground state via a high-finesse cavity. As optomechanical systems, levitated nanoparticles benefit from the absence of physical contact with the external environment, which makes it possible to achieve extremely low damping rates and, as a result, ultra-high quality factors of mechanical oscillations. We use electrodynamic traps (Paul traps) to levitate charged dielectric particles (and ions) in ultra high vacuum (10e-11 mbar) and cool their center-of-mass (CoM) motion using cold-damping techniques.

Co-trapping: It has been proposed to simultaneously trap a mesoscopic particle and a single atomic ion by superimposing two radiofrequency quadrupole fields. A slow field in the kilohertz range is used to confine the mesoscopic particle while the fast megahertz field confines the lighter calcium ion. An alternative approach is based on a hybrid trap which uses different trapping mechanisms for both objects. Here we present a such hybrid trap, consisting of an optical dipole trap and an electrodynamical trap. A silica nanoparticle is transferred from the former to the latter. This approach could open up new possibilities for levitated optomechanical systems combining the benefits of both types of traps. Nonetheless, we also use Paul traps to explore routes towards other hybrid systems, such as levitated particles with internal degrees of freedoms.

Sympathetic cooling of nanoparticles: In contrast to optical traps, Paul trap do not rely on strong optical fields and thus open up possibilities to investigate nanoparticles that are sensitive to optical fields. However, state-of-the-art experiments use a laser field to measure the particleÕs position, and an additional laser is used for cold damping, both of which do heat the particle and limit the range of materials that can be measured and manipulated. A solution to this problem is offered by sympathetic cooling of the trapped particle, which is achieved by coupling it via Coulomb interaction to an auxiliary particle. Such sympathetic cooling has been realized in experiments with atomic ions, molecular ions and proteins. Here, we demonstrate sympathetic cooling of a levitated mesoscopic silica particle without direct laser illumination by cooling an identical particle in the same trap. Furthermore, it is possible to detect the particle motion sympathetically, which paves the way for experiments investigating absorptive particles in high and ultra-high vacuum.

Levitodynamic spectroscopy for single nanoparticle characterisation

Jonathan Gosling, Markus Rademacher, Jence Mulder, Marko Toros, A. T. M. Anishur Rahman, Antonio Pontin, Arjan Houtepen, and Peter Barker

Fast detection and characterisation of single nanoparticles such as viruses, airborne aerosols and colloidal particles is important for medicine, material science and levitated optomechanics. In this poster, we present a spectroscopic technique based on the measurement of pendular and oscillatory motion of a nanoparticle levitated in an optical dipole trap. We apply this technique to colloidally grown YLF nanocrystals and demonstrate that both the pendular motion, and the linewidths of the translational motion, can be used to characterise the shape of a single nanocrystal, with size differences as small as a few nanometers.

SQUID-based center-of-mass motion detection of a superconducting 50um lead sphere levitated on a chip

Marti Gutierrez Latorre, Achintya Paradkar, Gerard Higgins, and Witlef Wieczorek

Magnetic levitation of superconducting objects allows for extreme isolation from the thermal environment, no internal mechanical losses, tunability of mechanical properties, and coupling to superconducting quantum circuits. These are advantageous features that can be employed to generate motional quantum states of massive objects. Thus, levitated superconductors have been proposed as a promising platform for macroscopic quantum experiments [1-4], and the development of very precise force and acceleration sensors [2,5].

We demonstrate magnetic trapping and detection of the center-of-mass (COM) motion of a \SI{50}{\micro\meter} superconducting lead sphere inside a chip-based trap, at \SI{4}{\kelvin} and millikelvin temperatures. We fabricate sub-100$\,\mu$m lead spheres by ultrasonic cavitation. The magnetic trap is made of two chips, each with several microfabricated, co-planar, niobium superconducting coils. The two chips are stacked on top of each other to form an anti-Helmholtz-like coil arrangement.

One pair of integrated, multi-winding coils is used to create the magnetic quadrupole-like trapping field. A second pair of coils, located within the larger, multi-winding coils, is used as a pick-up loop, connected to a DC-SQUID magnetometer, to detect the COM motion of the particle. We show that the measured COM frequencies (between 30-\SI{150}{\hertz}) are in good agreement with 3D FEM simulations of the system's mechanics [6,7]. We further show stability of the system over at least one day. Quality factors are on the order of 10^{3} to 10^{4}. Future experiments focus on increasing COM frequencies and quality factors, as well as feedback cooling of the COM modes using independent integrated coils.

Cooling the mechanical motion of a magnetically levitated superconductor by interferometric readout

Jannek J Hansen, Stefan Minniberger, Gerard Higgins, Philip Schmidt, Joachim Hofer, Remi Claessen, Stephen Z. D. Plachta, Markus Aspelmeyer and Michael Trupke

Quantum optomechanics has become a leading frontier in quantum control. The missing exper- imental link between gravity and the quantum world might be in reach for tabletop experiments with quantum control of massive particles [1]. Recently, the quantum mechanical ground state of the mechanical mode of optically levitated particles has been demonstrated [2, 3]. Simultaneously, the gravitational interaction between mm-sized objects has been measured [4]. Compared to the optically levitated dielectric particles, magnetic levitation of superconductors could enable quantum control of significantly higher masses, therefore closing the gap between gravitational detectable masses and a sensitivity on the quantum level [5]. To control a harmonic oscillator on the quantum level, it needs to be well isolated from environmen tal noise. The Meissner effect causing the levitation of type-I superconductors is inherently dissipation free. Using persistent currents as field sources and superconducting shields, traps virtually free of electromagnetic noise can be realized. With effectively damped suspension of the trap setup, cryostat- and other vibrations can also be minimized, thus resulting in the best attainable decoupling from the environment. Cooling the mechanical motion towards the quantum limit requires a weakly coupled measurement with a precision in the order of the ground state motion resolved in the time frame of one oscillation. Laser interferometry is widely used to resolve position changes orders of magnitude below the wave- length of the employed light. In this experiment, one arm of a Michelson interferometer is reflected from the surface of a levitated sphere. For typical masses and frequencies, the ground state motion is on the order of several fm [6]. This is challenging but within the range of state of the art interferome- ters. Compared to schemes using SQUID based detection, this readout also works at low frequencies which is desirable in Cavendish like experiments [4]. In this first proof-of-principle experiment, we levitate a 100 micron sized sphere in a superconducting anti-Helmholtz coil configuration. The trap provides trapping frequencies in the 100 Hz regime, with the coil axis oriented vertically. We focus the laser on the sphere from above and detect the reflected light with a single photon counter. To lift the degeneracy in the horizontal plane, two lasers with different colors are installed. We are able to detect the reflected light and use it to cool all 3 axes of the motion to sub-um amplitude by direct feedback. At the current stage, the interferometric signal is being calibrated.

Detecting a Levitated Nanoparticle with Self-Interference

Katharina Heidegger, Lorenzo Dania, Dmitry S. Bykov, Giovanni Cerchiari,
Gabriel Araneda, Rainer Blatt, Tracy E. Northup

A sensitive method to detect the position of a levitated nanoparticle is one crucial factor to efficiently feedback-cool the particleÕs center-of-mass motion. A typical position detection is based on interference between the light scattered by the particle and a reference Gaussian beam in a homodyne setup. The efficiency of this scheme is mainly limited by the numerical aperture (NA) of the lens that collects the scattered light of the particle and by the mode mismatch between the reference beam and the dipolar scattered field. The NA limitation is especially pronounced in setups with low optical access, like Paul traps. Here we demonstrate a novel detection scheme that allows us to overcome these limitations. It provides interferometric detection of a dipolar scatterer that operates at the Heisenberg limit. The technique is based on self-homodyning the scattered light. For this purpose, the solid angle around the particle is divided into two halves, one covered by a hemispherical mirror and the other occupied by a hemispherical pixel detector. On the mirror side, the scattered light is back-reflected onto the particle and forms a secondary image. On the detector side, the directly scattered field and the reflected field interfere. From a comparison with commonly used techniques, we predict a superior performance of the self-homodyne method in terms of measurement imprecision for numerical apertures typically used in particle trapping setups. The major factors for this superior performance are the optimal mode match between source and reference field and the increased collection efficiency. We implement a first experimental realization of self-homodyne detection of a nanoparticle levitated in a Paul trap. We reach a position sensitivity of 1.7 x10^-12 m/\sqrt Hz, which corresponds to a detection efficiency of \eta = 2.1(4) % for a NA of 0.18. We show that this reduces the measurement imprecision by three orders of magnitude compared to a forward detection method that is implemented in the same setup. As an application, we use the signal obtained with the self-homodyne technique to cool the center-of-mass motion.

Testing quantum mechanics with heavy objects - using magnetically-levitated superconducting microparticles

Gerard Higgins, Joachim Hofer, Philip Schmidt, Stefan Minniberger, Jannek Hansen, Remi Claessen, Stephen Plachta, Michael Trupke, Markus Aspelmeyer, Marti Gutierrez Latorre, Achintya Paradkar, Avan Mirkhan, Witlef Wieczorek

It is unclear how our classical world emerges from the quantum world. It is also unclear how to incorporate effects of gravity into quantum mechanics. To get experimental insights into these problems, we need to prepare larger masses in quantum states. Magnetically-levitated superconducting microparticles make promising systems for doing this. We work with a lead microsphere of ~ 10^18 amu (~ 1 microgram) which we isolate from its surroundings using magnetic levitation. We read out the sphere's COM motion using a SQUID and cool the motion by applying additional magnetic fields. We observe excellent Q-factors of the COM motion, exceeding 10^7. We will extend our control by coupling the sphere's motion to superconducting resonators and qubits.

Hybrid quantum systems formed by cold atoms and levitated nanospheres

A P Hopper and P F Barker

Optical potentials created by incident and scattered optical fields around a levitated nanosphere can be used for sympathetic cooling and for creating a bound nanosphere-atom system analogous to a large molecule. We demonstrate that long range potentials can be produced allowing fast sympathetic cooling of a trapped nanosphere to microKelvin temperatures using cold atoms.

Rotational Optomechanics

Yanhui Hu, Maryam Nikkhou, James Sabin, Muddassar Rashid and James Millen

Levitated optomechanics opens the door for many quantum experiments and sensing applications with the advantage of minimising the dissipation to the environment. This has enabled control and cooling the motion of levitated nanoparticles to quantum level, yielding great potential for detecting a wide range of forces.

In this project, we present a clean, vacuum compatible method for loading nanoparticles into optical traps, based on laser-induced acoustic desorption (LIAD). We investigate the effect of the pulsed laser intensity and the pressure on trapping efficiency for an optical standing wave trap in vacuum. Furthermore, full control and cooling of all degrees of freedom (center-of-mass and rotational degrees of freedom) will be researched and demonstrated. By trapping a particle with anisotropic susceptibility (a silicon nanorod) in an optical tweezer, the trapping frequencies are increased, and rotations can be driven using circularly polarized light. Feedback will be applied to cool the librational motion by controlling the polarization of the trapping light field. A second trap is also being built using a cavity with a counter-propagating tweezer. This trap will use the tweezer to hold nanoparticles and use coherent scattering in order to cool the particles. By using elliptically polarized light in the tweezer, the translational and rotational degrees of freedom can be cooled simultaneously.

Dry & clean loading of nanoparticles in vacuum

Ayub Khodaee, Kahan Dare, Aisling Johnson, Uros Delic, Markus Aspelmeyer

One of the main challenges for any trapping mechanism is controlled dry loading of particles in vacuum. Surpassing this challenge will expand the optomechanical experiments with nanoparticles to ultrahigh vacuum, isolating the system from the environment sufficiently well to realize macroscopic quantum states, e.g. a superposition. Recently, loading of microparticles using piezoelectric shaking has been demonstrated, thus providing a simple and versatile method of launching dry particles. However, launching smaller nanoparticles has remained a challenge due to the strong binding forces between the deposited particles and the launching pad. Here, we are presenting successful launching of nanoparticles with piezoelectric shaking. We report loading a silica nanoparticle with diameter as small as 143 nm directly into an optical tweezer at high pressure. Finally, we discuss the limits of this launching method and propose a way to load the particles directly into an optical trap in high vacuum.

Mechanical squeezing via unstable dynamics in a microcavity

Katja Kustura, Carlos Gonzalez-Ballestero, Andres de los Rios Sommer, Nadine Meyer, Romain Quidant, Oriol Romero-Isart

We theoretically show that strong mechanical quantum squeezing in a linear optomechanical system can be rapidly generated through the dynamical instability reached in the far red-detuned and ultrastrong coupling regime. We show that this mechanism, which harnesses unstable multimode quantum dynamics, is particularly suited to levitated optomechanics, and we argue for its feasibility for the case of a levitated nanoparticle coupled to a microcavity via coherent scattering. We predict that for sub-millimeter-sized cavities the particle motion, initially thermal and well above its ground state, becomes mechanically squeezed by tens of decibels on a microsecond timescale. Our results bring forth optical microcavities in the unresolved sideband regime as powerful mechanical squeezers for levitated nanoparticles, and hence as key tools for quantum-enhanced inertial and force sensing.

Bayesian inference for near-field interferometric tests of collapse models

Shaun Laing

Standard quantum theories do not place any limits on the size and mass of objects that the theory is valid for. However, we do not see the predicted, and experimentally proven, quantum effects on everyday classical scales. A number of modifications to the standard quantum theory exist to explain this appar- ent quantum-to-classical transition. The parameters that define these modified theories remain a mystery, and further experiments with ever larger systems are needed to push the bounds of these parameters. We apply a Bayesian approach to a matter-wave interferometry experiment to find new upper bounds on the parameters of these models, specifically continuous spontaneous locali- sation theory, with the use of large test particles in the ranges of 108 to 1011 AMU.

Levitodynamics with optically active nanocrystals

Cyril Laplane, Reece P. Roberts, Peng Ren, Yiqing Lu and Thomas Volz

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 [R1, R2,R3]. 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. Optical levitation usually relies on the 'bulk' polarizability of the nanoparticle itself. Here we explore the possibility of harnessing the polarizability of electronic resonances of rare-earth ions. When embedded in nanocrystals, these 'quantum' polarizabilities contribute to the total optical force [R4]. For high enough doping, it should be possible to generate atomic-like dipole forces that can be attractive or repulsive and we also expect cooperative forces to play a role [R5]. Furthermore, rare-earth ion doped crystals are one of the few materials enabling laser refrigeration which is particularly relevant for levitation in vacuum as it enables control over the internal temperature of the levitated nanoparticle [R6]. This is particularly relevant since particle vaporization due to heat is a known loss mechanism for particles levitated in vacuum. In our lab, we investigate different materials and nanoparticle designs in order to better understand and control both atomic dipole forces and laser refrigeration. I will give an overview over our experimental efforts and highlight the outstanding challenges. Ultimately, our approach would enable access to advanced tools for the quantum manipulation of levitated mesoscopic systems, overcoming current bottlenecks in experimentation and possibly opening up new avenues for accessing fundamental physics.

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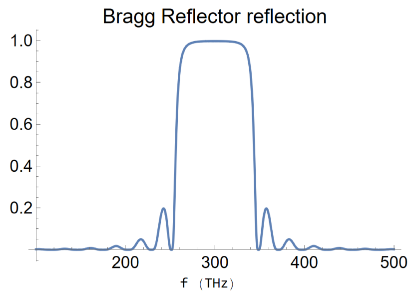
R2. F. Tebbenjohanns & al., Nature 595, 378_382 (2021).
R3. L. Magrini & al., Nature 595, 373_377 (2021).
R4. M. L. Juan & al., Nat. Phys. 13, 241_245 (2017)
R5. B. Prasanna Venkatesh & al., Phys. Rev. Lett. 120, 033602 (2018)
R6. A. T. M. Rahman and P. F. Barker, Nature Photonics 11, 634-638 (2017)

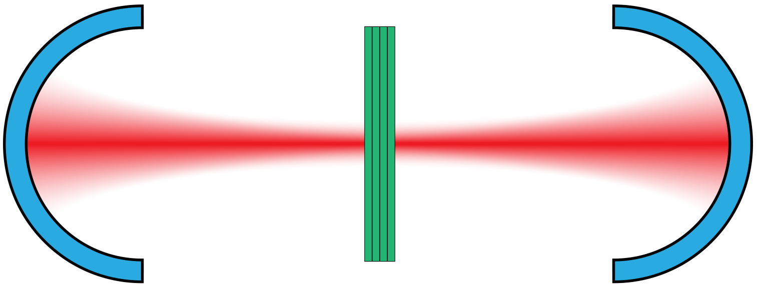
Boosting Optomechanical Coupling with a Bragg Mirror

Shalika Singh, Ruvi Lecamwasam, and Jason Twamley

Optomechanical systems explore the interaction between electromagnetic fields and mechanical motion, the prototypical example being an optical cavity where one mirror oscillates on a spring [1]. The ability to combine optical and mechanical techniques makes these systems some of the most sensitive measuring devices in existence — most notably the LIGO gravitational wave detector. There is thus much ongoing work on the application of optomechanics to metrology, generation of interesting quantum states, and fundamental experiments about the nature of quantum gravity and collapse theories. The power of an optomechanical system is quantified by the single photon optomechanical coupling, which measures how strongly each photon of the electromagnetic field affects the mechanical oscillator. Recent work has shown that this may be increased by using frequency-dependent mirrors formed by atomic resonances [2]. The system also showed improved ability to damp thermal noise, and interesting physical effects such as non-Markovianity. At present, frequency-dependent optomechanics is largely unexplored. A common optical element showing such frequency-dependent behaviour is a Bragg Reflector (BR), formed by alternating layers of dielectric material. Interference between different layers can lead to a very sharp dependence of reflection upon wavelength, as shown in Figure 1 Left. The shape of this reflection curve is highly tunable, depending on the refractive indices and relative sizes of the layers. Our work studies how this may be used in optomechanics.

We consider two cavities coupled by a movable Bragg reflector (BR) as in Figure 1 Right. As the BR is displaced reflection at the laser wavelength varies, leading to a coupling between the optical cavities mediated by the position of the reflector. We derive equations of motion for this system, and show that the optomechanical coupling is increased due to the properties of the BR. We quantify the performance attainable from real-world parameters. Finally we study how the position dependent force on the mirror may be used for levitation experiments.





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Towards On-Chip Spin-Magnetomechanical Levitated Systems

T. Madhavan, J. D. Schaefer, E. Rosenfeld, F. Fung, A. Mulski, M. D. Lukin

Interfacing quantum nonlinearities with the mechanical regime has become an exciting research direction with long term applications such as unprecedented quantum sensitivity and mechanically-mediated quantum networks. Moving these hybrid architectures towards an integrated on-chip technology is of particular interest for enhanced stability and scalability. We have demonstrated spin-mechanical coupling on a novel platform comprised of a mechanical resonator and a spin qubit. The mechanical resonator consists of a micromagnet in a three-dimensional trap formed by a type-II superconductor, offering excellent environmental isolation and a high magnetic gradient to mass ratio. We choose to work with NV centers in diamond as our spin qubit due to their long coherence times, large magnetic coupling, and optical initialization and readout. Coupling between the resonator and the spin is achieved by bringing the levitated magnet in close proximity to an NV center. We discuss recent improvements to the platform, which will allow us to achieve stronger spin-mechanical couplings, enabling near-term milestones such as the detection of quantum backaction, which is a first step towards mechanics in the quantum regime. In addition, we will also discuss our progression towards an on-chip spin-mechanical system, offering NV centers with microwave control and superconductor trapping on one compact device.

Towards deep laser cooling of the internal and external motion of trapped nano-particles

Lucas R. Mendicino, Christian T. 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.

Towards coupling a levitated superconducting microparticle to a flux-tunable superconducting cavity

Achintya Paradkar, Avan Mirkhan, Marti Gutierrez Latorre, Gerard Higgins, and Witlef Wieczorek

Levitating superconducting microparticles in an inhomogeneous magnetic field provides a tunable and passive trap, with no photon recoil heating and hysteresis and eddy current losses. It is then expected that the centre-of-mass (COM) motion of the levitated particle exhibits ultra-low dissipation. [1,2]. Particles with a diameter ranging from 1 micron to 100 micron can be levitated that are suitable for both acceleration and force sensing [2,3]. We have recently demonstrated levitation of a superconducting microparticle in a magnetic trap made of two on-chip superconducting coils in an anti-Helmholtz coil (AHC)-type configuration [4]. The levitation was performed at millikelvin temperature and the motion was readout using a SQUID sensor.

The magnetic trap enables flux-coupling the particle's COM motion to flux-tunable superconducting quantum circuit elements, such as transmon qubits or flux-tunable superconducting cavities. When coupling the particle motion to the latter, techniques from cavity optomechanics can be used to cool the COM motion, either via feedback cooling or resolved-sideband cooling. We achieve a trap frequency Omega_m on the order of 2pi 100 Hz, and target to achieve a mechanical quality factor (Q_m) of 10^8. Typical flux-tunable superconducting cavities operate at omega_c = 2pi 7 GHz and reach a quality factor (Q_c) of about 10^4. These parameters place the coupled system in the non-resolved sideband regime, i.e., kappa_c > Omega_m, which makes it impossible to reach the quantum ground-state with standard sideband-cooling. Thus, to achieve the quantum ground-state, we will rely on feedback-cooling. For this, two conditions must be met: (i) Q_m> initial phonon occupation n_th, which is possible with an initial temperature of 15 mK, and (ii) quantum cooperativity C_q>1 which can be achieved with a single-photon coupling rate of about 2pi 200 Hz and intra-cavity photons on the order of 10.

We present initial results in this direction. We have fabricated a first batch of flux-tunable cavities by realizing a Josephson junction-based SQUID shunted to ground at the end of a quarter-wave coplanar waveguide resonator. We characterized the cavity frequency response to a magnetic-flux applied from an external coil. Coupling to the levitated particle can be achieved either off chip via using a flux transformer or by integrating the flux-tunable cavity within the trap chip. We analyse both architectures with the goal to achieve feedback-based ground state cooling of the COM motion of the particle.

Rotational dynamics of a levitating diamond in a Paul trap

Maxime Perdriat, Clement Pellet-Mary, Gabriel Hetet

Levitation of large objects is promising for testing the limit between the quantum and the macroscopic world. It can also enable development of ultra-sensitive mechanical force sensors as well as to test stochastic thermodynamic models at the nanoscale [1]. Moreover, being able to fully control the rotational dynamic of a levitating particle opens bright prospects towards the detection of intrinsic angular properties such as the Einstein-de Haas and the Barnett effects [2]. Our platform consists in a micron-sized diamond embedded with NV centers levitating in an electrodynamic trap also called Paul trap. The angular stability of the diamond offered by the Paul trap makes this platform ideal to couple the NV centers spin to the librational modes. It has led to the first observation of mechanical cooling using the NV centers spin inside the diamond [3]. More recently, a full control of the diamond orientation has been achieved using NV centers diamagnetism due to a spin level anticrossing [4]. Aside from NV coupling to the motion, the ponderomotive nature of the Paul trap features regime where the diamond fully rotates stably at half the trap frequency. NV centers inside the rotating diamond have been used to reconstitute the full angular trajectory of the particle proving the high stability of the diamond rotation induced by the Paul trap.

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A magnetically levitated librator for measuring the gravitational interaction between milli- and micro-gram masses

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Probing gravitational interactions with small masses enables the investigation of open questions in physics, such as whether modifications to Newtonian dynamics occur at short ranges or low accelerations. It also relates to fundamental questions regarding dark matter, dark energy, and possible new (chameleon) forces. Ultimately, the preparation and measurement of the gravitational field of a quantum source mass in a superposition of spatial locations will address the apparent incompatibility of quantum mechanics and general relativity. To undertake this challenging endeavor requires systems that resolve small gravitational forces while decoupling sufficiently from all other effects of the environment. Therefore, magnetically levitated oscillators could be a perfect match. To confirm the feasibility of this idea, we present a first proof-of-principle experiment employing a diamagnetically stabilized ring magnet. We demonstrate a thermal force noise resolution on par with present state-of-the-art tethered systems. Next-generation devices could probe gravity on the microgram scale, paving the way for fundamental tests of gravitational interactions below the Planck mass and potentially at the quantum level.

Precision measurement of levitated nanoparticles via light scattering

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The field of levitated optomechanics has seen a recent increase in interest with the achievement of the cooling a single optically levitated nanoparticle to the quantum ground state in three different experimental setups [1-3]. Knowledge of the characteristic properties of the optically trapped nanoparticle has great importance for future quantum experiments ranging from quantum-limited sensing of gravity [4], to creating quantum superpositions [5]. A long-standing problem has been obtaining detailed information on the structure and geometry of the levitated nanometre-sized objects [6]. Previously established techniques fail when considering shapes different to spheres in an optical tweezer [7]. Additionally, recent work in our laboratory suggests that most of the time when load- ing spherical nanoparticles, we do not trap perfect spheres but rather get nanoparticles that have the shape of an ellipsoid with a small degree of anisotropy. Despite the importance of the laser scattering behaviour of optically trapped nanoparticles to the optimal detection [8] and nanoparticle size consistency [9], no experimental research has been done on using the scattering pattern of the optically trapped object to study the shape and geometry of a single particle in situ. Here we show a new nanoparticle characterisation technique based on observing the particle's inherent light scattering pattern. In this study, we present the underlying laser Rayleigh scattering theory on which the characterisation technique is based, show the results obtained in the laboratory and compare the experimental data to simulations modelled in a photonic design suite using the finite-difference time-domain method. Our results indicate that this method is effective in determining the geometry of the optically levitated particle in a vacuum, opening up a new method for measuring the geometry of nanocrystals.

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Optimal Generation and Detection of Nonclassical Correlations in Levitated Optomechanics

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Nonclassical correlations provide a resource for many applications in quantum technology as well as providing strong evidence that a system is indeed operating in the quantum regime. Optomechanical systems can be arranged to generate quantum entanglement between the mechanics and a mode of travelling light. Here we propose automated optimisation of the production of quantum correlations in such a system, beyond what can be achieved through analytical methods, by applying Bayesian optimisation to the control parameters. Two-mode optomechanical squeezing experiment is simulated using a detailed theoretical model of the system, while the Bayesian optimisation process modifies the controllable parameters in order to maximise the non-classical two-mode squeezing and its detection, independently of the inner workings of the model. A resource-efficient strategy to detect the nonclassical correlations is proposed.

We find that in the experimentally relevant thermal regimes, the ability to vary and optimise a broad array of control parameters provides access to large values of two-mode squeezing that would otherwise be difficult or intractable to discover. In particular we observe that modulation of the driving frequency around the resonant sideband, when added to the set of control parameters, produces strong nonclassical correlations greater on average than the maximum achieved by optimising over the remaining parameters. We also observe that our optimisation approach finds parameters that allow significant squeezing in the high temperature regime. This extends the range of experimental setups in which non-classical correlations could be generated beyond the region of high quantum cooperativity.

Preparation of Levitodynamics experiments in high vacuum with a cavity optomechanical system

A. Ranfagni, P. Vezio, M. Calamai, A. Chowdhury, F. Marino and F. Marin

We present a reliable and simply reproducible method to systematically capture and place a levitated nanoparticle inside an optical cavity, followed by a procedure to stabilize the motion of the oscillator down to high vacuum where the system is suitable for quantum optomechanics experiments. The protocol relies on the transfer of a levitating silica nanosphere between two optical tweezers at low pressure. Both optical traps are mounted on the heads of optical fibers and placed on translation stages in vacuum chambers. Our setup allows to physically separate the particle loading environment from the experimental chamber, where the second tweezer can position the particle inside a high Finesse optical cavity. The separation prevents from spoiling the cavity mirrors and the chamber cleanliness during the particle loading phase. The mechanical stability of the system, together with the low initial pressure set by the transfer protocol, allow us to reliably reach a high vacuum in a reasonable time. The experimental vacuum chamber is evacuated while the three dimensional mechanical motion is stabilized through the coherent scattering method. During the evacuation, the particle is positioned on the cavity optical axis with sub micrometric precision.

As the pressure is decreased, the deduced total decoherence rate for the motion on the plane perpendicular to the trapping beam shows that no significant extra noise is present in our system. In line with this result, in high vacuum we can distinguish the dipole scattering rates in the two normal modes. The observed difference is in excellent agreement with the theoretical model. At such low pressures the oscillator is highly decoupled from the thermal environment and quantum optomechanical effects are unveiled.

Levitated Electromechanics

Katie O'flynn, Yugang Ren, Muddassar Rashid, James Millen

Levitation of mesoscopic particles in high vacuum provides a promising platform to investigate nanoscale thermodynamics and the boundary between the classical and quantum worlds. In this work we levitate charged microparticles in electrodynamics traps. We explore nanothermodynamic processes by generating synthetic environments using fluctuating electric fields. We also present the use of event based imaging to enable real-time multi-particle tracking.

Observation of strong and tunable light-induced dipole-dipole interactions between optically levitated nanoparticles

Jakob Rieser, Mario A. Ciampini, Henning Rudolph, Nikolai Kiesel, Klaus Hornberger, Benjamin A. Stickler, Markus Aspelmeyer, Uros Delic

ptically levitated nanoparticles have shown great advances as a research platform in recent years. By achieving ground state using cavity opto-mechanics, and feedback schemes the excellent control is demonstrated. An obvious step forward is to extend this control to trap arrays, which allow the study of interparticle interactions that couple their motion, promising enhanced force sensitivity or even using such coupling to generate entanglement. In this poster we focus on light mediated coupling, the dipole dipole interaction, of two nanoparticles levitated in independent optical tweezers. Optical interactions, in the form of optical binding, were already studied with dielectric microparticles, or using liquid suspended metallic nanoparticles in single optical traps. In contrast to these experiments our system allows independent control of the phase, power and position of each trap via a Spatial Light Modulator allowing us to tune and probe light mediated coupling in a wide range of parameters. This allows us to study even non-conservative and non-reciprocal light mediated interactions.

Normal modes, Non-normal modes, Bifurcations, Limit Cycles and Synchronization: Levitational Optomechanics of Multi-Particle systems

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Optical traps are often thought of in terms of systems of conservative forces, confining particles at thermodynamic equilibrium within an all-embracing potential. This is an appealing picture, with great utility. However, it is at odds with the fact that light is a flow of momentum, and that optomechanical systems combine dissipative and non-conservative forces and should, therefore, exhibit the rich and diverse dynamical features we expect from such systems. Here, we demonstrate these two facets of optomechanics. Starting with a highly symmetric geometry we describe the formation of normal modes, typical of conservative systems, for small displacements of small numbers of microspheres in a cross-polarized, counter-propagating trap. In addition we quantify the non-linearities encountered for greater displacements as well as the mode splitting induced by hydrodynamic coupling [1]. Next we describe the linearly non-conservative effects introduced by symmetry breaking first by optical spin momentum, and then by material birefringence [2,3]. In both cases, a non-conservative instability results in a Hopf bifurcation and the formation of noisy limit cycles whose coherence increases with increasing optical power or decreasing pressure. Finally, we show that such limit cycles can be synchronized through optical interaction forces, leading to highly coherent coordinated motion. In conclusion, these non-Hermitian optomechanical systems provide an ideal testbed for the a range of non-equilibrium stochastic phenomena, and could form the basis for a new class of optomechanical crystal.

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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.

Generation of macroscopic quantum motional superpositions using superconducting quantum circuits

S. Raman Nair*, S. Tian*, G.K. Brennen, M. Toroÿs, S. Bose and J. Twamley

Trapping, cooling and driving a large massive object towards novel quantum motional states, or Schrodinger cats, is a highly challenging but much sought after goal and is useful for quantum sensing, testing quantum mechanics at large scales and exploring the role of gravity in quantum systems [1]. The goal is to achieve macroscopic quantum superpositions, where the spatial separation between the individual cats: \Delta x, is much larger than their zero point motion xzpm. To achieve this one requires systems which possess ultra-low decoherence, and some way to provide a coherent superposition of forces to displace the object into an ultra-large spatial superposition. In this work we examine two methods to produce ultra-large spatial superposition of massive nanometer to micron sized objects where the ratio can reach values \chi= \Delta x/xzpm > 10^6 [2]. In the first method we consider the levitation of an insulating ferromagnetic spherical particle of radius R ~ 50 nm, held in a low frequency trap and we use nearby superconducting circuits that produce quantum magnetic forces to create a spatial superposition and find we can achieve \chi> 10^4 , with motional Q ~ 10^6 - 10^9 [3]. In the second method we propose the magnetic levitation of an entire superconducting quantum circuit. We note that certain types of superconducting circuits can be driven via induced couplings and do not require a direct galvanic contact with the driving circuit. This permits entire superconducting circuits to be levitated and driven inductively. We consider superconducting circuits on spatial scales of 100-300 microns and show under what conditions they can be levitated and compute, both analytically and numerically (via Comsol), their motional trap frequencies. We find that by driving these circuits inductively we can achieve extremely large values for \chi> 10^6 , again with ultra-high motional Q values.

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Probing Modified Gravity with Magnetically Levitated Resonators

Chris Timberlake, Andrea Vinante, Francesco Shankar, Andrea Lapi and Hendrik Ulbricht

Levitated magnets are highly decoupled from their environment, making them exceptional candidates for force and acceleration sensing. Here, we propose an experiment based on Meissner effect levitation of NdFeB magnets as a method to measure the gravitational interaction between two levitated, and electromagnetically isolated, 4mg magnets. Given the low accelerations being measured here, we argue it is possible to probe Modified Newtonian Dynamics (MOND) theories, which offer alternative explanations to dark matter theories to account for observed galaxy dynamics, with a table-top experiment.

Precision calibration of the Duffing oscillator with phase control

Marc T. Cuairan, Jan Gieseler, Nadine Meyer, Romain Quidant

The Duffing oscillator is a nonlinear extension of the ubiquitous harmonic oscillator and as such plays an outstanding role in science and technology. Most nonlinear oscillators are well described by the lowest order nonlinear coefficients. For spatially symmetric oscillators the two dominant nonlinear contributions are the damping coefficient and amplitude squared dependent spring constant, also known as the Duffing or \chi3 nonlinearity. Experimentally, the system parameters are determined by a measurement of its response to an external excitation. When changing the amplitude or frequency of the external excitation, a sudden jump in the response function reveals the nonlinear dynamics prominently. However, this bistability leaves part of the full response function unobserved, which limits the precise measurement of the system parameters. Precision measurements require to determine all system parameters precisely and accurately. This is done through calibration measurements and model fitting. Generally, the richer the dataset employed in model fitting, the higher is the accuracy; and the bigger the dataset is, the higher is the precision of the parameters. We show that with active phase stabilization of a driven nonlinear nanomechanical oscillator we are able to probe the otherwise unstable branch of the oscillator's response function . The phase control allows us to precisely determine the system parameters. Our results are particularly important for characterizing nano-scale resonators, where nonlinear effects are observed readily and which hold great promise for next generation of ultra-sensitive force and mass measurements. We demonstrate our approach experimentally with an optically levitated particle in high vacuum.

Towards Macroscopic Spatial Superposition of Nanodiamonds

B. D. Wood, G. A. Stimpson, J. E. March, Y. N. D. Lekhai, C. J. Stephen, B. L. Green, A. C. Frangeskou, L. Gines, S. Mandal, O. A. Williams, S. Bose, and G. W. Morley

Levitated nanodiamonds containing negatively-charged nitrogen-vacancy centres (NV-) have gained interest as a platform to generate macroscopic spatial superpositions [1-4]. Requirements for this include having a long NV- spin coherence time (T2), and avoiding excess internal heating due to the trap. We propose an experimental scheme to generate a macroscopic spatial superposition that relies on magnetic teeth which we introduce to allow spin dynamical decoupling pulses to be applied [5]. This maximises the NV-T2 time without cancelling the spatial superposition generation through the Stern-Gerlach effect. In nanodiamonds the longest NV- spin coherence times measured up to now are 708 μs and 210 μs for isotopically-purified and natural-abundance diamond respectively [6,7]. Here, we show that the T2 of NV- in natural abundance 13C nanodiamonds produced by milling can exceed 400 μs at room temperature [8]. We are building a diamagnetic trap to levitate micron sized diamonds at low pressure without excess heating, similar to that in reference 9. This trap should be suitable for putting one of these diamonds into a spatial superposition with a femtometer superposition distance, without free-fall [2,3].

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